Multi-Machine, Multi-Discharge Validation of TGLF on Alcator C-Mod and ASDEX Upgrade

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A multi-machine, multi-discharge validation study of the turbulent transport code TGLF [1] has been performed with experimental data from 11 discharges on Alcator C-Mod and ASDEX Upgrade. Results are used in order to determine when multi-scale simulations are necessary, and when ion-scale simulations are sufficient.

If one would like to eventually use turbulent transport models to predict the performance of future fusion devices (such as ITER and SPARC), one must first validate the outputs of these models against current experimental results. There are many levels of physics fidelity of turbulent transport models. At the top (including the most physics) are multi-scale gyrokinetic simulations [2, 3], though these can take tens of millions of CPU hours for a single local simulation. In many, but not all, cases, however, ion-scale gyrokinetic simulations (which only simulate down to roughly the ion gyro-radius) contain enough physics to sufficiently model the plasma behavior, and can run tens or hundreds of times faster. Specifically, cases have been identified in which ion-scale simulations: match both heat fluxes and other constraints [4], match heat fluxes but not other constraints [3], and match neither heat fluxes nor other constraints [2]. In cases in these particular studies where ion-scale simulations disagree with experiment, the inclusion of multi-scale effects resolves the discrepancy. When eventually predicting the performance of a future machine, it would be convenient to be able to run ion-scale simulations, but one would like to know when the significantly more expensive multi-scale simulations are necessary.

Below nonlinear gyrokinetic simulations in the fidelity hierarchy are quasi-linear gyro-fluid models, such as TGLF [1]. These models do not contain the nonlinear physics that is in gyrokinetic codes, but instead use the results of gyrokinetic simulations to 'tune' an approximation of the nonlinear interactions of different turbulent modes. The disadvantage of these models is that one likely does not trust their results outside of the parameter space where they have been tuned. The major advantage is that they run much, much faster than gyrokinetic simulations (seconds or minutes on a few cores). TGLF can also be run in ion- and multi-scale configurations.

This study uses TGLF in order to determine when multi-scale physics is important, in the hope of informing when one must run multi-scale gyrokinetic simulations in the future, and when ion-scale gyrokinetic simulations are sufficient. In the course of this process, this study also validates TGLF on all of the discharges under consideration.

While ion and electron heat fluxes may eventually be the most relevant predictions for the purpose of predicting temperature profiles in a future machine, a significant amount of recent work has shown that one must compare many experimental parameters to the outputs of simulation in order to avoid fortuitous agreement between the simulations and experiment (getting the right answer for the heat fluxes in one particular parameter space, but for the wrong physics reasons) [5]. For this reason, this validation study will compare heat fluxes (calculated with TRANSP), electron temperature fluctuations (measured with Correlation Electron Cyclotron Emission [6, 7, 8]), and perturbative thermal diffusivity (measured with partial sawtooth heat pulses [4, 9]).

Unlike most past validation studies, which focus on one or maybe two discharges, this study will use 11 discharges, some with multiple radial locations (for a total of 17 cases), on both Alcator C-Mod and ASDEX Upgrade. In order to determine what makes the multi-scale effects important in simulations, one must use many discharges and attempt to separate those in which multi-scale effects are important from those in which ion-scale simulations are sufficient, using some set of parameters. Though several attempts have been made in the past to develop a 'rule of thumb' as to when multi-scale effects are important, a very small number of discharges makes any such analysis difficult. The large number of discharges in this study, on the other hand, elucidates larger trends. This new validation methodology is facilitated by the VITALS framework [10], which optimizes inputs (within experimental uncertainty) into TGLF in order to best match experimental constraints. This study allows the input ion temperature gradient, electron temperature gradient, density gradient, and effective charge to vary within experimental uncertainty.

All together, this study employs 2 machines, 11 plasma discharges, 17 total plasma cases, 4 varied inputs, 4 validation constraints, and 2 TGLF settings.

The five Alcator C-Mod discharges are: 1120706008, 1120706017, 1120706018, 1120706019, and 1120706030. The six ASDEX Upgrade discharge are: 33585, 34301, 34303, 34309, 34508, and 34623. All 11 are L-mode plasmas. Alcator C-Mod discharges were all run with 5.4 T on-axis magnetic field and 0.8 MA plasma current. Heating power ranged from 1.2 to 4.5 MW of ICRH. Simulations were performed at $\rho_{tor} = 0.75$ and local densities ranged from 6.0 to 10.0 x 10^{19} m^{-3}. ASDEX Upgrade discharges were run at 2.5 T

on-axis magnetic field with currents from 0.6 to 1.0 MA. Heating power ranged from 0.3 to 0.6 MW of ECH. Simulations were performed at two radii in each discharge, an inner radius (ρ_{tor} = 0.3 - 0.5 depending on the simulation) and an outer radius (ρ_{tor} = 0.65 - 0.75). Local densities ranged from 1.4 to 3.9 x 10^{19} m^{-3}.

In all cases, TGLF was run with the SAT-1 saturation rule [1]. The 'mutli-scale' TGLF runs utilized wavenumbers up to $k_\theta \rho_s \approx 24.0$, while the 'ion-scale' TGLF runs utilized wavenumber up to $k_\theta \rho_s \approx 1.0$.

The results of this validation study show that the multi-scale TGLF model agrees with all available experimental validation constraints within experimental uncertainty for all 17 cases studied here. The ion-scale TGLF model agrees in only 6 of the 17 cases.

Preliminary analysis reveals that the ratio of the peak linear growth rate at electron scales (γ_{high-k}) to the peak linear growth rate at ion scales (γ_{low-k}), is correlated with the importance of multi-scale effects. Higher values of ($\gamma_{high-k}/\gamma_{low-k}$) generally lead to a larger difference between the ion- and multi-scale models.

Future work will include additional analysis of the relationship between linear growth rates and the importance of multi-scale effects, as well as investigations into the physical mechanisms behind these relationships.

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