Comparison between measured and predicted turbulence frequency spectra in ITG and TEM regimes

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Reproduction of distinct reflectometry features in Tore-Supra discharge by GK modelling

Reflectometry spectrum, TS shot #48102 at r/a~0.15-0.2

Ohmic discharges with current (density) ramp and distinct phases

SOC – broad spectrum

LOC – “quasicoherent” modes

- ‘Quasicoherent modes’ observed in LOC phase of a LOC-SOC transition Tore-Supra discharge. Similar observations in many machines and regimes [H. Arnichand, et al., NF Lett 2014, NF 2015, PPCF 2016]

- Can nonlinear gyrokinetic simulations shed light on source of feature?

- This work was in support of Hugo Arnichand PhD (CEA Cadarache)
Linear gyrokinetics shows ITG in SOC phase, and TEM in LOC phase

Studied at $\rho = 0.37$ due to poor $T_i$ diagnostics in inner core.

<table>
<thead>
<tr>
<th>Phase</th>
<th>$R/L_{T_i}$</th>
<th>$R/L_{T_e}$</th>
<th>$R/L_{ne}$</th>
<th>$T_e/T_i$</th>
<th>$\beta_e$ [%]</th>
<th>$\hat{s}$</th>
<th>$q$</th>
<th>$\nu^*$</th>
<th>$Z_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOC (t=3.8-3.4 s)</td>
<td>4.7±0.5</td>
<td>9.2±0.35</td>
<td>2.8±0.1</td>
<td>1.8±0.1</td>
<td>0.13</td>
<td>0.7</td>
<td>1.3</td>
<td>0.012</td>
<td>3.0±0.1</td>
</tr>
<tr>
<td>SOC (t=5.8-6.4 s)</td>
<td>5.0±0.4</td>
<td>8.9±0.25</td>
<td>1.8±0.1</td>
<td>1.6±0.1</td>
<td>0.14</td>
<td>0.75</td>
<td>1.25</td>
<td>0.029</td>
<td>1.4±0.1</td>
</tr>
</tbody>
</table>

• LOC $\rightarrow$ SOC transition here associated with TEM $\rightarrow$ ITG transition

• Lower $Z_{\text{eff}}$ and lower $R/Ln$ more responsible for TEM $\rightarrow$ ITG transition than increase in $\nu^*$

• LOC regime ion mode at higher $k_y$ is a carbon-ITG. Stabilized with a 30% reduction in $R/L_{TC}$

Uncertainties in linear results from propagation of logarithmic gradient uncertainties
Nonlinear GENE simulations of each case: flux spectra and power balance matching

- Power balance uncertainties from propagation of $T_i$ and $T_e$ errors in collisional heat transfer
- GENE error bars underpredicted since they don’t include propagation of input parameter statistical and systematic errors (see Ian’s talk tomorrow)
- From additional simulations with sensitivity studies, easy to get power balance agreement for all cases apart from apart from SOC $q_e$. Systematic experimental $T_i$ error?

Correspondence deemed close enough to justify qualitative comparison of spectra

<table>
<thead>
<tr>
<th></th>
<th>$q_i$</th>
<th>$q_e$</th>
<th>$q_i$</th>
<th>$q_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOC</td>
<td>4.5 ± 1</td>
<td>6.7 ± 1</td>
<td>1 ± 1</td>
<td>12 ± 3</td>
</tr>
<tr>
<td>SOC</td>
<td>14 ± 3</td>
<td>-1 ± 3</td>
<td>14 ± 2</td>
<td>9 ± 2</td>
</tr>
</tbody>
</table>

Comparison of simulated and exp fluxes. All values in kW/m²
Nonlinear simulations show sharper drift-wave TEM peaks compared to ITG

Comparison of kx-averaged frequency spectrum per toroidal wavenumber

- Difference in broadening and nonlinear spectrum has major ramifications
- LOC narrow broadening and “condensation” to fewer drift waves leads to emergence of TEM modes in nonlinear spectrum
- SOC modes all overlap and smear out the frequency spectrum
Summed frequency spectrum shows gap for TEM (LOC) spectrum compared to ITG (SOC)

Summed frequency spectra (logy scale, as in diagnostic)

Summed spectra qualitatively show same characteristics as the reflectometry measurements – a separated peak in drift-wave frequencies for TEM (LOC) vs broad band for ITG (SOC)

Note: reflectometry will not observe the $\omega = 0$ peak
Experimental QCM feature recovered with synthetic reflectometry diagnostic

GENE fluctuations used in synthetic reflectometry diagnostic (S. Hacquin submitted to PPCF). Quantitatively recovers measured spectrum

\[ V = V_{\text{phase}} + V_{\text{ExB}} \]: ExB velocity estimated from \( E_r \) maintaining ambipolarity in ripple dominated regime

[Trier NF 2008]

Adds to fundamental validation of underlying turbulence model
Comparison of linear and nonlinear frequency spectra

\[ \omega_{nl} \text{ comparable to } \omega_{lin} \text{ where linear drive is strong} \]
• $\Delta \omega_{nl}$ comparable to $\gamma_{lin}$ where linear drive is strong: validates quasilinear assumptions
• LOC nonlinear broadening less than SOC
• Speculation: related to nonlinear saturation mechanisms? $\eta_e > 1$ TEM saturation mechanism not related to ZF (Merz, Jenko PRL 2008)
TEM frequency broadening converges to similar behaviour as ITG for $\eta_e < 1$

$\eta_e (L_{ne}/L_{Te})$ scan. (Nominal $\eta_e$ was 3.3)

Motivation: TEM saturation physics depends on $\eta_e$. For $\eta_e > 1$ does not depend of ZF coupling (Merz, Jenko, Ernst)

Frequency broadening comparison

- $\eta_e = 3.3$
- $\eta_e = 1.6$
- $\eta_e = 1$
- $\eta_e = 0.3$

Trend for increased frequency broadening as $\eta_e \leq 1$

Note: R/Lte and R/Lne parameters were tweaked (while maintaining each $\eta_e$) such that all cases have similar fluxes agreeing with $q_e$ power balance (within 20%)
Quasicoherent mode signature predicted to reduce as $\eta_e < 1$

Summed frequency spectra comparison

$\eta_e = 3.3$  $\quad$  $\eta_e = 1.6$  $\quad$  $\eta_e = 1$  $\quad$  $\eta_e = 0.3$

Drift-wave gap is filled in at lower $\eta_e$.

Prediction that quasicoherent modes should disappear for density gradient dominated TEM regime?
Nonlinear simulations show narrower frequency broadening of TEM modes

“quasi-coherent” modes measured in LOC phase and disappear in SOC phase, in multiple regimes. We have focused on one Tore-Supra example. Linear GENE simulations relate LOC\( \rightarrow \)SOC to TEM\( \rightarrow \)ITG

Non-linear simulations show that TEM nonlinear frequency broadening is narrower than the ITG case

TEM frequency spectra thus shows a distinct peak in the drift-wave frequencies. ITG is broadband.

Synthetic diagnostic shows quantitative agreement with experiment

Open question: reduced TEM nonlinear frequency broadening related to different nonlinear saturation mechanism? Effect seems to be reduced when \( \eta_e < 1 \) (similar saturation mechanism to ITG)

QC-modes an experimental signature of \( \eta_e > 1 \) TEM?