Correlation Electron Temperature Fluctuation Measurements on Alcator C-Mod and ASDEX Upgrade: Cross Machine Comparisons and Transport Model Validation

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Validation and cross-machine comparisons are important for improving predictive capabilities

- Results from nonlinear gyrokinetic codes can be compared to experiment in detail; very active Validation activities in international fusion community

- Comparisons of power balance results (heat fluxes), turbulence measurements (density, temperature fluctuations, etc.) help to constrain reduced model predictions for ITER and DEMO

- Understanding landscape of linear ITG/TEM/ETG modes and their relation to nonlinear turbulent state is of interest for quasilinear model development (e.g. TGLF) [Staebler PoP 2007 & 2016]
Correlation Electron Cyclotron Emission (CECE) diagnostics measure low-k turbulent $\delta T_e/T_e$

- Correlate two closely spaced radiometer channels; detect low amplitude turbulence below thermal noise [Cima 1995, Sattler 1994]
- Low-k $\delta T_e/T_e$ ($k_\theta \rho_s < 0.4$) CECE sensitive to ion-scale scale turbulence

I-mode validation: Alex Creely invited talk, Thursday VI2.00004
Predictive simulations played important role in designing CECE systems at C-Mod and AUG

- Nonlinear GYRO and GENE simulations were run before CECE systems were built

- A synthetic diagnostic [Holland PoP 2009, Goerler PoP 2013] was used to predict spectrum and amplitude of temperature fluctuations

- Nonlinear gyrokinetic simulations & synthetic diagnostic modeling constrains design of new CECE diagnostics

GYRO predictions for $\delta T_e/Te$ in L-mode at C-Mod

Increasing spot-size reduces amplitude & width of spectrum
C-Mod Validation Results:

Example from Ohmic plasmas, the LOC/SOC transition
C-Mod: CECE has been used to measure $\delta T_e/T_e$ across Linear to Saturated Ohmic Confinement transition

- $B_t = 5.4T, I_p = 0.8\text{MA}$

**SOC**
- $n_e (10^{20}\text{m}^{-3})$

**LOC**
- $r/a = 0.8$
  - $\delta T_e/T_e \approx 1.0\%$

**LOC**
- $r/a = 0.8$
  - $\delta T_e/T_e \approx 0.7\%$

SoC
- $r/a = 0.8$
  - $\delta T_e/T_e \approx 0.7\%$
C-Mod: Ion-scale nonlinear GYRO simulations suggest that multi-scale effects may be significant in these plasmas.
C-Mod: no clear indication of crossing the “ITG/TEM” boundary across LOC/SOC transitions

- C-Mod LOC and SOC plasmas are robustly linearly ITG dominant [Sung NF 2013, Kwak MS 2015], different from AUG [McDermott NF 2014]

- Nonlinear GYRO simulations show no evidence of change in “ITG/TEM” features in turbulent spectrum in C-Mod [Sung PoP 2016]
AUG Validation Results:

Example from ECRH L-modes, Helium and Deuterium Plasmas
AUG: New CECE has been used to measure $\delta T_e/T_e$ in L-mode plasmas, make comparisons with GENE.

**Bt = 2.67T, Ip = 1.0MA**

<table>
<thead>
<tr>
<th>Plasma Type</th>
<th>$\rho_{\text{tor}}$</th>
<th>$\delta T/T$ (±%)</th>
</tr>
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<tbody>
<tr>
<td><strong>Helium Plasma</strong></td>
<td>0.82</td>
<td>(0.76 ± 0.08)%</td>
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<tr>
<td></td>
<td>0.75</td>
<td>(0.67 ± 0.04)%</td>
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<tr>
<td></td>
<td>0.68</td>
<td>(0.59 ± 0.03)%</td>
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<thead>
<tr>
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<th>$\delta T/T$ (±%)</th>
</tr>
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<tbody>
<tr>
<td><strong>Deuterium Plasma</strong></td>
<td>0.82</td>
<td>(0.67 ± 0.08)%</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
<td>(0.67 ± 0.05)%</td>
</tr>
</tbody>
</table>

Polluted with noise

**References**
Freethy RSI 2016
Freethy *Proc. EPS*, (2016)
Freethy EU TTF 2016, Invited
AUG: Ion-scale nonlinear GENE simulations suggest that multi-scale effects may not be significant in these plasmas.
Cross-machine work highlights continued effort to identify conditions when multi-scale models are needed

- Relative strengths of ITG and ETG drive may be important [Goerler PRL 2008, Howard PoP 2016]
- ITG vs TEM dominance may affect importance of ETG / multi-scale effects [Howard NF 2013]
- Multi-scale effects and cross-scale coupling under active investigation see Howard next talk
Summary of validation & cross-machine comparisons

- LOC/ SOC does not tend to correlate with “TEM/ ITG” transition at C-Mod [Sung NF 2013, PoP 2016], but does tend to correlate at AUG [Fable TTF 2016]

- C-Mod: Nonlinear GYRO ion-scale simulations can match $Q_i$ and low-k CECE, but underpredicts $Q_e$ in most plasmas; suggests multi-scale simulations are often needed in C-Mod [Sung PoP 2016, Howard PoP 2016]

- AUG : Nonlinear GENE ion-scale simulations can match $Q_i$ and low-k CECE, and can match $Q_e$; suggests single-scale simulations may be sufficient for plasmas studied [Told PoP 2013, Freethy APS 2016]

- AUG/C-Mod results appear to be due to differences in turbulence, but GENE/GYRO Verification is important ongoing effort [R. Bravenec Poster Tues JP10.00120]
Backup
Cross-machine comparisons: begin probing differences in LOC/SOC plasmas in C-Mod and AUG

**AUG**: Ohmic plasmas considerably more “TEM” dominant ($k_\theta \rho_s = 0.3$)  
[McDermott NF 2014, fig 10, shown here]

**C-Mod**: Ohmic plasmas typically “ITG” dominant ($k_\theta \rho_s = 0.3$)  
[Kwak MS thesis 2015]
New CECE at AUG shares existing transmission line and in-vessel optics for steerable reflectometer

- **Correlation Electron Cyclotron Emission (CECE); $\delta T_e$**
- **Steerable Reflectometer; density fluctuations, $\delta n_e$**
- **New n-T phase measurements at AUG will allow for more detailed validation of nonlinear GENE simulations** [Freethy Mon BP10.00055]