Measurements of Core Electron Temperature Fluctuations

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Presented at
PPPL, Princeton, NJ
May 20, 2008

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UCLA

Both Electron Temperature and Density Fluctuations Provide Information about Physics of Turbulence and Transport

- **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 ($k_\theta \rho_s > 2$)

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

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

- **Measurements of $\tilde{T}_e$ probe physics of non-Boltzmann electron response, in particular, trapped electrons**
  - Turbulence models: electron heat and particle transport result from non Boltzmann (non-adiabatic) electrons
  - Trapped electrons destabilize ITG mode, drive TEM unstable

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Summary of Results

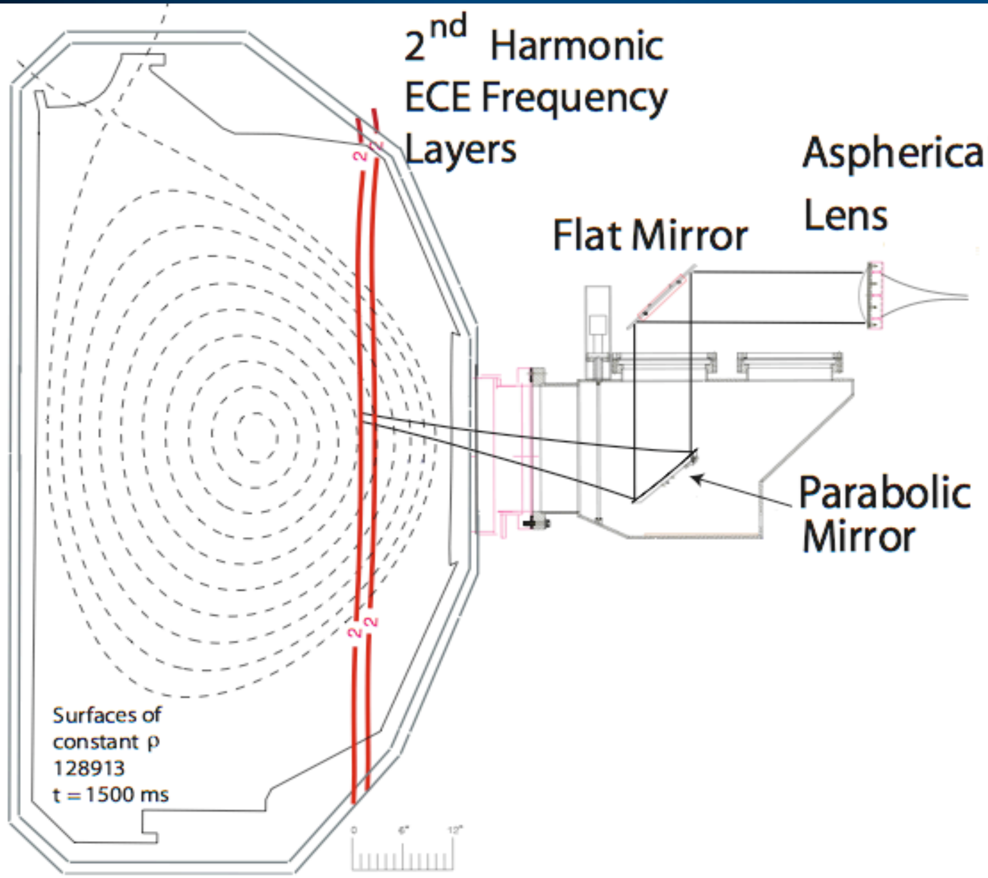
- Time history of $\tilde{T}_e/T_e$ during single discharge reveals changes in amplitude in L-mode, H-mode and Ohmic plasmas

