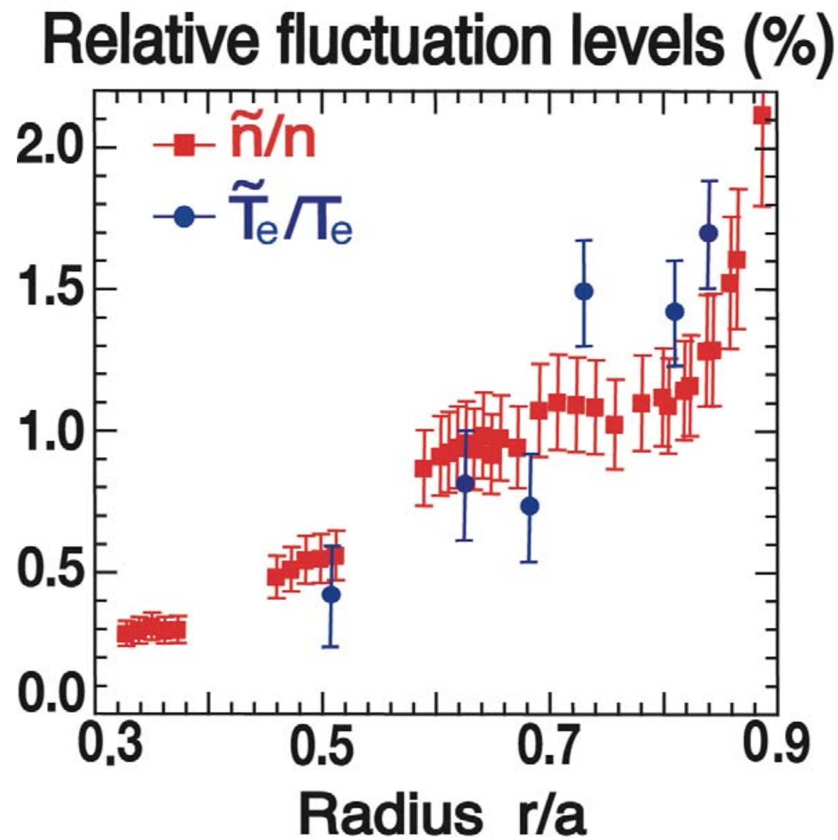
$\tilde{T}_e/T_e$ Turbulence Profile Measurements in DIII-D : Comparison to $\tilde{n}/n$ & Turbulence Model Predictions

by
A.E. White[1]

In collaboration with
L. Schmitz[1], G. McKee[2], C. Holland[3], W. A. Peebles[1], T. A. Carter[1], M. Shafer[2], M. Austin[5], K. H. Burrell[4], J. Candy[4], J. DeBoo[4], E. J. Doyle[1], M. Makowski[1], R. Prater[4], T. L. Rhodes[1], G. Staebler[4], G. Tynan[3], R. Waltz[4], G. Wang[1], and the DIII-D team[4]

[1] University of California, Los Angeles
[2] University of Wisconsin, Madison
[3] University of California, San Diego
[4] General Atomics
[5] University of Texas, Austin



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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 $\tilde{T}_e/T_e \sim \tilde{n}_e/n_e$, 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 $\tilde{n}/n$

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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)

$$Q_e = \frac{3}{2}\langle \tilde{p}_e \tilde{v}_r \rangle = \frac{3}{2} n_e \langle \tilde{T}_e \tilde{v}_r \rangle + \frac{3}{2} T_e \langle \tilde{n}_e \tilde{v}_r \rangle$$

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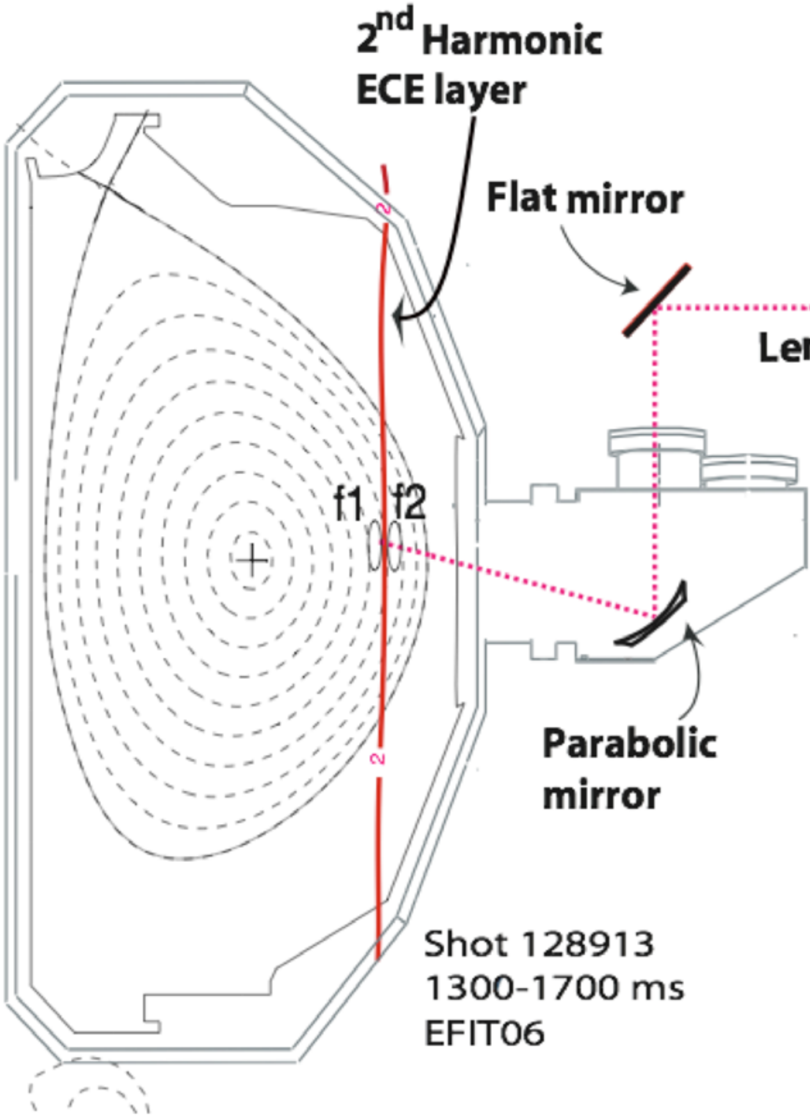
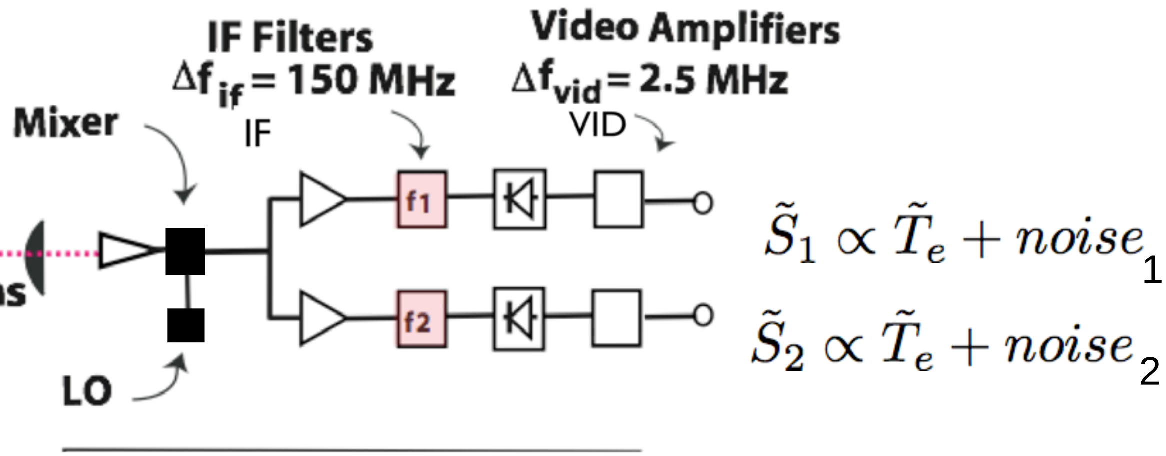
Correlation Electron Cyclotron Emission (CECE) Diagnostic Measures Local, Low-k Electron Temperature Fluctuations





