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Summary of Results

- Time history of $\tilde{T}_e/T_e$ during single discharge reveals changes in amplitude in L-mode, H-mode and Ohmic plasmas.

- Electron temperature fluctuations, $\tilde{T}_e/T_e$, and density fluctuations, $\tilde{n}/n$, have similar spectra, amplitudes and increase with radius.

- GYRO predicts $\tilde{T}_e/T_e \sim \tilde{n}/n$, consistent with observations. GYRO/synthetic diagnostics do not fully reproduce increase in fluctuation level with radius.

- Electron Cyclotron Heating (ECH) during beam heated L-mode plasmas results in increased $\tilde{T}_e/T_e$, but not $\tilde{n}/n$. 
Comparisons Using Both Electron Temperature and Density Fluctuations Provide Rigorous Tests of Gyrokinetic Simulations

- Several types of instabilities may contribute to electron heat and particle transport in the tokamak:
  - Ion temperature gradient (ITG) mode \((k_\theta \rho_s < 1)\),
  - Trapped electron mode (TEM) \((k_\theta \rho_s < 2)\)
  - Electron temperature gradient (ETG) mode \((k_\theta \rho_s > 2)\)

- Measurements of \(\tilde{T}_e\) probe physics of non-Boltzmann electron response:
  - In simulations, electron heat and particle transport result from non-Boltzmann (non-adiabatic) electrons (Ross 2002, Dannert 2005, Kinsey 2005)
  - The pure ITG mode (Boltzmann-response) is not associated with electron temperature fluctuations
  - Non-Boltzmann electrons destabilize ITG mode. Trapping allows for TEM.

- Core electron temperature and density fluctuations both contribute to energy transport flux (Liewer 1985, Wootton 1990, Ross 1992)

\[
Q_e = \frac{3}{2} \langle p_e \tilde{v}_r \rangle = \frac{3}{2} n_e \langle \tilde{T}_e \tilde{v}_r \rangle + \frac{3}{2} T_e \langle \tilde{n}_e \tilde{v}_r \rangle
\]
Correlation Electron Cyclotron Emission (CECE) Diagnostic Measures Local, Low-k Electron Temperature Fluctuations

Thermal noise in single ECE signal

\[ \frac{\tilde{T}_e}{T_e} \geq \frac{\Delta f_{VID}}{\Delta f_{IF}} \]

Standard cross-correlation techniques reduce the thermal noise

\[ < \tilde{S}_1 \tilde{S}_2 > \propto \tilde{T}_e^2 \]

Gaussian focusing optics and narrow IF filters provide wavenumber resolution required for turbulence measurements

Beam Emission Spectroscopy (BES) Diagnostic Measures Local, Low-k Density Fluctuations

- CECE and BES diagnostics sample volumes are separated toroidally and vertically, but measure at same radius.
- CECE and BES diagnostics are sensitive to wavenumbers relevant to ITG/TEM, but not ETG.

CECE: $\tilde{T}_e/T_e$
- $k_r < 6 \text{ cm}^{-1}$
- $k_\theta < 1.8 \text{ cm}^{-1}$

BES: $\tilde{n}/n$
- $k_\perp < 3 \text{ cm}^{-1}$
• Temporal evolution of electron temperature fluctuations

• Comparison between electron temperature and density fluctuations in beam heated L-mode plasmas

• Comparison with linear and nonlinear simulations

• Comparison of electron temperature and density fluctuations in ECH experiment
Temperature Fluctuations Are Measured in L-mode, H-mode and Ohmic Plasmas in a Single Discharge

- Shot parameters
  - \( I_p = 1 \) MA
  - \( B_T = 2.1 \) T
  - 2.5 -10 MW beam power
  - upper single null

- Measure \( \tilde{T}_e/T_e \) at \( r/a = 0.75 \)
  - Early L-mode 700-900 ms
  - Stationary L-mode 1400-1600 ms
  - ELM-free H-mode 1895-1930 ms
  - Ohmic 3700-3900 ms
Spectra Evolve in Time, with Large Reduction in $\tilde{T}_e/\tilde{T}_e$ After L-H Transition

- **Typical cross-power spectra** of $\tilde{T}_e/\tilde{T}_e$ at $r/a = 0.74$
  - Spectrum broadens and narrows in response to Doppler shifts due to changing ExB rotation
  - Normalized fluctuation levels in Ohmic (1%) are lower than L-mode (1.5%) at same radius
  - H-mode temperature fluctuations are below sensitivity limit (0.5%, 35 ms)

H-mode results are consistent with QH-mode experiments, a factor 5 reduction has been observed at same radius (L. Schmitz et al., PRL, accepted for publication)
Outline

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The Profile of Temperature Fluctuations in L-mode Is Compared to the Profile of Density Fluctuations

Use series of repeat discharges to measure profiles of $\tilde{T}_e/T_e$ and $\tilde{n}/n$

Stationary, sawtooth-free L-mode.

