Validation of Gyrokinetic Transport Simulations Using DIII-D Core Turbulence Measurements

Christopher Holland
University of California, San Diego
Dept. of Mechanical and Aerospace Engineering

collaborators
G. R. Tynan, UCSD
J. Candy, R. E. Waltz, G. Staebler, J. Kinsey, General Atomics
G. R. McKee, M. W. Shafer, UW-Madison
A. E. White, L. Schmitz, T. Peebles, T. Rhodes, UCLA

Presented at 2008 IAEA Fusion Energy Conference
13-18 October, Geneva, Switzerland
Motivation and Overview

• The development of validated transport models is essential for predicting the performance of ITER and other future reactor devices with confidence.

• Comparisons of turbulent transport predictions against “experimental” energy and particle flows are only weakly discriminating.
  - The “experimental” flows are calculated via a power balance model with its own assumptions and limitations (e.g. for fast ion transport).

• Much better are comparisons against directly measured characteristics of the underlying turbulence (e.g. spectra and correlation functions).

• In this study, use the GYRO code to model a basic L-mode DIII-D discharge, and compare both predicted energy flows and fluctuation characteristics against experiment.
Summary of Results

- Local GYRO simulations match ion and electron energy flows at r/a < 0.6, but underpredict the flows at larger r/a.
- Local and global GYRO simulations give nearly identical predictions for the energy flows across the entire plasma.
- Using synthetic diagnostics, the GYRO-predicted fluctuation spectra are shown to agree well with experimental measurements at r/a = 0.5.
- At r/a = 0.75, GYRO underpredicts fluctuation amplitudes by an amount consistent with the underprediction of the energy flows, but still achieves relatively good agreement in the density correlation functions.
- Using the quasilinear TGLF transport model in conjunction with the new TGYRO transport code, the ability to perform nonlinear, predictive fixed-flow transport modeling is now available.
Use Data From a Steady, Sawtooth-Free L-Mode Plasma for This Study

- Obtain profiles of long wavelength density and electron temperature fluctuations at outboard midplane via beam emission spectroscopy (BES) and correlation electron cyclotron emission (CECE) radiometry.
Use GYRO Code to Predict Turbulent Fluctuations and Transport

- **GYRO is an initial value Eulerian (continuum) 5D gyrokinetic $\delta f$ code**

- **GYRO can be run in a local (flux-tube) or nonlocal (global) mode**:
  - **Local**: This case corresponds to the $\rho^* = \rho_s/a \rightarrow 0$ limit of the GK equations, in which each equilibrium profile and gradient is taken to have a fixed (and independent) value across the box
  - **Nonlocal**: spatial variation of equilibrium profiles (and their gradients) is retained

- **Believed to contain the necessary ingredients for quantitatively accurate core transport predictions**
  - takes measured experimental profiles as inputs
  - equilibrium sheared $E\times B$ and toroidal rotation profiles
  - realistic geometry (Miller formulation)
  - trapped and passing electrons
  - $e-i$ pitch angle collisions
  - finite beta (magnetic fluctuations)
Local GYRO Simulations Approximately Match Energy Flows for $r/a \leq 0.6$ In Magnitude and Trend With Radius

- **Use the ONETWO code to calculate ion and electron energy flows $Q_i$ and $Q_e$**
  - GYRO error bar shows magnitude of response to 20% change in $\gamma_{\text{ExB}}$
  - ONETWO error bar shows magnitude of response to using different fits to Thomson electron density profile measurements
Local GYRO Simulations Systematically Underpredict Energy Flows for $r/a > 0.6$ in This Discharge

- Mismatches at $r/a > 0.6$ are too large to be reconciled with plausible uncertainties of local gradients
- Cause of mismatch at larger radii unknown at this time
Local GYRO Simulations in Very Good Agreement With Global Simulation Results Everywhere but $r/a = 0.35$