Thermal noise in single ECE signal

$$(\tilde{T}_e/T_e)^2 \geq \frac{\Delta f_{VID}}{\Delta f_{IF}}$$

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

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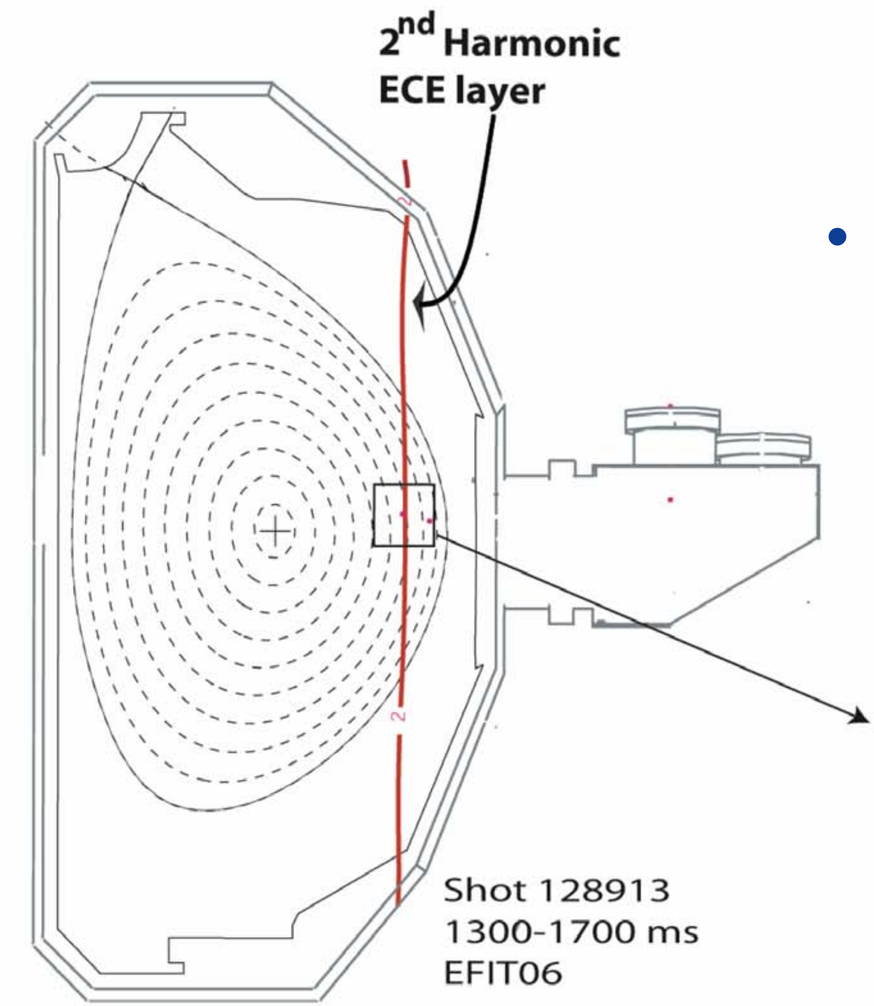
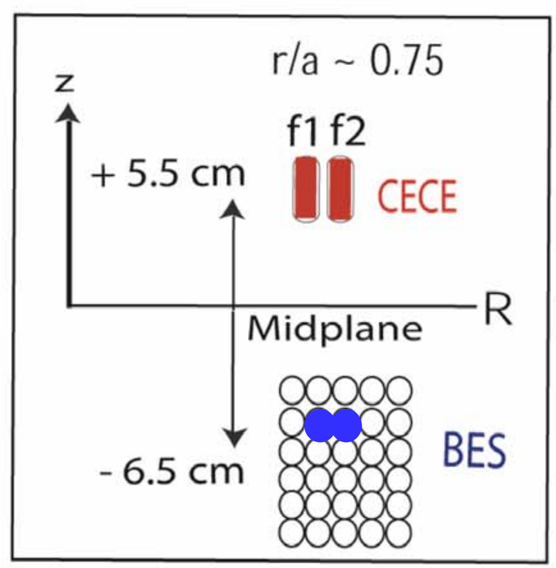
TEXT, Cima 1995, W7-AS, Sattler 1994

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 $\tilde{T}_e/T_e$

$k_r < 6 \ \ cm^{-1}$

$k_\theta < 1.8 \ \ cm^{-1}$

BES $\tilde{n}/n$

$k_\perp < 3 \ \ cm^{-1}$

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Outline

- 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

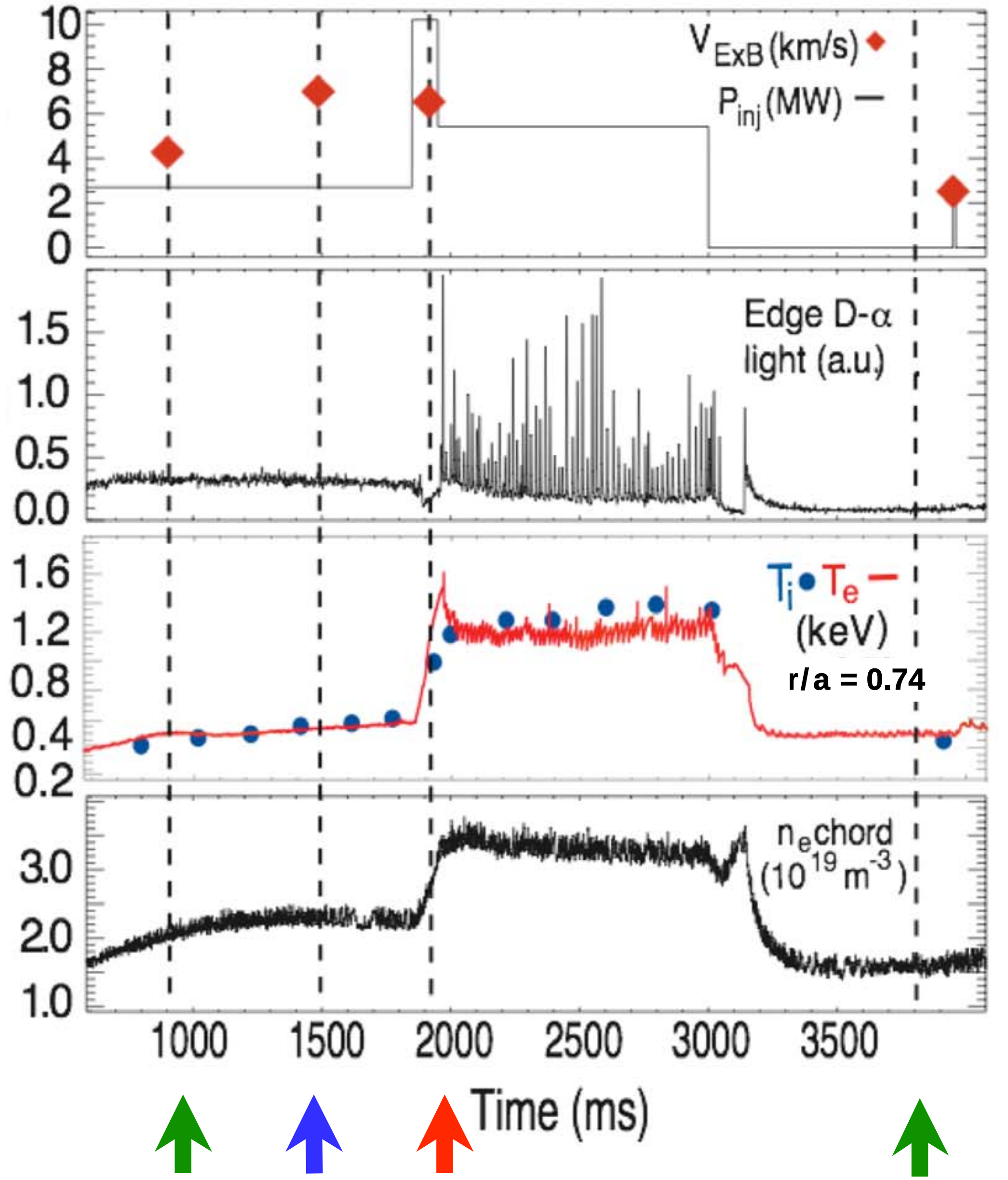
Temperature Fluctuations Are Measured in L-mode, H-mode and Ohmic Plasmas in a Single Discharge

