Predicting Internal Transport Barriers with the TGLF Model

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Recent advances in the calculation of momentum transport [1] and $E \times B$ velocity shear effects [2] with the Trapped Gyro-Landau Fluid (TGLF) transport model have improved the fidelity of this quasilinear model to nonlinear gyrokinetic turbulence simulations [2]. The present paper reports on the first predictions of DIII-D discharges that have internal transport barrier (ITB) regions in the deep core. It will be shown that TGLF, combined with the high accuracy neoclassical transport code NEO [3], is capable of predicting the electron density, electron and ion temperatures and $E \times B$ toroidal rotation simultaneously in a three species plasma (electrons, deuterium, carbon). This is a strong validation of the gyrokinetic and neoclassical theory requiring different physical transport mechanism in different channels.

Many of the pieces of the transport puzzle have been known since the first ITB discharges were produced in 1994 [4,5]. The suppression of driftwave turbulence by $E \times B$ velocity shear was consistent with linear stability analysis [6] interpreted with the quench rule [7]. It was also known that the negative central magnetic shear and fast ion dilution reduced the linear gyrokinetic growthrates making a transport barrier accessible. Nonlinear adiabatic electron gyrofluid simulations had shown that the parallel velocity shear in a toroidally rotating plasma provided an additional Kelvin-Helmoltz type drive that mitigated, and could even overcome, the stabilizing impact of the $E \times B$ velocity shear [7]. This was later confirmed in gyrokinetic simulations [8] where it was also found that kinetic electrons prevented a complete quenching of the turbulence by shear in the $E \times B$ velocity.

Putting these pieces of the theoretical puzzle together in the quasilinear transport model GLF23 [9] was only partially successful. The GLF23 predictions for DIII-D negative central shear discharges [9,10] were able to produce an $E \times B$ velocity induced transport barrier. The ion thermal transport within the barrier was reduced to neoclassical level by the $E \times B$ shear suppression of low wavenumber ion temperature gradient (ITG) and trapped electron modes (TEM) in agreement with data. The electron energy transport was approximately in agreement with the prediction from the high-wavenumber electron temperature gradient (ETG) modes in GLF23 that are not suppressed by $E \times B$ shear due to their high growth rates. But ETG modes do not produce particle or ion momentum transport, and hence GLF23 predicted that particle and momentum transport would be reduced to neoclassical levels in dramatic conflict with the data. The toroidal ion momentum transport inferred from the data is two orders of magnitude larger than the standard neoclassical level [11]. It was not clear if the GLF23 result represented an actual shortfall in the transport due to gyrokinetic turbulence or was a consequence of the inaccuracy of the GLF23 model. The nature of the particle and momentum transport within an ITB has remained unresolved until now. The TGLF model was, in part, motivated by this ITB transport shortfall issue. The trapped gyro-Landau fluid equations used in TGLF [12] can continuously cover the poloidal wavenumbers from ITG up to ETG modes. This allows for ion momentum and particle transport in the transition region between ITG and ETG modes to be included that was missing in GLF23. There are more parallel velocity moments in TGLF compared to GLF23 so TGLF gives a more accurate toroidal Reynolds stress calculation and Kelvin-Helmholtz instability drive contribution than GLF23. Finally, the new *spectral shift* paradigm [1] for the way in which $E \times B$ velocity shear suppresses transport has resulted in greater fidelity of TGLF [2] to nonlinear gyrokinetic simulations with GYRO [13]. In particular, with the spectral shift model the turbulence does not completely quench and the Reynolds stress due to the Doppler shift part of the $E \times B$ velocity shear can be computed.

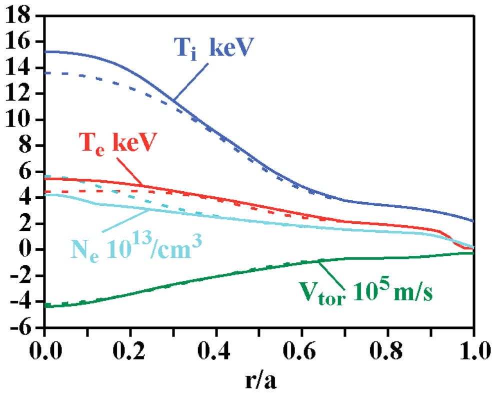

Fig. 1 TGLF+NEO prediction (solid) for 0.1<*r*/*a*<0.7 of ion and electron temperature, electron density and carbon toroidal rotation compared to data (dashed) for DIII-D discharge 103740 at 1880 ms [13].

Selection criteria for a suitable DIII-D ITB discharge to model were narrow. The discharge needs to be in a quasi-steady state to enable single time slice analysis. The MHD equilibrium was required to be stable to interchange modes. These instabilities are often present in strongly negative magnetic shear cases. A complete set of plasma profile measurements were required and only published data was considered.

One of the selected discharges (103740 at 1880 ms) that met these criteria is a quiescent double barrier (QDB) discharge [14]. This QH-mode type of discharge has a multi-harmonic saturated MHD mode at the top of the edge transport barrier instead of periodic edge localized mode bursts. In addition to the edge barrier, this discharge has an ITB. This type of discharge is formed with neutral beam injection counter to the plasma current direction yielding a toroidal rotation (negative) contributing to a negative radial electric field. The TGLF+NEO simulations are done by evolving electron density, electron and ion temperatures and $E \times B$ toroidal velocity simultaneously. The electrons, deuterium and Carbon 6 ions are all included as kinetic species in both TGLF and NEO. Fast ion dilution is included. The perpendicular magnetic field perturbations and Coriolis drift are included in TGLF. The predicted plasma profiles (solid) are compared to a spline fit to the measurements (dashed) in Fig. 1. The boundary for the simulation is at r/a=0.7 (to avoid the multi-harmonic mode region) and the inner boundary was taken at $r/a=0.1$. For $r/a<0.1$ the experimental effective transport diffusivities were used.

