ITER Predictions Using The GYRO Verified and Experimentally Validated TGLF Transport Model

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General Atomics

23rd IAEA Fusion Energy Conference

October 11-16, 2010
Daejeon, Korea
Overview

• A comprehensive driftwave model has been developed for predicting the turbulent transport in tokamak
  – Trapped Gyro-Landau-Fluid (TGLF) quasilinear transport model
  – TGLF philosophy:
    ✓ VERIFY by comparing TGLF to gyrokinetic linear and nonlinear simulations
    ✓ VALIDATE TGLF using experimental data

• TGLF has been well verified against gyrokinetic simulations
  – TGLF energy diffusivities are within 20% of GYRO results for 191 nonlinear simulations

• TGLF has been well validated against experimental data
  – TGLF shows better agreement than GLF23 model for Te & Ti profiles from a database of 133 discharges from DIII-D, JET, TFTR

• TGLF is now being used to predict the performance in ITER for the conventional H-mode scenario
Overview (ITER Projections)

- Realistic finite aspect ratio shaped geometry reduces the predicted fusion power compared to the $s$-$\alpha$ model
  - Predictions from TGLF (Miller shaped geometry) are less optimistic than from GLF23 (infinite aspect ratio $s$-$\alpha$ geometry)

- ITER fusion projections are characteristically stiff
  - Fusion $Q \propto P_{aux}^{-0.8}$
  - Fusion power $\propto \beta_{ped}^2$, so any pedestal optimization has a large payoff

- Synergistic effects of density peaking, finite $\beta$, and ExB shear due to small toroidal rotation are found to be significant
  - Together they yield a 60% increase in fusion power above the simplified ITER base case (flat density, no rotation, electrostatic)
  - Individually they are small effects (5%)
  - With all 3 ingredients, TGLF predicts $Q=15$ and $P_{\text{fusion}}=450$ MW near the maximum pedestal $\beta$

- TGLF results are confirmed using nonlinear GYRO transport runs
The TGLF Gyro-Landau-Fluid Transport Model

- TGLF is the next generation GLF model with improved comprehensive physics compared to its predecessor, GLF23
  - Model valid continuously from low-k ITG/TEM to high-k ETG
  - Extended range of validity
  - Valid for shaped geometry using Miller local equilibrium which replaces the s-\(\alpha\) infinite aspect ratio shifted circular geometry
  - Solves set of 15-moment gyro-fluid equations for linear driftwave eigenmodes
  - Computationally more expensive than GLF23

- Was tested against a database of 1800 linear growth rates and frequencies computed using the GKS gyrokinetic code
  - Avg \(\sigma (\gamma)\) = 11% for TGLF, 38% for 1997 GLF23

- A model for the nonlinear saturation levels was found using the net linear mode growth rates (w/ ExB shear) and nonlinear GYRO simulations with Miller shaped geometry

- Results shown here use TGLF with improved collision model (TGLF-09)
Verification of the TGLF transport model
Against GYRO nonlinear simulations
The TGLF Quasilinear ITG/TEM Energy Diffusivities Agree with 191 Nonlinear GYRO Miller Geometry Simulations Very Well

- TGLF saturation rule was fit to 83 nonlinear GYRO Miller geometry collisionless simulations
- TGLF saturation rule has now been compared against 108 new GYRO cases w/ collisions
  - 108 cases NOT included in saturation rule fitting
  - Total GYRO transport database is now 191 simulations
- Quasilinear theory works amazingly well
  - RMS errors for \([\chi_i, \chi_e] = [13\%, 16\%]\)
- Many of the GYRO cases are far above ITG threshold

\(\chi\)'s are normalized: \(\chi / \chi_{GB}\)
Validation of the TGLF transport model against experimental profile database

“Model testing is meant to demonstrate that developers have correctly understood the underlying physics and have made the right set of choices.” – Greenwald, PoP 2010
TGLF Exhibits Lower Average Global & Local Errors than GLF23 for a Large Profile Database of 133 Discharges