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

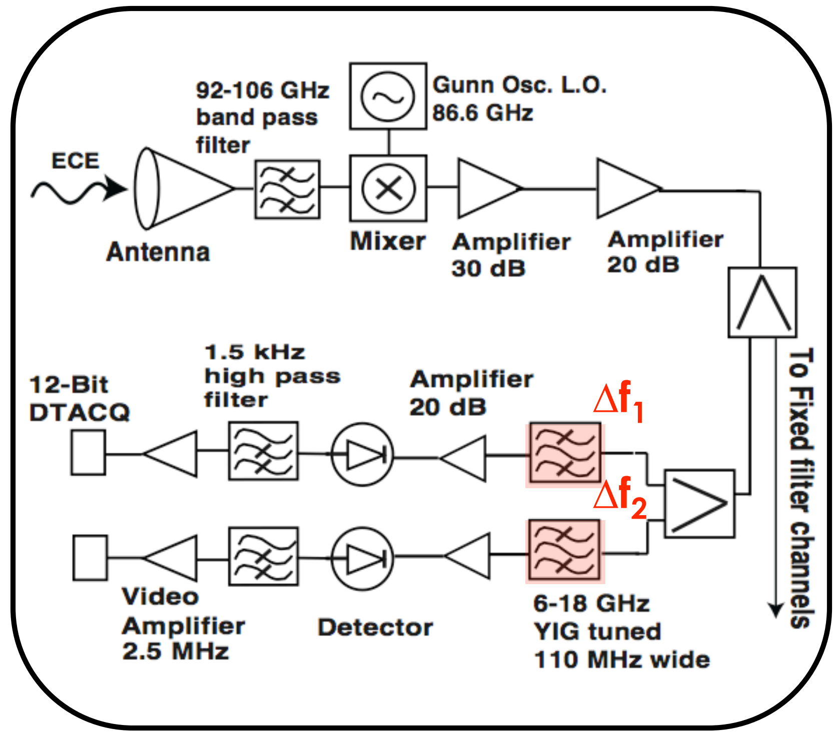
- GYRO predicts $\tilde{T}_e/T_e \sim \tilde{n}_e/n_e$, consistent with observations. GYRO/synthetic diagnostics do not fully reproduce increase in fluctuation level with radius.

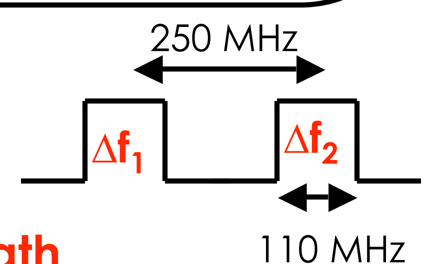
- Electron Cyclotron Heating (ECH) during beam heated L-mode plasmas results in increased $\tilde{T}_e/T_e$, but not $\tilde{n}/n$

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



SSB receiver with two channel filter bank





- Emission in non-overlapping frequency bands
- Separated by less than turbulence correlation length
- Cross-correlate signals to measure RMS amplitude and spectrum

