Direct Comparison of GEMR Edge Turbulence Simulations with Alcator C-Mod SOL Turbulence Measurements

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We report a direct comparison of measured SOL turbulence in Alcator C-Mod plasmas to a computational model. The turbulence measurements were made with gas puff imaging (GPI) and Langmuir probes, and the simulations were performed by the GEMR gyro-fluid electromagnetic code [Phys. Plasmas 12 (2005) 102307].

Plasma conditions were chosen to match the capabilities of the computational model: near-circular, Ohmic, inner wall limited, with $B = 2.9-5.4$ T and $I_p = 0.4-0.8$ MA at fixed $q(a) \sim 3$.

The measured radial and poloidal correlation lengths in the C-Mod SOL were approximately a factor 1.5-2 larger than those predicted by GEMR, and both measured and computed correlation lengths showed a slow decrease with $B$, with relatively little change with SOL density. The measured and simulated autocorrelation times and frequency spectra were very similar at low $B$, but the measured autocorrelation time increased with $B$ more strongly than in the simulations. Additional comparisons and limitations of these comparisons will be described.
Caveats on this Comparison

• GEMR is a “local model” which is limited to one set of plasma parameters in the SOL, so mid-SOL values were chosen as the GEMR inputs from C-Mod

• The full-2D GPI imaging system was not working well during 2006-2007, so only GPI data from two linear arrays of views coupled to individual “fast diode” detectors were used

• Effect of GPI cloud sightline averaging not yet included in the post-processing of GEMR results

• This comparison should be considered a ‘first iteration’ of an attempt to ‘validate’ the GEMR code
Choice of Plasma Conditions

• Choose discharges best suited for comparisons with GEMR
  - limited Ohmic plasma
  - near-circular plasma
  - wide outer SOL

• Vary $B$ and $<n>$ at fixed $q(a)$, to vary $\rho_s$ and collisionality (C)

<table>
<thead>
<tr>
<th>$B$ (T)</th>
<th>$I$ (MA)</th>
<th>$&lt;n_e&gt;/10^{14}$</th>
<th>$n_e(a)/10^{13}$</th>
<th>#shots</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.9</td>
<td>0.4</td>
<td>0.84-1.36</td>
<td>~ 3</td>
<td>10</td>
</tr>
<tr>
<td>4.1</td>
<td>0.6</td>
<td>1.36-2.02</td>
<td>~ 5</td>
<td>4</td>
</tr>
<tr>
<td>5.4</td>
<td>0.8</td>
<td>1.56-2.51</td>
<td>~ 7</td>
<td>8</td>
</tr>
</tbody>
</table>

$n$ correlated with $B$, so difficult to separate $\rho_s$ & C scaling
Plasma Evolution and Equilibrium

Typical time dependences

- \( B \) (Tesla)
- \( I \) (MA)
- \(<n>/10^{13} \text{ cm}^{-3}\)
- GPI diode (rel.)

Equilibrium

GPI data

GPI diode views

Shot: 1060412026  Time: 1.160  Ip = 0.78
Gas Puff Imaging (GPI) Diagnostic

- Views $D_\alpha$ light from local D puff $\propto n^{0.4-0.6} T_e^{0.6-0.8}$ (here)

- GPI “fast diode” views have $\sim 3$ mm spatial resolution
  $\sim 3$ $\mu$s time resolution

For these comparisons, the GPI diode results are averaged over 5 diodes in either the radial or the poloidal arrays

no attempt at fine-scaled radial resolution in this comparison!
GEMR Model and Assumptions

• GEMR is an electromagnetic gyrofluid model with a "δ-f" formulation, advancing six moment variables \( n, u_\parallel, T_\parallel, T_\perp \) and the \( \parallel/\perp \) components of the parallel heat flux), for each of two species (ions/electrons). The fields \( \phi \) and \( A_\parallel \) are solved self-consistently at each time step.