- **Red** global simulation centered at $r/a = 0.5$ (local $\rho^* = 0.0026$)
- **Blue** global simulation centered at $r/a = 0.35$ (local $\rho^* = 0.0033$)
- Nonlocality leads to reduction of local $r/a = 0.35$ predictions, but does not meaningfully impact other local results
  - Decrease likely arises from proximity to inner stable region

![Graphs showing comparison between local and global simulations](image-url)
Next Step: Compare Predicted Fluctuation Characteristics at $r/a = 0.5$ and 0.75 Against Experimental Measurements

- Use local GYRO simulation results for these comparisons
Comparing Fluctuation Characteristics at \( r/a = 0.5 \)
• In order to do “apples-to-apples” comparisons of simulation and experiment, need to not just model the turbulence, but also how a given diagnostic “sees” the turbulence

• This is done by creating a synthetic diagnostic which models what the diagnostic would have seen had it observed the simulation fluctuations
  - For the BES and CECE systems, this modeling is done by convolving point-spread functions (PSFs) that describe the spatial sensitivity of each diagnostic with the fluctuation fields

• For a synthetic diagnostic which measures fluctuations at \((R_0, Z_0, \varphi_0)\), record at each timestep in steady-state portion of simulation:
  - A “unfiltered” reference signal \(\delta X_{GYRO}(R_0, Z_0, \varphi_0, t)\)
  - A synthetic signal \(\delta X_{\text{synthetic}}(t) = \int d^2r \psi_{PSF}(R - R_0, Z - Z_0) \delta X_{GYRO}(R - R_0, Z - Z_0, \varphi_0, t) \sqrt{\int d^2r \psi_{PSF}^2(R - R_0, Z - Z_0)}\)
Agreement between synthetic and experimental spectra requires that GYRO accurately reproduces both the fluctuation amplitudes and the poloidal mode spectra

- Lab-frame frequency spectra is essentially Doppler-shifted poloidal mode spectrum
- In this talk, always refer to normalized fluctuation levels $\delta X \equiv \tilde{X}/X_0$
Very Good Agreement is Found Between Synthetic and Experimental Density Correlation Functions at $r/a = 0.5$

- Agreement in vertical correlation function $C(\Delta Z)$ consistent with agreement in lab-frame power spectra
- Solid lines are Gaussians fit to experimental BES and synthetic BES
Comparing Fluctuation Characteristics at $r/a = 0.75$
Synthetic Spectra Consistently Underpredict Experimental Measurements at all Frequencies at $r/a = 0.75$

- **Magnitude of underprediction consistent with generic scaling of $Q \propto \delta X^2$**

- **Use** $\delta X^{\text{RMS}} = \int df \langle |\delta X(f)|^2 \rangle$

**Use** to find

\[
\sqrt{\frac{Q_i^{\text{PB}}}{Q_i^{\text{GYRO}}}} = 2.7
\]

\[
\sqrt{\frac{Q_e^{\text{PB}}}{Q_e^{\text{GYRO}}}} = 2.7
\]

\[
\frac{\delta n^{\text{BES}}}{\delta n^{\text{syn}}} = 3.3
\]

\[
\frac{\delta T_e^{\text{CECE}}}{\delta T_e^{\text{syn}}} = 3.2
\]
Synthetic Spectra Match Experiment In Shape But Not Magnitude at $r/a = 0.75$

- If synthetic spectra are renormalized to contain same power as corresponding experimental spectra, find good agreement with measured BES and CECE spectral shapes over 40-400 kHz
  - Source of mismatch in $\delta T_e$ spectra below 40 kHz unknown

- Is spectral shape more robust than magnitude?
Synthetic Density Correlation Functions at $r/a = 0.75$ Exhibit Similar Behavior and Agreement With Experiment as at $r/a = 0.5$. 