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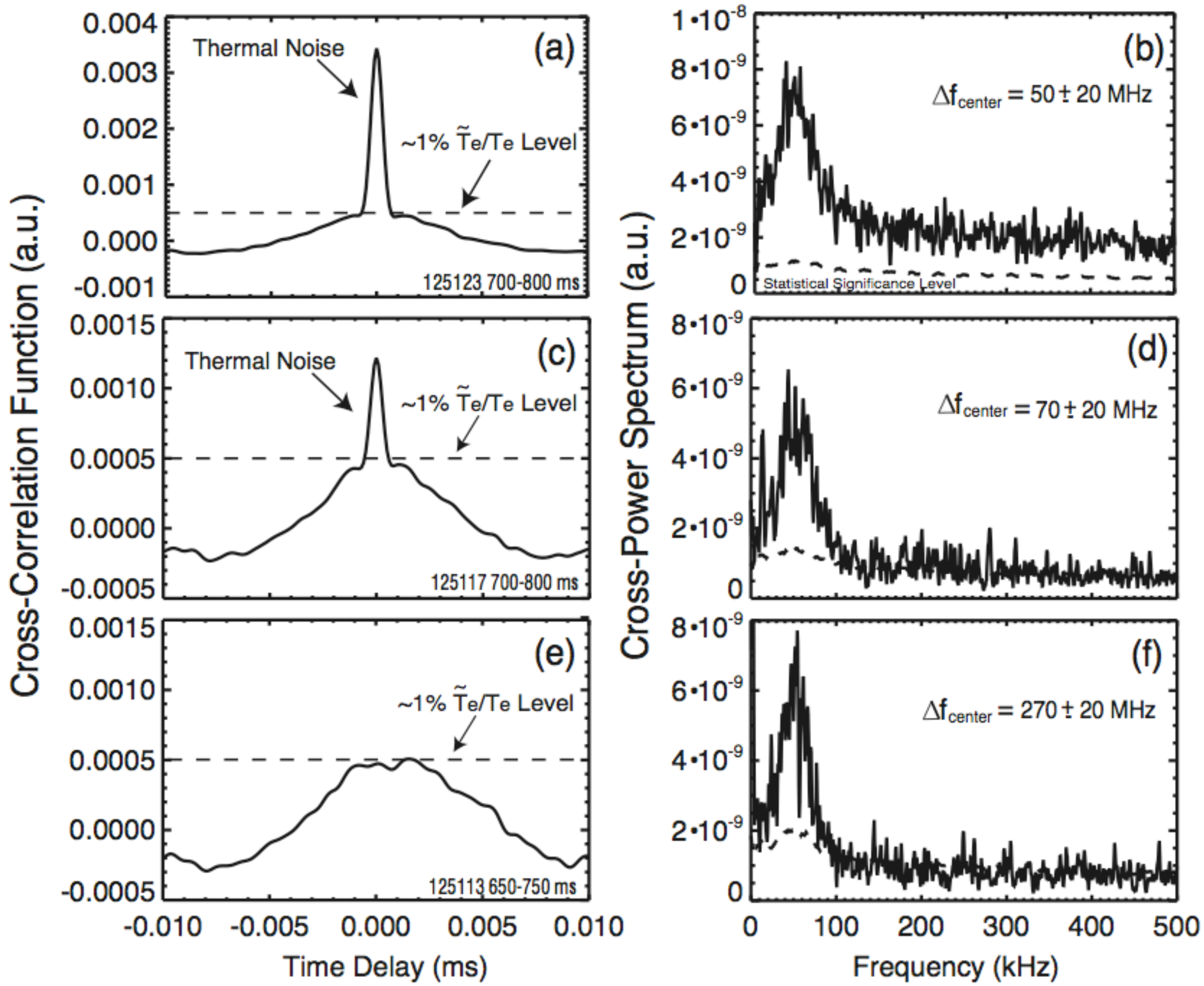
The Thermal Noise is Uncorrelated When Intermediate Frequency Filter Bandwidths Do Not Overlap

- The thermal noise feature is broadband in frequency

- The temperature fluctuation feature can be measured (~ 100 ms average) in cases of moderate filter overlap when $B_{sig} < B_{vid}$