- **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



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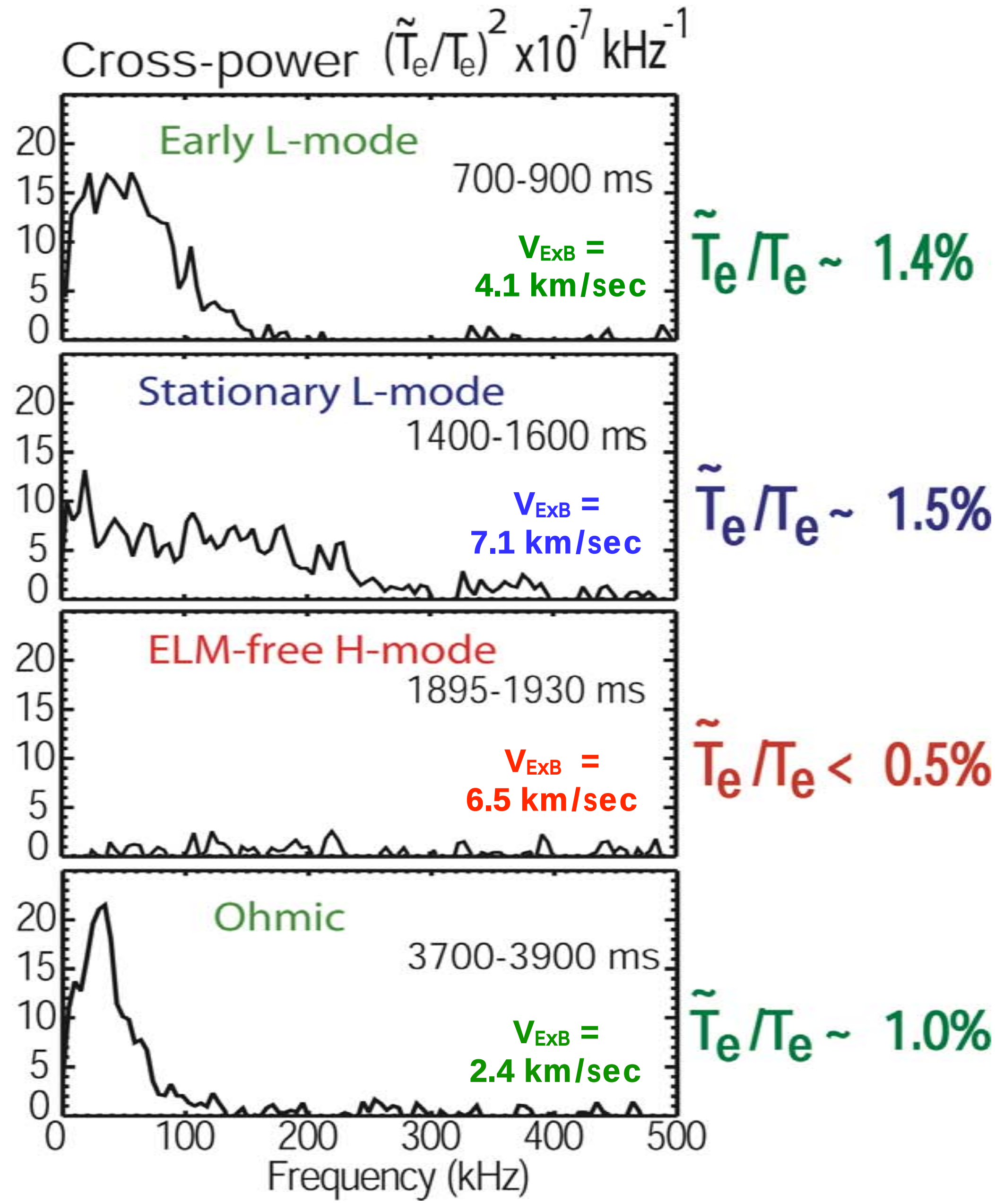
Spectra Evolve in Time, with Large Reduction in $\tilde{T}e/Te$ After L-H Transition

- **Typical cross-power spectra of $\tilde{T}_e/T_e$ 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)



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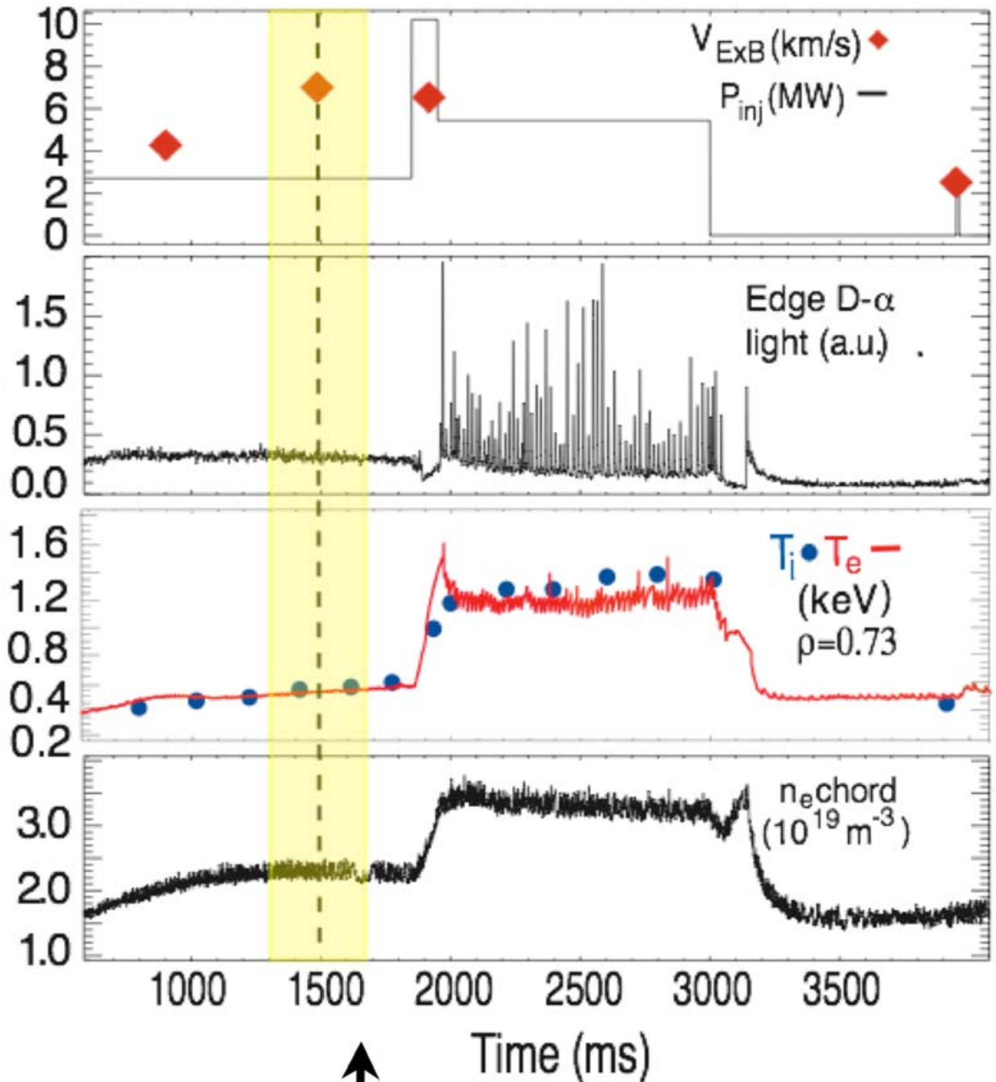
The Profile of Temperature Fluctuations in L-mode Is Compared to the Profile of Density Fluctuations



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

Stationary, sawtooth-free L-mode.