The agreement between the measured and predicted profiles in the predicted region ($0.1<r/a<0.7$) is excellent. This is a weak ITB with the neoclassical ion power flow only becoming dominant near the axis. Despite the simple agreement between the predicted and plasma profiles the gyrokinetic transport in this discharge is complex. The carbon content is high due to the counter neutral beam injection. About half of the ion energy flux is carried by the carbon in this case. The toroidal Reynolds stress is predominantly produced by the carbon ions. Because the low wavenumber (ITG/TEM) modes are not fully suppressed, only about half of the electron energy is transported out by the ETG modes in the inner region ($r/a<0.3$) and a declining fraction further out. Stabilization by fast ion dilution, kinetic carbon and negative magnetic shear play a significant role in the improved confinement of this discharge. The parallel velocity shear is not significantly increasing the linear growthrates for this case but has been found to be important for stronger ITB cases.

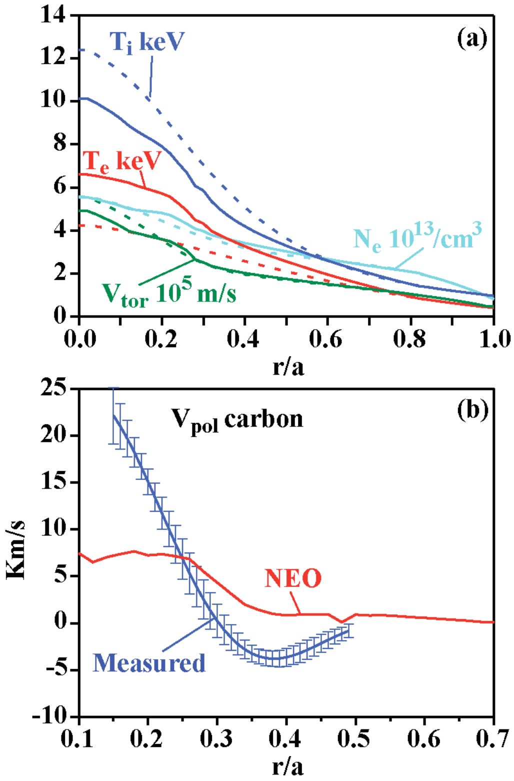

Fig. 2 (a) TGLF+NEO prediction (solid) for $0.1<r/a<0.8$ of ion and electron temperature, electron density and carbon toroidal rotation compared to data (dashed) for DIII-D discharge 149472 at 1645 ms [14]. (b) Comparison of measured carbon poloidal velocity and NEO prediction using the measured profiles.

Using GLF23+NEO on this same discharge produces a run away transport barrier starting at the outer boundary ($r/a=0.7$). All of the transport channels are reduced to neoclassical. The central electron density is driven up to $72\times10^{13}\text{cm}^{-3}$ and the central toroidal velocity is -362×10^{5} m/s. This is in stark contrast to the relatively good agreement between GLF23 and the data when the density and rotation profiles were not evolved [14]. A somewhat lower power, earlier phase of the discharge is being used here rather than 3305 ms which was analyzed in Ref. 14 because it was found that at 3305 ms the deep core was resistive interchange unstable. The higher accuracy of the linear eigenmodes and the continuous poloidal wavenumber spectrum coverage of TGLF compared to GLF23 are the primary reasons for the successful prediction of this QDB discharge.

Several other ITB discharges have been predicted with TGLF+NEO with good agreement with the data. A discharge with neutral beam injection in the same direction as the plasma current is shown in Fig. 2. This is a recent DIII-D case (149472 at 1645 ms) run at low power in order to achieve a quasi-stationary condition. The profiles are predicted by TGLF+NEO over the range $0.1<r/a<0.8$. The agreement between prediction (solid) and measurement (dashed) for the electron density and carbon toroidal rotation is quite good. The predicted ion temperature is low and the predicted electron temperature is too high for this case. There is considerable uncertainty in the fast ion density computed from the neutral beam source since there is Alfvén eigenmode (AE) activity in this discharge. The AE modes are known to broaden the fast ion density and could increase the electron energy transport. This case is also a weak ITB with neoclassical a minor contributor even for the ion energy transport. The carbon content is much lower than in the QDB case above and the carbon energy flux and toroidal Reynolds stress are small compared to deuterium. Both of these cases were predicted neglecting the diamagnetic and neoclassical poloidal flow contributions to the parallel flows of each species. For these high rotation cases the difference between the deuterium and carbon parallel flows predicted from NEO are small. A test of the predicted neoclassical poloidal flow of carbon compared to the measured value is shown in Fig. 2(b). A novel technique was used for the carbon poloidal flow measurement [15]. The difference in the toroidal velocity of carbon measured inside and outside of the magnetic axis is used to compute the poloidal flow contribution using the incompressible form of the carbon velocity vector. There is not very good agreement in the predicted and measured poloidal velocity in Fig. 2. In the future, the parallel momentum balance for each ion including the neoclassical and turbulent stresses will be solved as part of the transport system to see if the turbulent stress can explain this difference.

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