- MHD modes ($B_{sig} << B_{vid}$) often observed in a single radiometer channel



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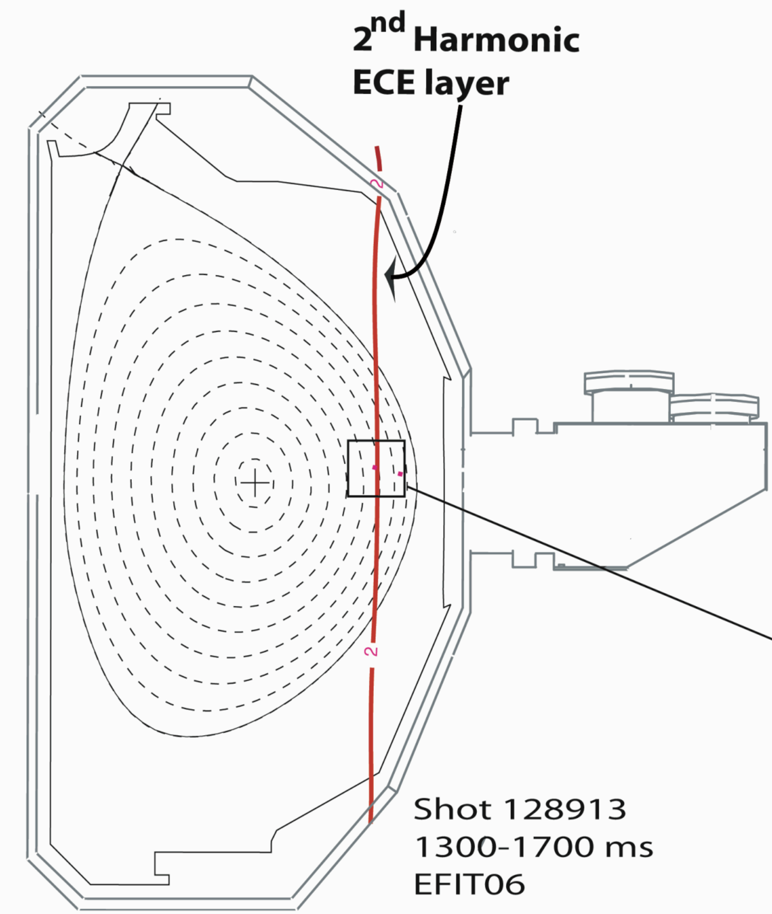
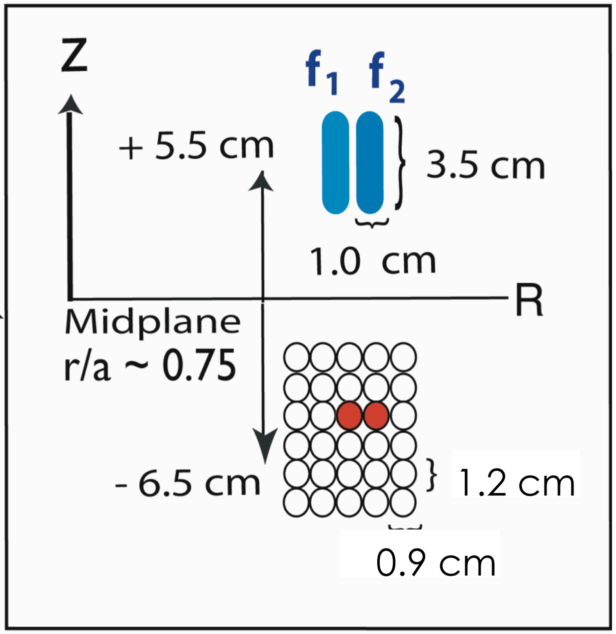
Beam Emission Spectroscopy (BES) Diagnostic Measures Local Density Fluctuations at Same Radius as CECE



- Measurement locations separated toroidally and vertically
- CECE and BES measure turbulence on Ion Temperature Gradient (ITG) and Trapped Electron mode (TEM) scales



CECE $\tilde{T}_e/T_e$

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

$k_r < 4 \ \ cm^{-1}$

BES $\tilde{n}/n$

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

$k_r < 2 \ \ cm^{-1}$

Outline

- Temporal evolution of electron temperature fluctuations
- Comparison between electron temperature and density fluctuations in beam heated L-mode plasmas
- Comparison with nonlinear simulations
- Comparison of electron temperature and density fluctuations in ECH experiment