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

1300-1700 ms used in analysis

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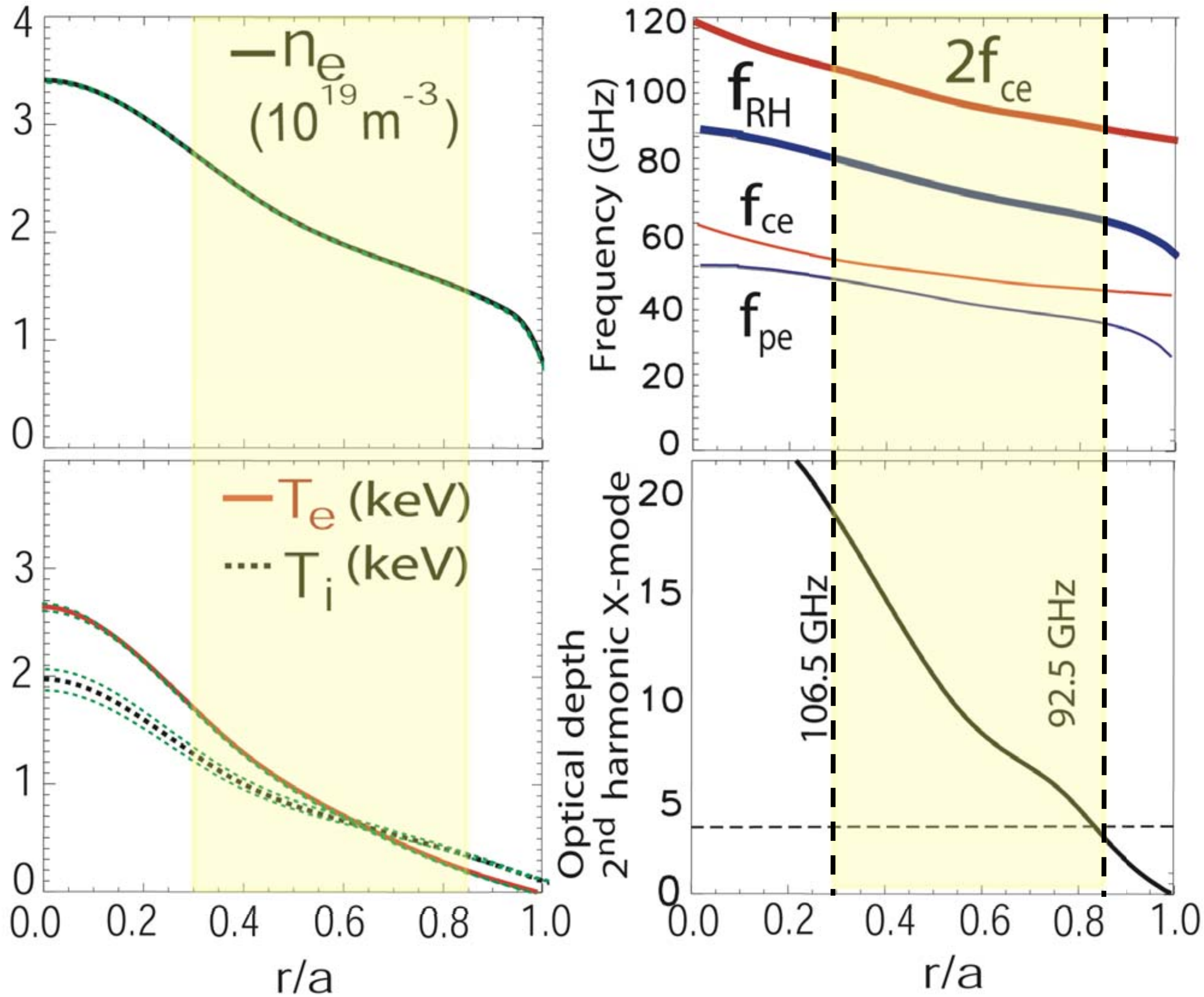
Plasma Profiles, Plasma Frequencies, and Optical Depth in L-mode Plasma of Interest

- **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**



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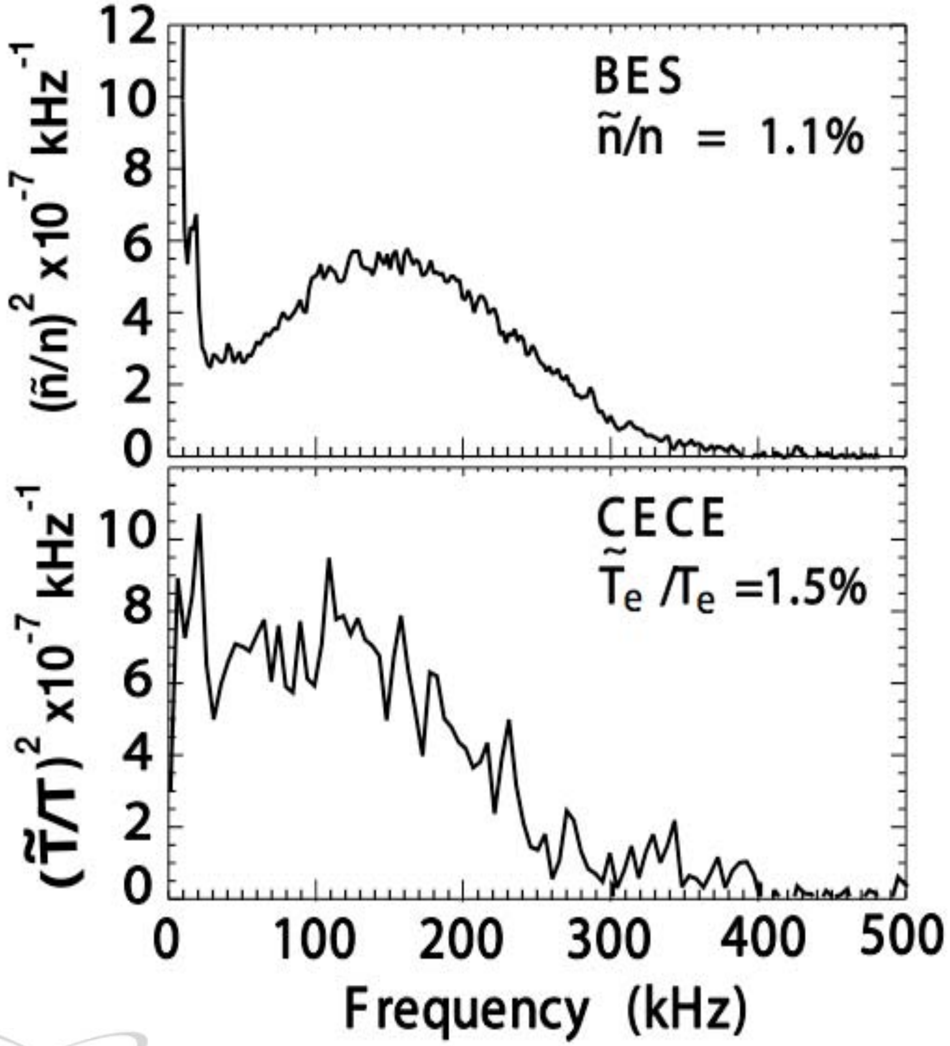
CECE and BES diagnostics scanned between *0.3 < r/a < 0.9*