- **Radial Correlation Function**
  - $C(\Delta R)$
  - Synthetic (red squares)
  - Experiment (blue diamonds)
  - $\Delta R$ (cm)

- **Vertical Correlation Function**
  - $C(\Delta Z)$
  - Synthetic (red squares)
  - Experiment (blue diamonds)
  - $\Delta Z$ (cm)
Addressing Profile Uncertainties
Via Fixed-Flow Simulations
Stiff Transport Magnifies Gradient Uncertainties, Necessitating Flow-Matching Simulations

- **Systematic uncertainties in fitting equilibrium profiles create large uncertainties in local equilibrium gradients, which are magnified further when the stiff turbulent flows are calculated.**
  - Ex: fitted profiles rely on diagnostic calibrations, analyst’s selection of a non-unique fitting function.

- **One way of addressing this issue is to predict a set of profiles needed to match the energy flows calculated via power balance, and compare these predicted profiles against measurements.**
  - Because flows are volume integrals of (computed) sources, they have in general less uncertainty than local gradients.

**Caveat:** this approach assumes one has accurate models of the relevant sources.
Use the TGLF Model to Make Initial Profile Predictions

- **TGLF** is a quasilinear transport model fit against > 80 nonlinear GYRO runs
- **TGLF predictions** are outside statistical uncertainties of initial spline fit, but systematic uncertainties remain
Global GYRO Simulation Using the TGLF Predicted Profiles Yields Significantly Improved Agreement with ONETWO Calculation

- Using **TGLF profiles**, improved agreement with ONETWO results achieved at all r/a, particular at r/a > 0.6

![Graphs showing Ti and Te profiles](image-url)

**C Holland/IAEA/Oct2008**
Next Step: Flow-Matching Calculations Using the TGYRO Transport Driver Code

- A new TGYRO transport code has been developed to predict flow-matching profiles using either a global GYRO or a combination of multiple local GYRO and TGLF simulations in parallel.

- Basic global simulation algorithm: every $a/c_s$, adjust local scale lengths by an amount proportional to the difference between GYRO simulation and power balance flows at each radial location.
  - Example: $\Delta(a/L_t) \propto (Q_i^{GYRO} - Q_i^{PB})$
  - Keep $T_i$ and $T_e$ at the center of the simulation fixed, and pivot profiles about this point. Contrasts with traditional approaches of specifying pivot at some large $r/a$ near the top of the pedestal.

- First results from the local TGYRO algorithm for ITER plasmas available at this conference in poster TH/P8-28 by Nordman and Candy.
Tiny Changes to TGLF Profile Predictions by TGYRO Yield Exact Matches to Power Balance Flows

- Small but finite changes to local values of TGLF profile gradients by TGYRO translate into essentially equivalent temperature profile predictions.
Summary of Results

- Local long-wavelength ($k_r \rho_s < 1$) GYRO simulations of this particular discharge match ion and electron energy flows calculated via ONETWO at $r/a < 0.6$ within experimental uncertainties, but underpredict the flows at larger $r/a$.
  - Define flow as total amount of energy crossing a flux surface, specified in MW.

- Local and global GYRO simulations give nearly identical predictions for the energy flows, with the only meaningful difference at $r/a = 0.35$.

- Using synthetic diagnostics, the GYRO-predicted density and electron temperature fluctuation spectra are shown to agree well with experimental measurements at $r/a = 0.5$.
  - Good agreement is also found for the density correlation functions.

- At $r/a = 0.75$, GYRO underpredicts fluctuation amplitudes by an amount consistent with the underprediction of the energy flows, but still achieves relatively good agreement in the density correlation functions.

- Using the quasilinear TGLF transport model in conjunction with the new TGYRO transport code, the ability to perform nonlinear, predictive fixed-flow transport modeling is now available.
Backups
Need Only Small Changes to Fitted Profiles Inside $r/a = 0.6$ to Match ONETWO Energy Flows
Finite Wavenumber Sensitivities of Each Diagnostic Have Significant Impact on Measured Spectra

- Observe a 40%-50% attenuation of fluctuation amplitudes for both diagnostics
Primary Impact of PSF Appears in Radial Correlation Function