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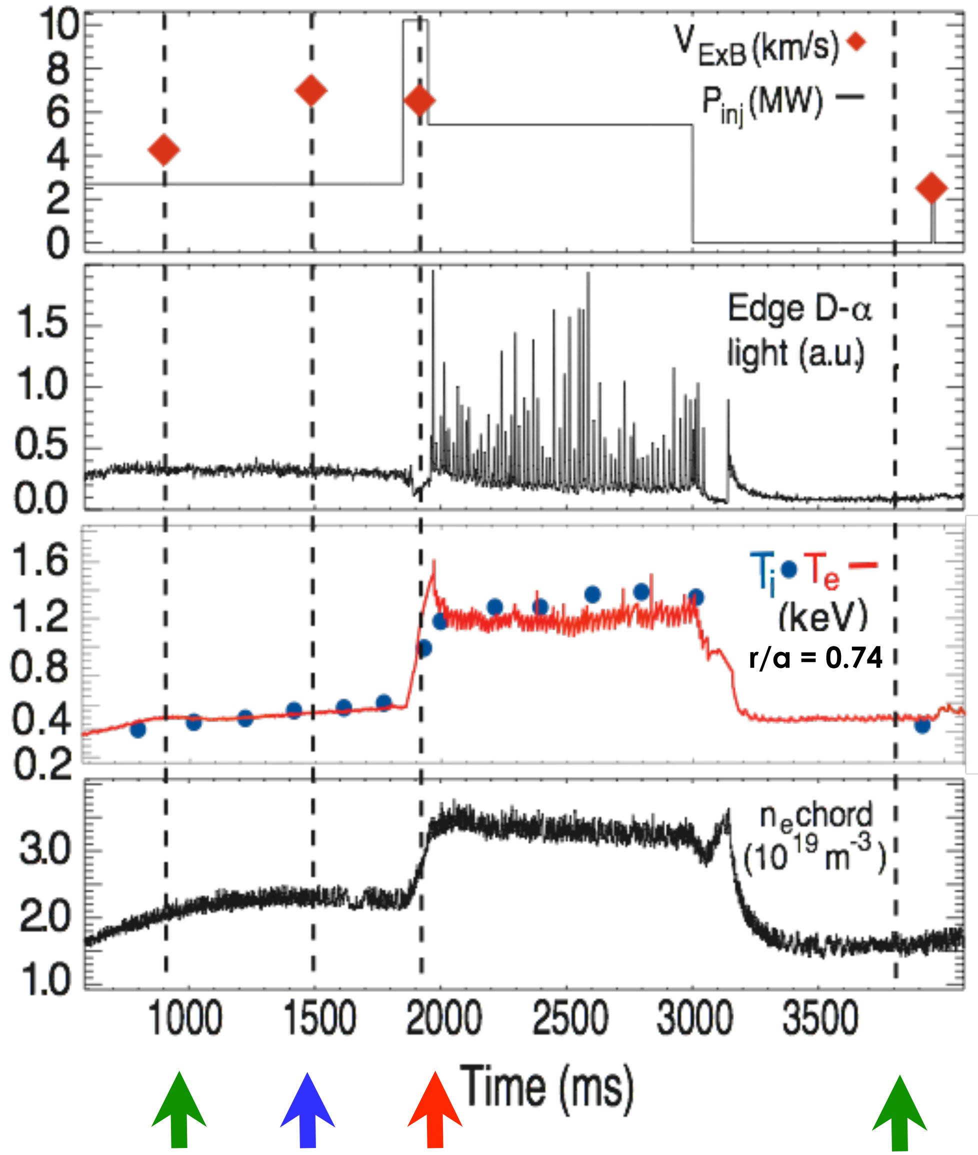
Temperature Fluctuations Are Measured in L-mode, H-mode and Ohmic Plasmas in a Single Discharge