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

$$\tilde{n}/n = 1.10 \pm 0.17\%$$

$$\tilde{T}_e/T_e = 1.5 \pm 0.2\%$$

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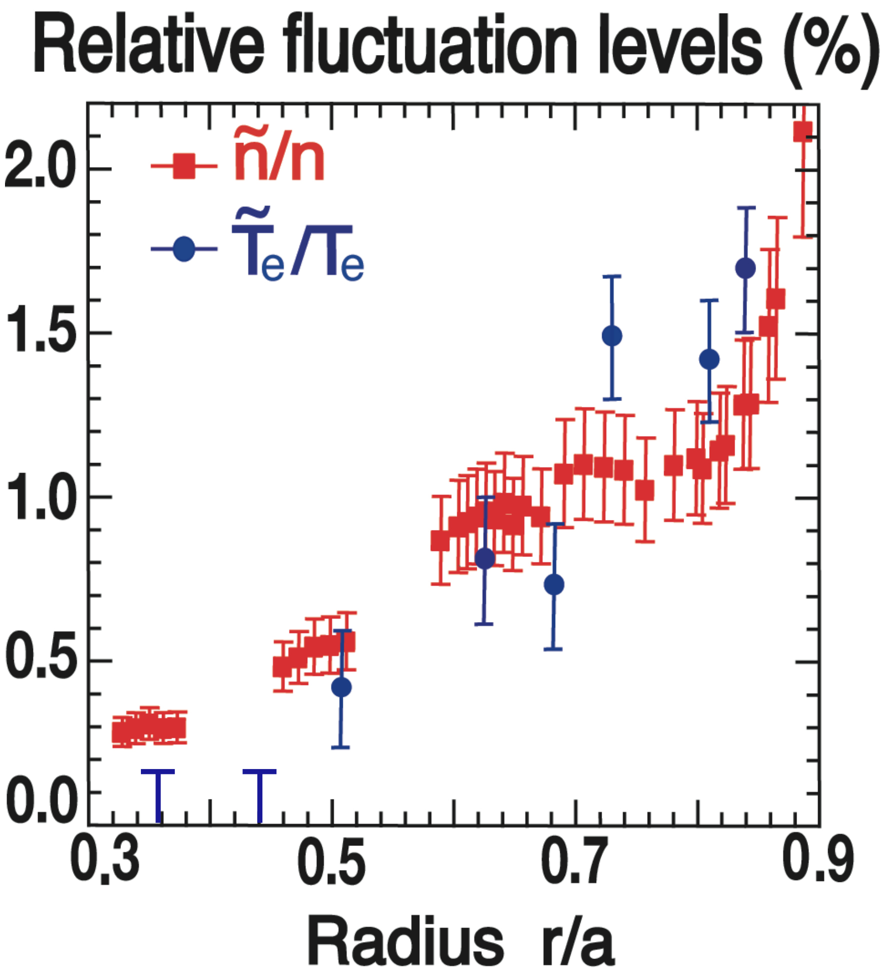
Profiles of Temperature and Density Fluctuations Are Similar During Beam Heated L-mode



- $\tilde{T}_e/T_e$ 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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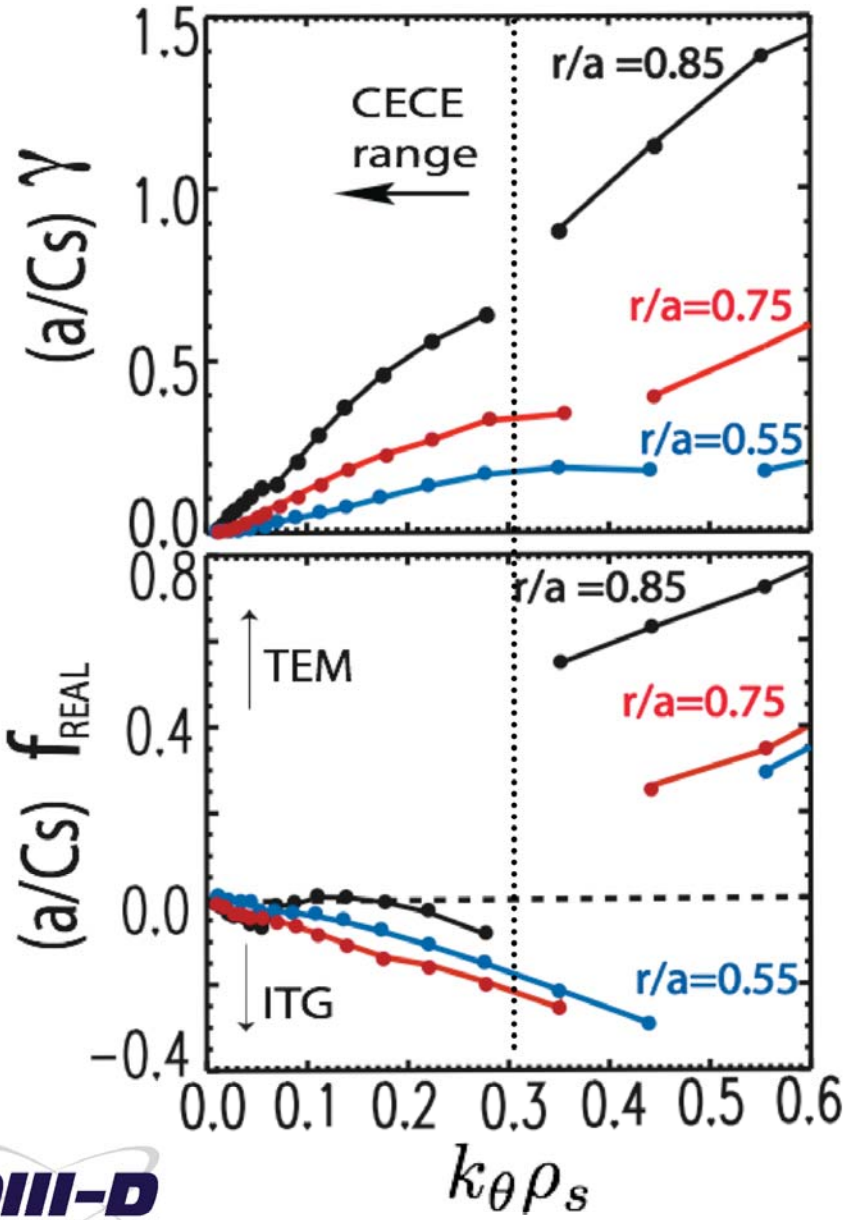
Growth Rate of Most Unstable Mode Increases With Radius, Consistent With Measured Fluctuations



- TGLF (Trapped gyro-Landau-fluid) code used for linear stability analysis J. E. Kinsey BI2.00006, G. Staebler UP8.00050
- ITG mode (f_{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 $k_\theta \rho_s$ ~ 0.7
- Transport fluxes peak at longer wavelengths
  $k_\theta \rho_s$ ~ 0.2 at r/a = 0.75