- Agreement in vertical correlation function $C(\Delta Z)$ consistent with agreement in lab-frame power spectra
- Solid lines are Gaussians fit to experimental BES, synthetic BES, and unfiltered signals
Synthetic Spectra Consistently Underpredict Experimental Measurements at all Frequencies at r/a = 0.75

- **Magnitude of underprediction consistent with generic scaling of** $Q \propto \delta X^2$

- **Use** $\Delta X^2_{\text{RMS}} = \int \frac{df}{40 \text{ kHz}} \langle |\delta X(f)|^2 \rangle$

  to find

  $\sqrt{Q_{PB}^{i} / Q_{i}^{\text{GYRO}}} = 2.7$

  $\sqrt{Q_{PB}^{e} / Q_{e}^{\text{GYRO}}} = 2.7$

  $\delta n^{\text{BES}} / \delta n^{\text{syn}} = 3.3$

  $\delta T_{e}^{\text{CECE}} / \delta T_{e}^{\text{syn}} = 3.2$
Synthetic Spectra Match Experiment in Shape but not Magnitude at \( r/a = 0.75 \)

- If synthetic spectra are renormalized to contain same power as corresponding experimental spectra, find good agreement with measured BES and CECE spectral shapes over 40-400 kHz
  - Source of mismatch in \( \delta T_e \) spectra below 40 kHz unknown

- Is spectral shape more robust than magnitude?
Synthetic Density Correlation Functions at $r/a = 0.75$ Exhibit Similar Behavior and Agreement with Experiment as at $r/a = 0.5$

**Radial Correlation Function**

$C(\Delta R)$
- black circle: unfiltered
- red square: synthetic
- blue diamond: experiment

**Vertical Correlation Function**

$C(\Delta Z)$
- black circle: unfiltered
- red square: synthetic
- blue diamond: experiment

C Holland/IAEA/Oct2008
Simulations Exhibit Excellent Convergence in Dn

- A 32-mode simulation with $\Delta n = 4$ exhibits excellent agreement with 16-mode $\Delta n = 8$ results
  - Agreement in spectral shape as well as net flow and fluctuation levels
BES and CECE Fluctuation PSF Visualizations in (R,Z) Plane Overlaid on Local r/a = 0.5 Fluctuations

- In this talk, always refer to normalized fluctuations labeled via \( \delta X = \tilde{X}/X_0 \)

50% contours of BES and CECE PSFs
Quasilinear TGLF Model Gives Quick and Accurate Approximations to Full GYRO Calculations

- TGLF ((T)rapped Gyro-Landau-Fluid) model uses a combination of linear phase information and a semi-analytic saturation rule to quickly predict turbulent flows
  - Model calculates linear eigenvalues for set of 15-moment gyro-fluid equations (per species)
  - Uses a mixing-length type saturation rule for fluctuation intensity $V_k^2$ which is fit to database of >80 nonlinear GYRO runs
  - Includes both long-wavelength ITG/TEM transport and short-wavelength ETG-driven transport
  - By combining TGLF flow predictions with experimentally measured sources, one can predict a set of profiles necessary to match experimental flows
  - See G. Staebler's poster TH/P8-42 for latest info

- Simple approach: use TGLF to predict a set of steady-state flow-matching temperature profiles, then use those profiles in the GYRO calculation

\[
\Gamma = n \sum_{k_y} \rho_s c_s \left[ \frac{\text{Re} \left< i k_y \tilde{\phi}_k \tilde{n}_k \right>}{\tilde{V}_k^* \tilde{V}_k} \right] V_k^2
\]

\[
Q = \frac{3}{2} p \sum_{k_y} \rho_s c_s \left[ \frac{\text{Re} \left< i k_y \tilde{\phi}_k \tilde{p}_{T,k} \right>}{\tilde{V}_k^* \tilde{V}_k} \right] V_k^2
\]

\[
\tilde{V}_k = (\tilde{n}_k, \tilde{u}_{\perp,k}, \tilde{p}_{\perp,k}, \tilde{p}_{T,k}, \tilde{q}_{\perp,k}, \tilde{q}_{T,k})
\]

\[
\frac{\partial n}{\partial t} + \frac{1}{V'} \frac{\partial}{\partial r} (V' \Gamma) = S_n
\]