- 25 DIII-D L-, 40 DIII-D H-, 30 DIII-D hybrid, 22 JET H-, and 16 TFTR L-mode discharges
- Avg RMS error in incremental stored energy ($W_{\text{inc}}$): 20% for TGLF, 32% for GLF23
- Offset in $W_{\text{inc}}$ much smaller for TGLF (+2% vs -17%)
- Avg RMS error for $[T_i,T_e]$ profiles: TGLF = [14%,15%], GLF23 = [21%,22%]
ITER Predictions Using TGLF
Realistic Finite Aspect Ratio Shaped Geometry Reduces the Predicted Fusion Power Compared to the s-\(\alpha\) Model

- TGLF uses finite aspect ratio Miller geometry and has larger transport than with s-\(\alpha\) geometry
- TGLF with shifted circle geometry agrees with GLF23 shifted circle (s-\(\alpha\)) results
- ITER predictions sensitive to collision model in TGLF
  - TGLF with new collision model (TGLF-09) leads to more optimistic predictions than TGLF-APS07 version
  - Mostly impacts very low-k modes which survive in ITER since ExB shear effects are small

* Snyder THS/1-1: Peeling-ballooning + KBM pedestal model range of predictions

\[ P_{\text{Fus}} (\text{MW}) \]

- GLF23
- TGLF (s-\(\alpha\))
- TGLF-APS07
- TGLF-09

**Base case: flat density, \(v_\phi=0\), electrostatic, \(n_e/n_{GW}=0.8\)**
TGLF Fusion Projections Exhibit Stiff Transport Characteristics: Fusion Gain $Q$ is Sensitive to Auxiliary Heating Power

- Fusion $Q$ sensitive to auxiliary heating, scales like $P_{aux}^{-0.8}$ at fixed $\beta_{ped}$
  - $Q = \frac{P_{fusion}}{P_{aux}}$ larger at low auxiliary power
  - Temperature profiles insensitive to $P_{aux}$

\[
Q = \frac{P_{fusion}}{P_{aux}} \quad \text{(at fixed $\beta_{ped}$)}
\]

Temperature profiles insensitive to $P_{aux}$

\[
Q = 10 \quad \text{at fixed $\beta_{ped}$}
\]
TGLF Fusion Projections Exhibit Stiff Transport Characteristics: Pedestal Optimization Essential

- Fusion Q sensitive to auxiliary heating, scales like $P_{aux}^{-0.8}$ at fixed $\beta_{ped}$
  - $Q = \frac{P_{fusion}}{P_{aux}}$ larger at low auxiliary power
  - Temperature profiles insensitive to $P_{aux}$

- Fusion power scales like $\beta_{ped,N}^2$

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**Graphs**

**Left Graph**
- ITER conv. H-mode
- $T_{ped} = 5.0$ kev
- $n_{ped} = 9.19 e19$
- $n_{eo}/n_{ped} = 1.3$
- $V_{phi} = 0$
- $\beta_{ped,N} = 0.9$

**Right Graph**
- ITER conv. H-mode
- $P_{aux} = 50$ MW
- $n_{eo}/n_{ped} = 1.3$

- TGLF-09 model
- Based on TRANSP 20100216

- $P_{fus} \alpha \beta_{ped,N}^{2.0}$
- $T_{ped} = 1.0$
- $T_{ped} = 3.0$
- $T_{ped} = 5.0$

**EPED**
TGLF Predicts a Density Peaking Factor of \(n_{e0}/n_{ped}=1.3\) for ITER

- Density peaking has been observed in low collisionality JET, AUG, and C-mod discharges

- Predictions compared for ITER conventional ELMy H-mode case using TGLF
  - \(T_e\) & \(T_i\) predicted using prescribed density profiles with various peaking factors (lines)
  - \(n_e, T_e, T_i\) predicted using TRANSP beam source (dots)
  - \(Z_{eff}\) held fixed for all cases

- Density peaking of \(n_{e0}/n_{ped}=1.3\) increases fusion power by 5% above simplified base case with a flat density profile

Lines = cases with prescribed \(n_e\) profiles
Dots = TGLF predicted density profiles
Base case: \(v_\phi=0\), electrostatic, \(n_e/n_{GW}=0.8\)
Synergistic Effects of Density Peaking, Finite $\beta$, and ExB Shear due to Low Toroidal Rotation can Significantly Increase Fusion Power