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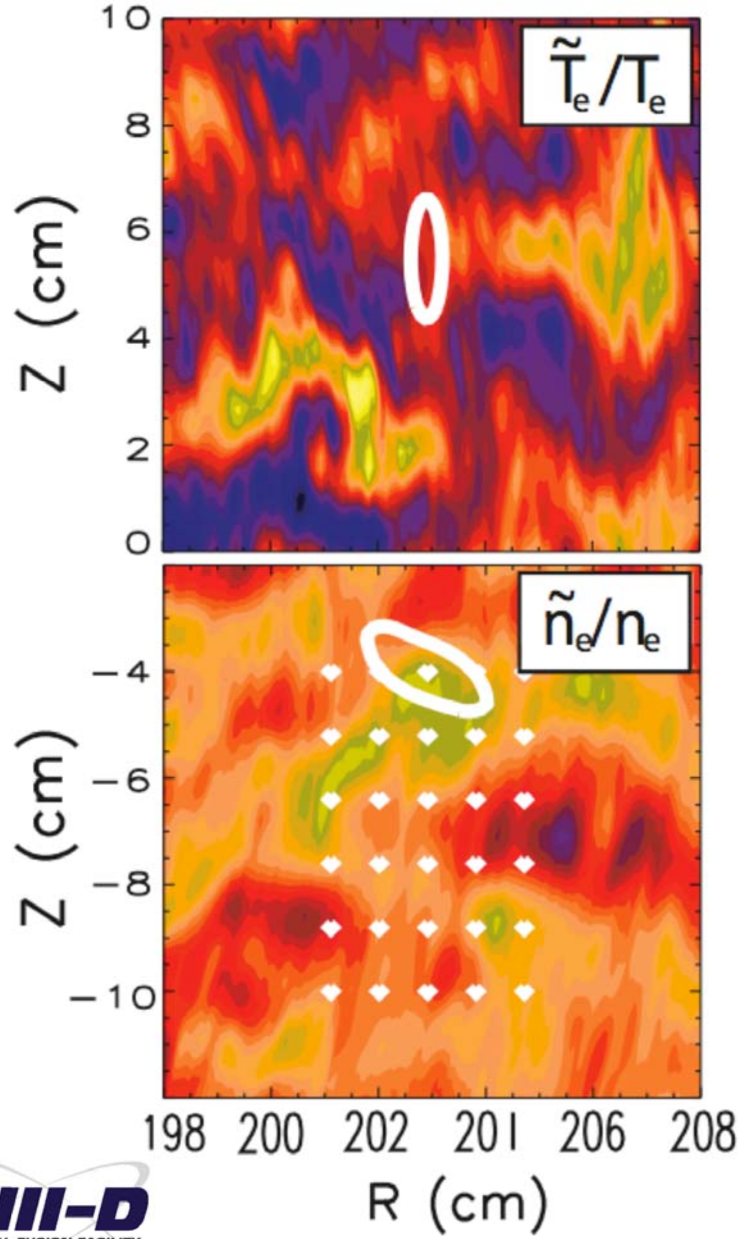
Compare Measured $\tilde{T}_e/T_e$ and $\tilde{n}/n$ With Results From Local, Nonlinear GYRO Simulations

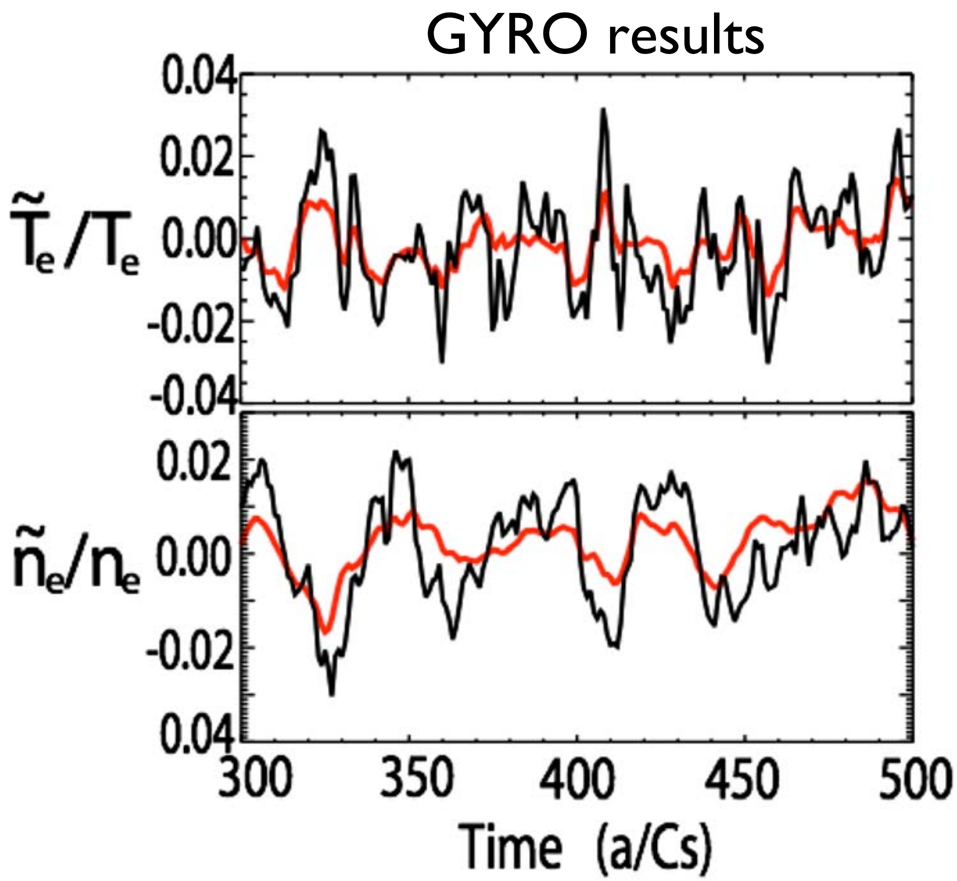
- **Comparisons between profiles of two fluctuating fields and nonlinear gyrokinetic simulations provide unique and challenging tests of the turbulence models**
  - GYRO is an initial value, Eulerian (Continuum) 5-D gyrokinetic transport code
  - Local simulations include real geometry, drift-kinetic electrons, e-i pitch-angle collisions, realistic mass ratio and equilibrium ExB flow
  - Take experimental profiles (T_e, T_i, n_e, E_r) as input

Synthetic Diagnostics Are Used to Calculate RMS Fluctuation Amplitudes from GYRO Output