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} nT \right) + \frac{1}{V'} \frac{\partial}{\partial r} (V'Q) = S_w
\]
Impact of Different Fit Choices to Electron Density on ONETWO Results

![Graph showing the impact of different fit choices to electron density on ONETWO results.](image-url)
Sensitivity Studies Indicate Only “Moderate” Stiffness of Transport at \( r/a = 0.5 \)

- All simulations used a 20% too large \( \gamma_{ExB} \) value
- As for previous simulations, each column required \(~3000\) cpu-hours
- All diffusivities normalized to \( \chi_{gB} = 0.866 \) m\(^2\)/s

<table>
<thead>
<tr>
<th>( \chi_i )</th>
<th>( a/L_{Ti} )</th>
<th>( a/L_{Te} )</th>
<th>( a/L_{ne} )</th>
<th>box size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expt. base</td>
<td>+5%</td>
<td>-5%</td>
<td>-10%</td>
<td>+5%</td>
</tr>
<tr>
<td>4.5</td>
<td>4.74</td>
<td>5.35</td>
<td>4.23</td>
<td>4.05</td>
</tr>
<tr>
<td>2.1</td>
<td>2.38</td>
<td>2.67</td>
<td>2.17</td>
<td>2.05</td>
</tr>
<tr>
<td>0.05</td>
<td>0.75</td>
<td>0.89</td>
<td>0.64</td>
<td>0.58</td>
</tr>
</tbody>
</table>

\[ Q = \frac{3}{2} \langle \tilde{p} \tilde{V}_r \rangle = -n \chi \frac{dT}{dr} \]

\[ \Gamma = \langle \tilde{n} \tilde{V}_r \rangle = -D \frac{dn}{dr} \]
Parameter Scans Show $r/a = 0.75$ Results Are Numerically Robust

- Each row used $\geq 4096$ processor-hours on Jaguar
- No ExB shear used in these cases

<table>
<thead>
<tr>
<th></th>
<th>$\chi_i/\chi_{gB}$</th>
<th>$\chi_e/\chi_{gB}$</th>
<th>$D_{ne}/\chi_{gB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>expt</td>
<td>22.5</td>
<td>15.5</td>
<td>0.25</td>
</tr>
<tr>
<td>base</td>
<td>9.24 ± 0.40</td>
<td>4.79 ± 0.15</td>
<td>-0.46 ± 0.083</td>
</tr>
<tr>
<td>Inc. grad-Ti 10%</td>
<td>11.5</td>
<td>5.5</td>
<td>0.36</td>
</tr>
<tr>
<td>Half $\Delta t$ (short run)</td>
<td>11.3</td>
<td>5.3</td>
<td>0.31</td>
</tr>
<tr>
<td>$\mu=40$</td>
<td>9.77</td>
<td>5.43</td>
<td>-.45</td>
</tr>
<tr>
<td>EM effects on</td>
<td>10.3</td>
<td>5.36</td>
<td>0.12</td>
</tr>
<tr>
<td>Inc. max $k_y$ 25%, $\Delta x$ 33%, red. $\Delta t$ 50%</td>
<td>9.69</td>
<td>4.72</td>
<td>0.11</td>
</tr>
<tr>
<td>Double max $k_y$, half binormal box size</td>
<td>10.98</td>
<td>5.07</td>
<td>0.47</td>
</tr>
<tr>
<td>Inc. ORBIT_GRID</td>
<td>10.8</td>
<td>5.58</td>
<td>-0.76</td>
</tr>
<tr>
<td>Inc. ENERGY_GRID</td>
<td>9.84</td>
<td>5.04</td>
<td>-0.28</td>
</tr>
<tr>
<td>Inc. radial box size 50%</td>
<td>9.79</td>
<td>5.08</td>
<td>-0.39</td>
</tr>
</tbody>
</table>