- Studied 3 effects using a ITER conventional H-mode case with a fusion Q near 10: $P_{\text{aux}}=30$ MW, $\beta_{\text{ped,N}}=0.90^*$
- Each effect has only a 5% increase in the predicted fusion power

<table>
<thead>
<tr>
<th>Scenario variation</th>
<th>$P_{\text{fus}}$ (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case with prescribed $n_e$ ($n_{e0}/n_{\text{ped}} = 1.1$)</td>
<td>285 (reduced physics)</td>
</tr>
<tr>
<td>Predicted density with $n_{e0}/n_{\text{ped}} = 1.3$</td>
<td>310</td>
</tr>
<tr>
<td>Finite $\beta$ with prescribed $n_e$ ($n_{e0}/n_{\text{ped}} = 1.1$)</td>
<td>311</td>
</tr>
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- Synergistic effect of 3 ingredients yields a 59% increase in the fusion power

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<tr>
<td>Predicted $n_{e0}/n_{\text{ped}} = 1.3$, Finite $\beta$</td>
<td>373</td>
</tr>
<tr>
<td>Predicted $n_{e0}/n_{\text{ped}} = 1.3$, Finite $\beta$, $v_{\phi,0} = 0.5 \times 10^5$ (m/s)</td>
<td>452* (Q=15)</td>
</tr>
</tbody>
</table>

$+ P_{\text{fus}}=350$ MW (Q=12) at $\beta_{\text{ped,N}}=0.74$ (unoptimized EPED limit)

* EPED model predicts a max $\beta_{\text{ped,N}} = 0.74-0.92$ depending on $n_{\text{ped}}$, global $\beta$
Nonlinear GYRO Transport Predictions Confirm TGLF Results for ITER

- GYRO was used for the energy transport within the TGYRO code*
  - ITER conventional H-mode simplified base case with \( \beta_{\text{ped,N}} = 0.72, \nu_\phi = 0 \)
  - 8 radial zones, 8 toroidal modes w/ \( k_y \leq 0.70, [L_x, L_y] = [64, 64] \)
  - Electrostatic, low-k modes only (no ETG)
  - Convergence of the TGYRO/GYRO results difficult since the profiles reside near threshold, zonal flows are bursty
  - 6hrs using 4608 cores on Jaguar @ ORNL

Outstanding Issues

• Outstanding challenges for transport models remain
  – Need experimental validation of core stiffness
  – More V & V needed for ITER relevant plasma conditions (e.g. low $v_\phi$, low nustar)
  – Momentum transport needs validation (recently implemented in TGLF)
  – Electromagnetic effects need studying (TGLF,GYRO)
  – Verification & Validation is ongoing work!

• Aspects of ITER modeling that need future study
  – Does treating D and T ion species separately change the transport?
  – Are helium ash effects important?
  – Equilibrium and sources not consistent with predicted profiles

• ITER results appear to be sensitive to various mechanisms near threshold
  – Need to understand synergistic effects

• Core/pedestal ITER predictions have not been optimized together
  – Further iterations between core & pedestal interaction needed
Summary

- Quasilinear saturation rule in TGLF shows remarkable agreement with large GYRO transport database of 191 simulations with Miller geometry.
- TGLF has good agreement with temperature profiles for a database of 133 discharges from DIII-D, JET, and TFTR, avg RMS error for \([T_i, T_e] = [14\%, 15\%]\). 
- TGLF is less optimistic than previously obtained \(s-\alpha\) results for ITER due to finite aspect ratio effects.
- TGLF fusion projections exhibit stiff core transport characteristics:
  - Fusion Q scales like \(P_{aux}^{-0.8}\) at fixed \(\beta_{ped}\).
  - Fusion power scales like \(\beta_{ped}^2\) -> pedestal optimization essential.
- Synergistic effects of density peaking, finite \(\beta\), and ExB shear driven by small toroidal rotation are significant, \(P_{fusion}\) increases by 60%.
  - Can achieve \(P_{fus}=450\) MW (\(Q=15\)) at \(\beta_{ped,N}=0.90\) (near maximum pedestal \(\beta\)).
- TGLF ITER results have been confirmed using nonlinear GYRO transport runs.