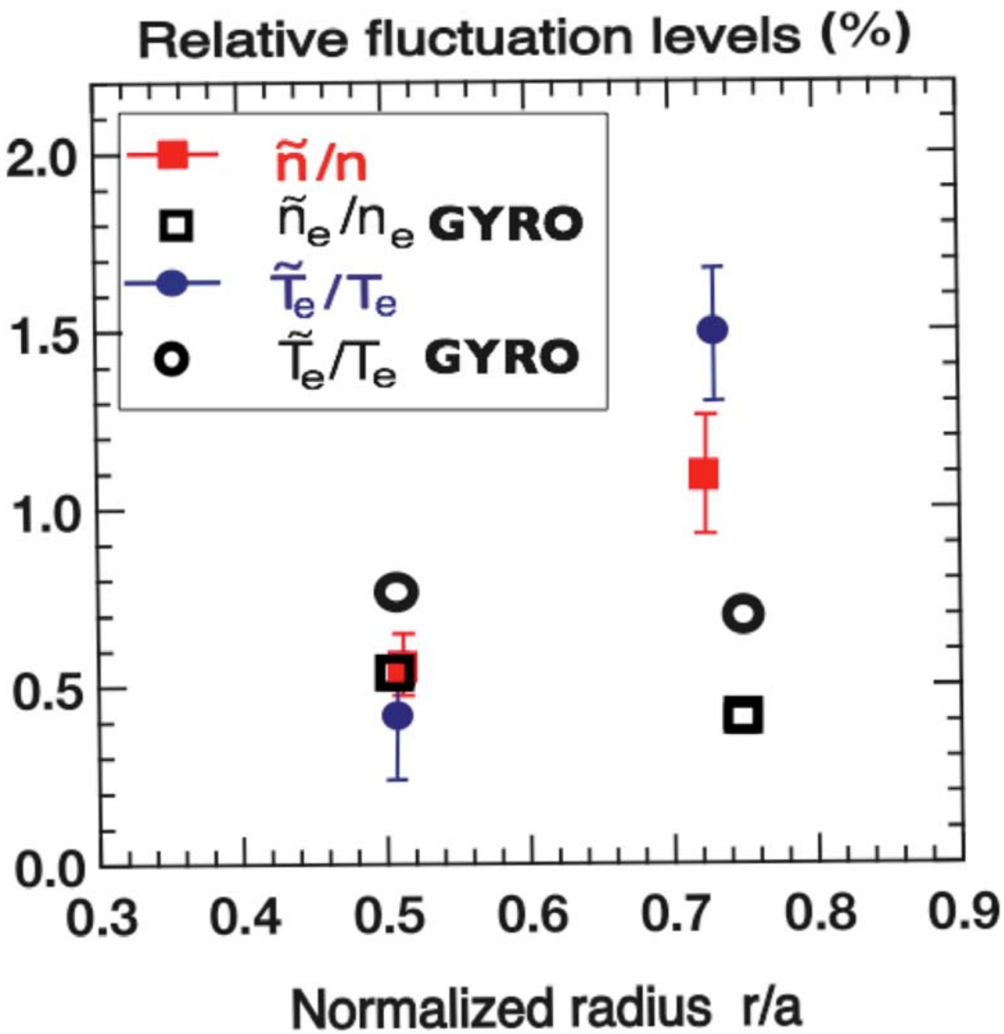


- Synthetic diagnostics use Point Spread Functions (PSFs) to model spatial sensitivity of CECE and BES diagnostics

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, $\chi_{EXP} \approx \chi_{GYRO}$
- At r/a = 0.75, $\chi_{EXP} > \chi_{GYRO}$
- Common result:

$$\chi \propto (\text{RMS level})^2$$

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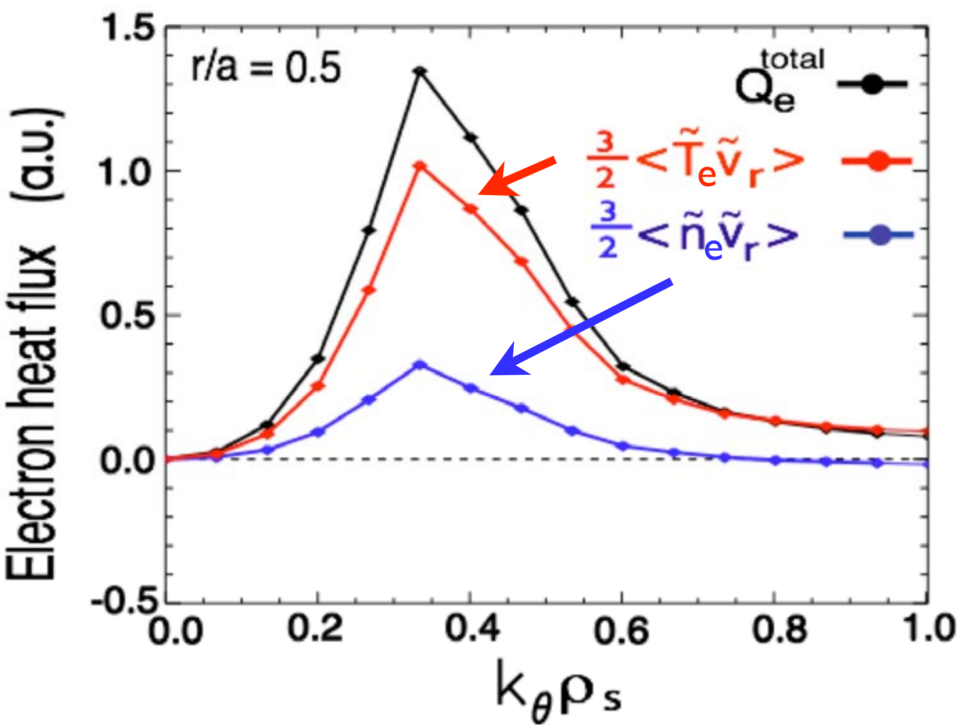
GYRO Predicts Temperature Fluctuations Drive 80% of Heat Flux at r/a = 0.5



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

$$Q_e = \frac{3}{2}\langle\tilde{p}_e\tilde{v}_r\rangle = \frac{3}{2}n_e\langle\tilde{T}_e\tilde{v}_r\rangle + \frac{3}{2}T_e\langle\tilde{n}_e\tilde{v}_r\rangle$$

- GYRO predicts
  $\tilde{T}_e$ drives 80% of energy transport
  $\tilde{n}_e$ drives 20% of energy transport

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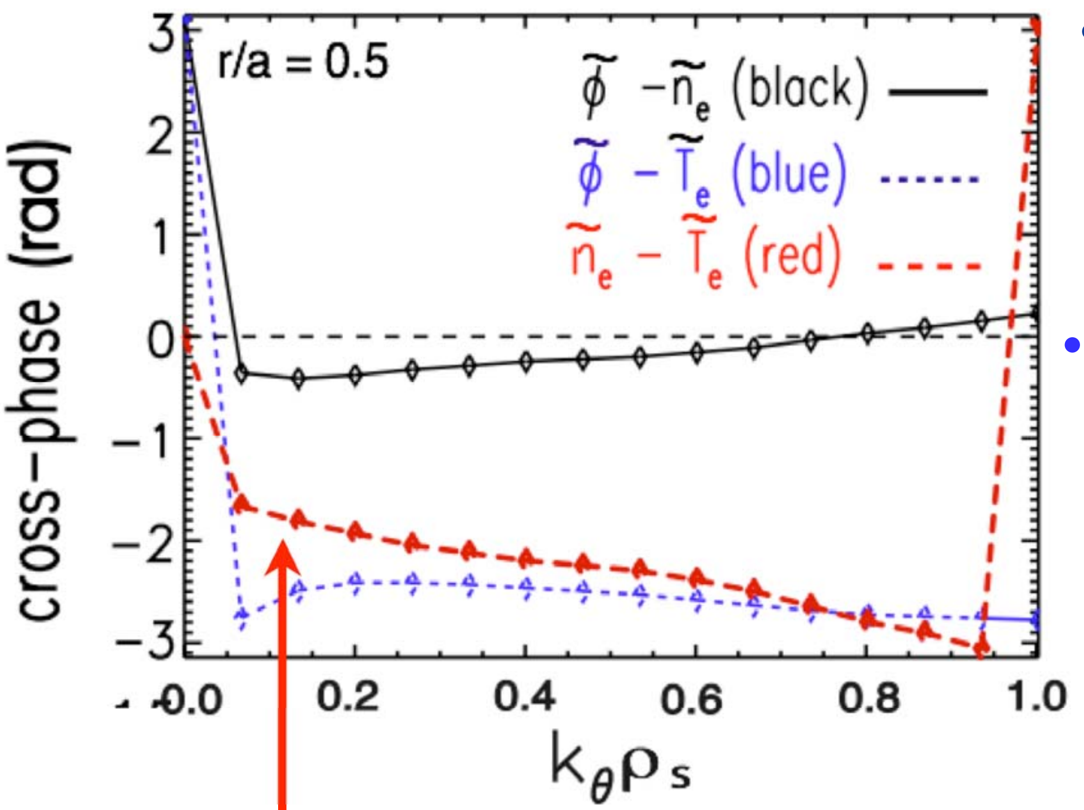
GYRO Predicts the Phase Difference Between $\tilde{T}_e$ and $\tilde{n}_e$ in the L-mode Plasma at r/a = 0.5