• For C-Mod cases, entire flux surfaces are modeled with circular equilibria, \( Z=2, M=2, q(a) \sim 3, q(r) \) parabolic

• Boundary conditions:
  - plasma-side boundary values input from C-Mod data
  - outer wall boundary conditions fixed at \( n, T = 0 \)
  - parallel sheath conditions at limiter \( (e\phi/T_e \sim 3) \)
GEMR Outputs and Analysis

- Output 12.7 cm (poloidal) x 2.6 cm (radial) x 1.4 msec (time)

- Smoothed by resolutions of “fast diodes” and converted to $D_\alpha$

<table>
<thead>
<tr>
<th>$D_\alpha$ raw</th>
<th>$D_\alpha$ smooth</th>
<th>B</th>
<th>n/$10^{13}$ cm$^{-3}$</th>
<th>T(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>27</td>
<td>1.6 (low)</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27</td>
<td>3.6 (high)</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38</td>
<td>2.2 (low)</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>38</td>
<td>4.6 (high)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>54</td>
<td>1.8 (low)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>54</td>
<td>3.2 (high)</td>
<td>19</td>
</tr>
</tbody>
</table>
Radial Profiles of GPI and GEMR

- Use 4 GPI radial views in middle of SOL for comparisons
- Use only 0.5-0.75 of GEMR radial profile for comparisons

Comparison of radial variations of GEMR and GPI in one case

The comparisons are done by averaging over the shaded box widths

these radial variations not included in the comparisons
Comparisons of GPI and GEMR

**Correlation lengths** - from cross-correlation between nearby points, assuming Gaussian correlation function

**Autocorrelation times** - time for autocorrelation function to go from 1.0 at zero time delay to 0.5

**Turbulence velocities** - from time delay of the peak of cross-correlation function between nearby points

**Frequency spectra** - from FFT of time series

**Poloidal k-spectra** - from Beall method for nearby points

**Fluctuation level, skewness, kurtosis** - moments of $D_\alpha$ signals
Correlation Lengths vs B

- GPI data averaged over 4 radii and all \( <n> \) cases
- GEMR results averaged over 0.5-0.75 of radial grid

\[ L_{\text{pol}} (\text{cm}) \]

\[ B (\text{T}) \]

=> GEMR correlation lengths ~2x lower than GPI data
Correlation Lengths vs $<n>$

- GPI data for each of 4 radii for each $<n>$ vs. B (colors)
- GEMR results averaged over 0.5-0.75 of radial grid

$=>$ GEMR and GPI size scales vary weakly with $<n>$ and B
Autocorrelation Time vs. B and <n>

- GPI data averaged over R and <n> (left), or not (right)
- GEMR results averaged over 0.5-0.75 of radial grid

=> GEMR correlation times ~1.5-2.5 x lower than GPI data
Poloidal and Radial Velocities

- GPI data averaged over 4 radii and all $<n>$ (left and right)
- GEMR results for 5 radii (left) or radially averaged (right)

$=>$ GEMR velocity magnitudes within ~ 2x of GPI
Frequency Spectra

- GPI data averaged over 4 radii, normalized at $f \sim 1$ kHz
- GEMR results averaged over 0.5-0.75 of radial grid

=> GEMR frequency spectra similar to GPI data
Poloidal k-Spectra

- GPI data averaged over 4 radii, normalized at $k \sim 1 \text{ cm}^{-1}$
- GEMR results averaged over 0.5-0.75 of radial grid

=> GEMR $k_{pol}$ spectra similar to GPI data, except $k_{pol} \leq 1 \text{ cm}^{-1}$
**Relative Fluctuation Levels**

- GPI data averaged over R and <n> (left), or not (right)
- GEMR results averaged over 0.5-0.75 of radial grid

=> GEMR fluctuation level ~2-5 times lower than GPI data
Skewness and Kurtosis

- GPI data averaged over 4 radii for one discharge
- GEMR results averaged over 0.5-0.75 of radial grid

=> GEMR skewness and kurtosis within ~2x of GPI data
Summary

- GEMR correlation lengths ~x2 lower than GPI data
- GEMR and GPI both weakly varying with \( <n> \) and B
- GEMR correlation times ~x1.5-2.5 lower than GPI data
- GEMR velocity magnitudes within ~x2 of GPI data
- GEMR frequency spectra similar to GPI data
- GEMR \( k_{\text{pol}} \) spectra similar to GPI data except \( k_{\text{pol}} \leq 1 \text{ cm}^{-1} \)
- GEMR fluctuation level ~x2-5 lower than GPI data
- GEMR skewness and kurtosis within ~x2 of GPI data
Tentative Interpretations

• The GEMR model is generally within a factor-of-two in reproducing the C-Mod SOL turbulence results

• The longest poloidal wavelength components in the C-Mod data may not be captured in the GEMR model, which could cause the underestimate of the L’s, $\tau$, and $\tilde{n}/n$

• The gyrofluid model is missing the trapped electrons, which could result in larger amplitudes for longer wavelengths (would be present in kinetic model under development)