$n_e \sim 2.5 \times 10^{19} \text{ m}^{-3}$
$T_e \sim 450 \text{ eV}$
$T_i \sim 500 \text{ eV}$

1300-1700 ms used in analysis
Plasma Profiles, Plasma Frequencies, and Optical Depth in L-mode Plasma of Interest

- 2nd Harmonic ECE is far from being cut-off by RH wave

- Plasma is optically thick ($\tau > 4$) in region of interest

- Density fluctuations will not contribute to temperature fluctuation signal

CECE and BES diagnostics scanned between $0.3 < r/a < 0.9$
Temperature and Density Fluctuations Have Similar Spectra and Normalized Fluctuation Amplitudes in L-mode

- $\tilde{n}/n$ and $\tilde{T}_e/T_e$ are measured simultaneously
  - Shot 128915
  - $r/a = 0.74$
  - Averaged over 1300-1700 ms
  - Integrated between 40-400 kHz

\[ \tilde{n}/n = 1.10 \pm 0.17\% \]
\[ \tilde{T}_e/T_e = 1.5 \pm 0.2\% \]
Profiles of Temperature and Density Fluctuations Are Similar During Beam Heated L-mode

- $\tilde{T}_e/T_e$ and $\tilde{n}/n$ measured between $0.3 < r/a < 0.9$
- Spectra are integrated between 40-400 kHz
- $\tilde{T}_e/T_e$ are below sensitivity limit (0.2%, 400 ms) inside $r/a < 0.5$
- Presence of large electron temperature fluctuations suggests non-Boltzmann electron response
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Growth Rate of Most Unstable Mode Increases With Radius, Consistent With Measured Fluctuations

- TGLF (Trapped gyro-Landau-fluid) code used for linear stability analysis
  J. E. Kinsey BI2.00006, G. Staebler UP8.00050

- ITG mode ($f_{\text{REAL}} < 0$) is fastest growing mode for long wavelengths in CECE range
  $\tilde{T}_e$ associated with ITG mode

- Linear growth rate of fastest growing mode (TEM) peaks at $k_\theta \rho_s \sim 0.7$

- Transport fluxes peak at longer wavelengths $k_\theta \rho_s \sim 0.2$ at $r/a = 0.75$
Comparisons between profiles of two fluctuating fields and nonlinear gyrokinetic simulations provide unique and challenging tests of the turbulence models.

- GYRO is an initial value, Eulerian (Continuum) 5-D gyrokinetic transport code.
- Local simulations include real geometry, drift-kinetic electrons, e-i pitch-angle collisions, realistic mass ratio and equilibrium ExB flow.
- Take experimental profiles \( \bar{T}_e/T_e \) and \( \bar{n}/n \) as input.
Synthetic Diagnostics Are Used to Calculate RMS Fluctuation Amplitudes from GYRO Output

- Synthetic diagnostics use Point Spread Functions (PSFs) to model spatial sensitivity of CECE and BES diagnostics

C. Holland UP8.00053
GYRO Predicts $\tilde{T}_e/T_e$ and $\tilde{n}_e/n_e$ are Similar in Amplitude but Radial Profile Trend is not Reproduced

- $\tilde{T}_e/T_e \sim \tilde{n}_e/n_e$, consistent with experiment
- At $r/a = 0.5$, good quantitative agreement
- Trend that fluctuation levels increase with radius not reproduced
- At $r/a = 0.5$, $\chi_{\text{EXP}} \approx \chi_{\text{GYRO}}$
- At $r/a = 0.75$, $\chi_{\text{EXP}} > \chi_{\text{GYRO}}$
- Common result: $\chi \propto (\text{RMS level})^2$
GYRO Predicts Temperature Fluctuations Drive 80% of Heat Flux at \( r/a = 0.5 \)

- **GYRO flux-tube simulation at \( r/a = 0.5 \) has good agreement with experiment**
  - fluctuation levels
  - energy fluxes

\[
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\]

- **GYRO predicts**
  - \( \tilde{T}_e \) drives 80% of energy transport
  - \( \tilde{n}_e \) drives 20% of energy transport
GYRO Predicts the Phase Difference Between $\tilde{T}_e$ and $\tilde{n}_e$ in the L-mode Plasma at $r/a = 0.5$

- Phase between density and potential fluctuations: $\sim 0$  
  - small transport contribution

- Phase between temperature and potential fluctuations: $\sim -\pi$  
  - large transport contribution

Phase between $\tilde{n}_e$ and $\tilde{T}_e$ could be measured in future experiments using CECE and reflectometry.
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Experiment Using Local ECH to Change Local $T_e$ Gradient and Turbulence Drives

- Baseline discharge with beam heating only
  - $I_p = 1$ MA,
  - $B_T = 2.0$ T,
  - 2.5 MW of co-injected beam power
  - Inner wall limited

- Compare to discharge with additional EC heating at $r/a \sim 0.17$
  - Heat fluxes and heat diffusivities increase
  - TGLF indicates increase in TEM growth rate

Times used in analysis: 1500-1700 ms
Increases in Heat Flux and TEM Growth Rate Correlate With Increase in $\tilde{T}_e/T_e$, but $\tilde{n}/n$ Does Not Change

CECE: $\tilde{T}_e/T_e$ increases by 50%
- NB only 1.0±0.2%
- NB + ECH 1.5±0.2%

BES: $\tilde{n}/n$ stays the same
- NB only 1.2±0.2%
- NB + ECH 1.2±0.2%

- Change in spectral shape due to dominant Doppler shift
  - Reduction in $E_r$ with ECH causes spectra to shift to lower frequencies

- The correlation reflectometer shows no change in correlation length of electron density fluctuations

G. Wang UP8.00057
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