- Phase between density and potential fluctuations: ~ 0
  - small transport contribution
- Phase between temperature and potential fluctuations: ~ $-\pi$
  - 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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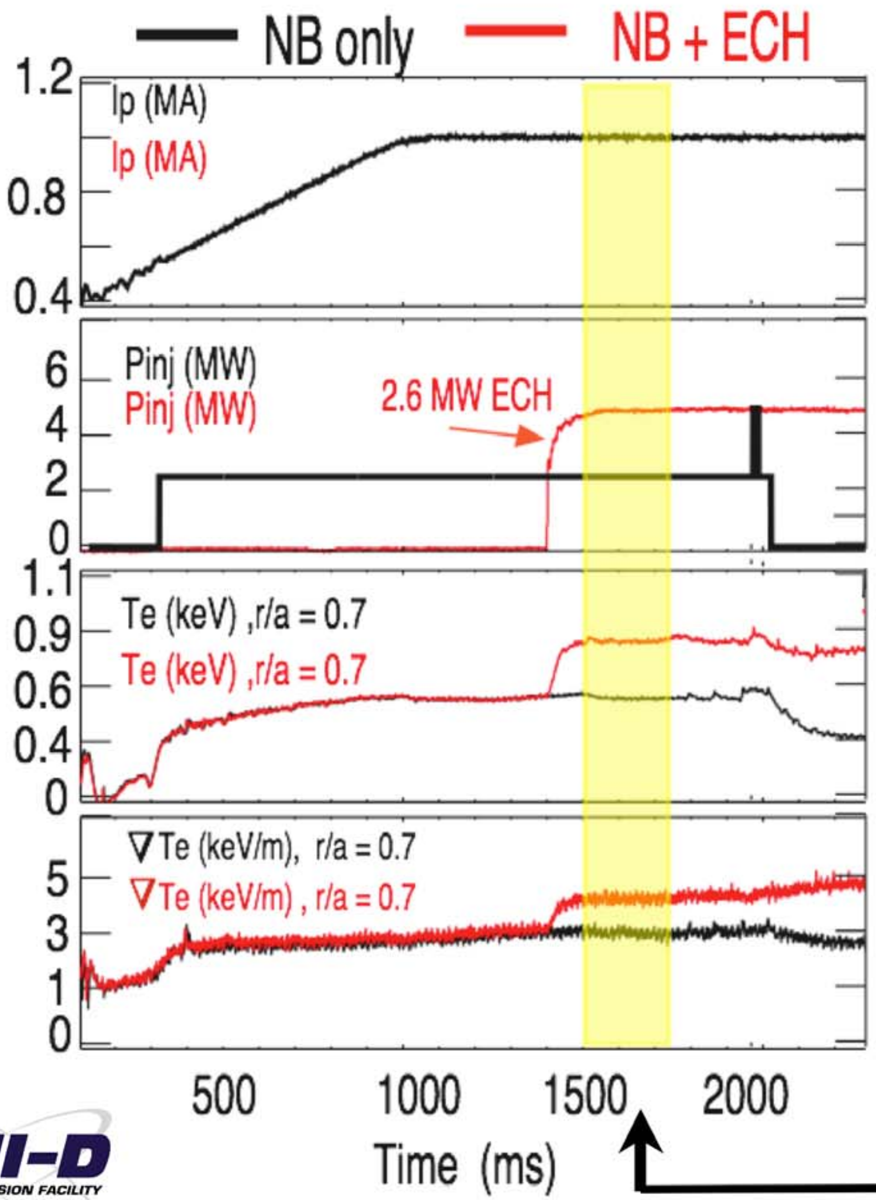
Experiment Using Local ECH to Change Local T_e Gradient and Turbulence Drives



- **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 ~ 0.17**
  - Heat fluxes and heat diffusivities increase
  - TGLF indicates increase in TEM growth rate

Times used in analysis 1500-1700 ms

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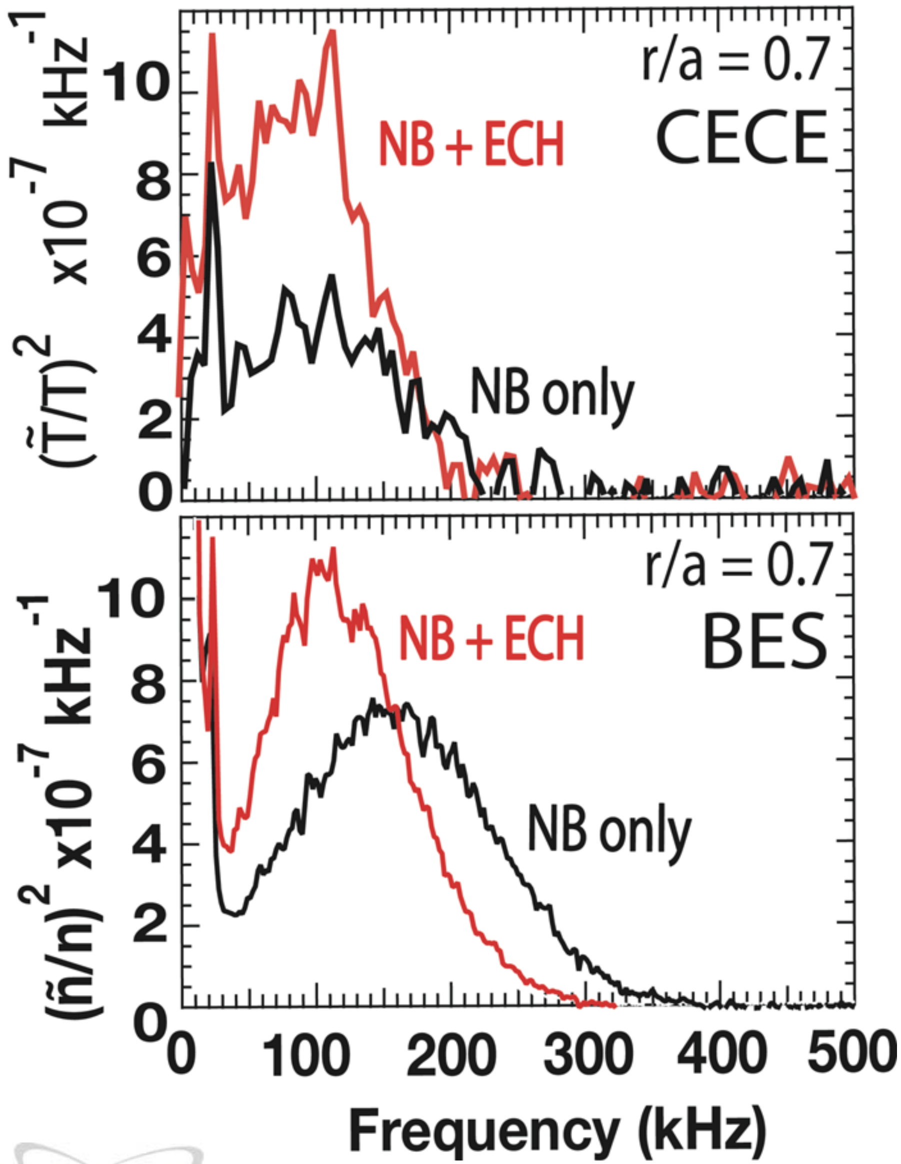
Increases in Heat Flux and TEM Growth Rate Correlate With Increase in $\tilde{T}_e/T_e$, but $\tilde{n}/n$ Does Not Change



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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