Successful Prediction of Tokamak Transport in the L-mode Regime

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A long standing shortfall in the predicted L-mode edge energy transport by reduced quasi-linear models has been resolved. The improved model TGLF-SAT2 has higher fidelity to gyrokinetic simulations of the electron-scale contribution to the electron energy transport and the ion-scale flux surface shape dependence of energy transport. The success of TGLF-SAT2 in predicting the L-mode and Ohmic edge profiles is critical to whole pulse simulation and opens the door to prediction of the H-mode power threshold.

The International Tokamak Physics Activity (ITPA) Transport and Confinement Topical Group established a joint research activity (TC-10) to investigate the cause of the underprediction of the L-mode transport near the last closed flux surface of tokamaks by reduced models in 2011. This presentation marks the closing of this activity by documenting the success of non-linear gyrokinetic simulations and a new saturation model for quasi-linear transport models (SAT2) in predicting the L-mode transport. It was expected that the gyro-Bohm scaling of gyrokinetic turbulence would lead to small transport in the low temperature edge region of L-mode tokamak plasmas [1]. This trend was indeed found with reduced transport models leading to edge temperature gradients that were predicted to be much steeper than experiment [2,3]. An example of this problem is shown in Fig. 1. The original saturation model (SAT0 red) in TGLF [2] (labeled TGLF-09 in [2]) predicts a steep temperature gradient in the L-mode edge of DIII-D compared to the measured values (blue dashed). Both electron (left) and ion (right) energy transport is underpredicted in the edge by TGLF-SAT0.

Fig. 1 Prediction of electron (left) and ion (right) temperatures in the outer half radius of DIII-D L-mode discharge 150139 [2] Showing a fit to the measurements (blue dashed), and the three saturation models for TGLF SAT0 (red), SAT1 (green) and SAT2 (blue solid). The boundary condition was taken at rho=0.993 and only temperatures were predicted.

However, fully spectral gyrokinetic turbulence simulations, in flux tube geometry, have been able to match the power balance fluxes with temperature gradients close to the measured values [4,5]. What is wrong with the TGLF-SAT0 model? The SAT0 model is 1-D with each poloidal wavenumber given an intensity that is independent of the others in the spectrum. A 2-D model of the saturated electric potential fluctuation intensity (SAT1), including poloidal and radial wavenumbers and the zonal flow mixing paradigm [6] (green curves in Fig. 1) improved the L-mode predictions but still shows some trend to underprediction for some cases. A more accurate 3-D model (SAT2) that fits the poloidal angle dependence [7] of the
saturated potential fluctuation amplitude in gyrokinetic simulations has been able to bridge the gap and produce quasi-linear fluxes that resolve the missing L-mode edge transport (blue curves in Fig. 1). The TGLF-SAT2 model is able to match the experimental trends of the DIII-D L-modes with plasma current, collisionality and flux surface shape including negative triangularity. Predictions of DIII-D L-mode discharges for a wide range of global conditions will be presented demonstrating that TGLF-SAT2 is able to track the properties of the data.

There are two properties of the saturation model that enhance the transport level. The first is a model of the multi-scale zonal flow mixing of electron temperature gradient instabilities (ETG) and ion scale modes that leads to a higher level of electron energy transport due to ETG (both SAT1 and SAT2). The second property is the inclusion of the change in the radial wavenumber spectral width of the potential fluctuations with changes in the flux surface geometry (SAT2). This improves primarily the ion energy flux agreement with gyrokinetic simulations and experiments. These properties were not among the expected candidates for resolving the missing L-mode edge transport. Resistive electromagnetic instabilities are a promising candidate but the high collisionality required for instability is achieved only very close to the separatrix [4]. The kinetic ballooning electromagnetic mode is included quasi-linearly in TGLF for all of the saturation models and it does not provide enough transport in the L-mode edge.

An extensive study of ASDEX Upgrade L-modes has recently been published using TGLF-SAT2 with remarkable success [8]. As shown in Fig. 2, the TGLF-SAT2 prediction of the stored energy is more accurate than the empirical scaling laws. These predictions were performed “data-free”, without taking boundary conditions at the separatrix for the plasma profiles from experiment. Electron and ion temperatures and electron densities were predicted. The TGLF-SAT2 predictions reproduce all of the experimentally explored dependences with relatively good accuracy, providing evidence, for the first time, that the main properties of L-mode confinement can be reproduced by full-radius transport modelling with a quasi-linear turbulent transport model.

The prediction of the Ohmic plasma profiles during the current ramp phase of the discharges is also improved resolving a significant issue with modeling complete pulses in tokamaks [3]. The lack of accurate prediction of the L-mode plasma profiles near the separatrix has been an obstacle to being able to predict the transition to H-mode. Now that this obstacle has been overcome, the goal of predicting the power threshold for the H-mode is within sight.

This work was supported in part by the US Department of Energy under DE-FC02-04ER54698

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