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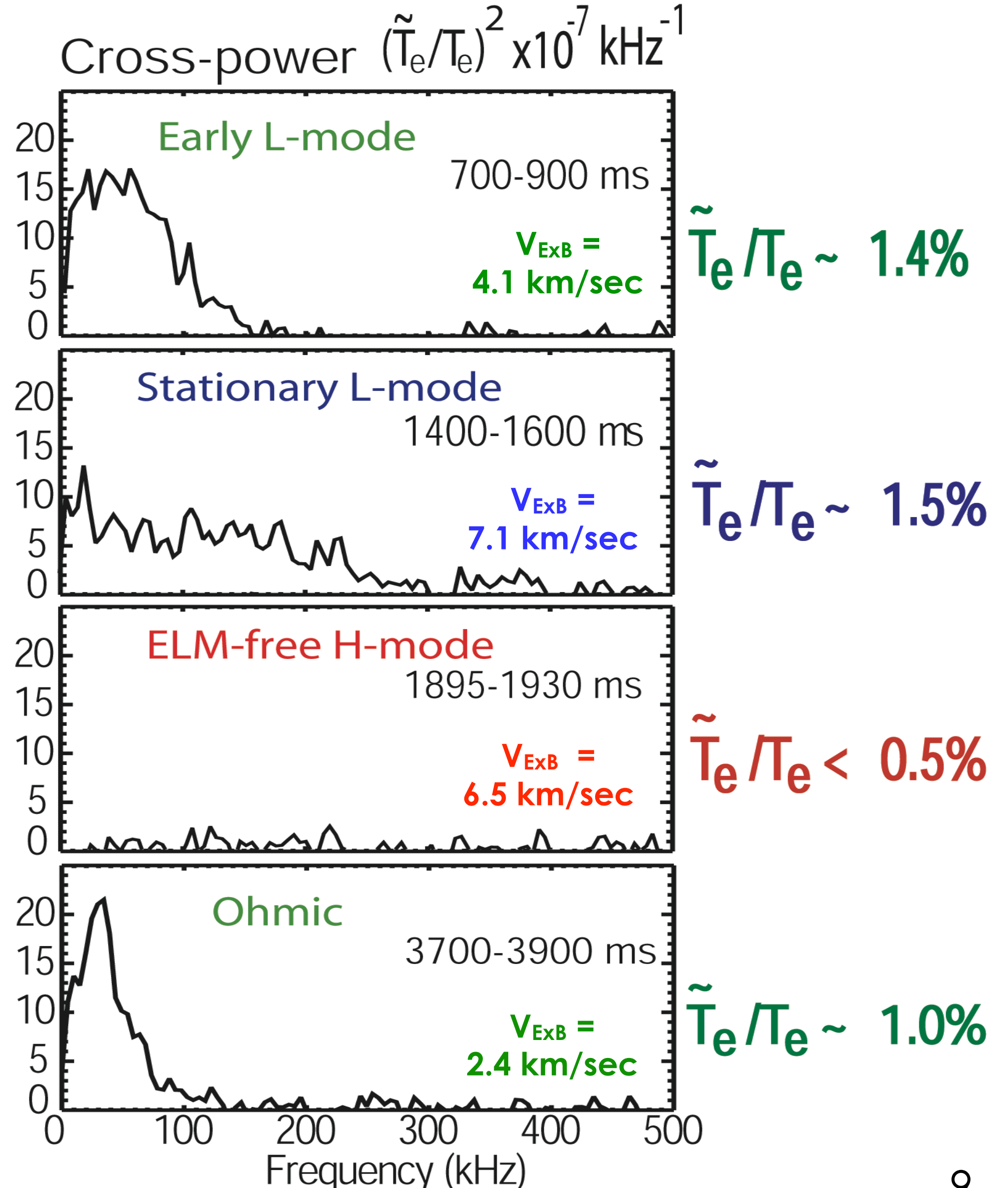
Spectra Evolve in Time, with Large Reduction in $\tilde{T}e/Te$ After L-H Transition

- **Typical cross-power spectra of $\tilde{T}_e/T_e$ at *r/a = 0.75***
  - 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
(Schmitz, PRL 100, 035002,(2008))



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Outline

- Temporal evolution of temperature fluctuations
- **Comparison between temperature and density fluctuations in beam heated L-mode plasmas**
- Comparison with linear and nonlinear simulations
- Comparison of temperature and density fluctuations in ECH experiment

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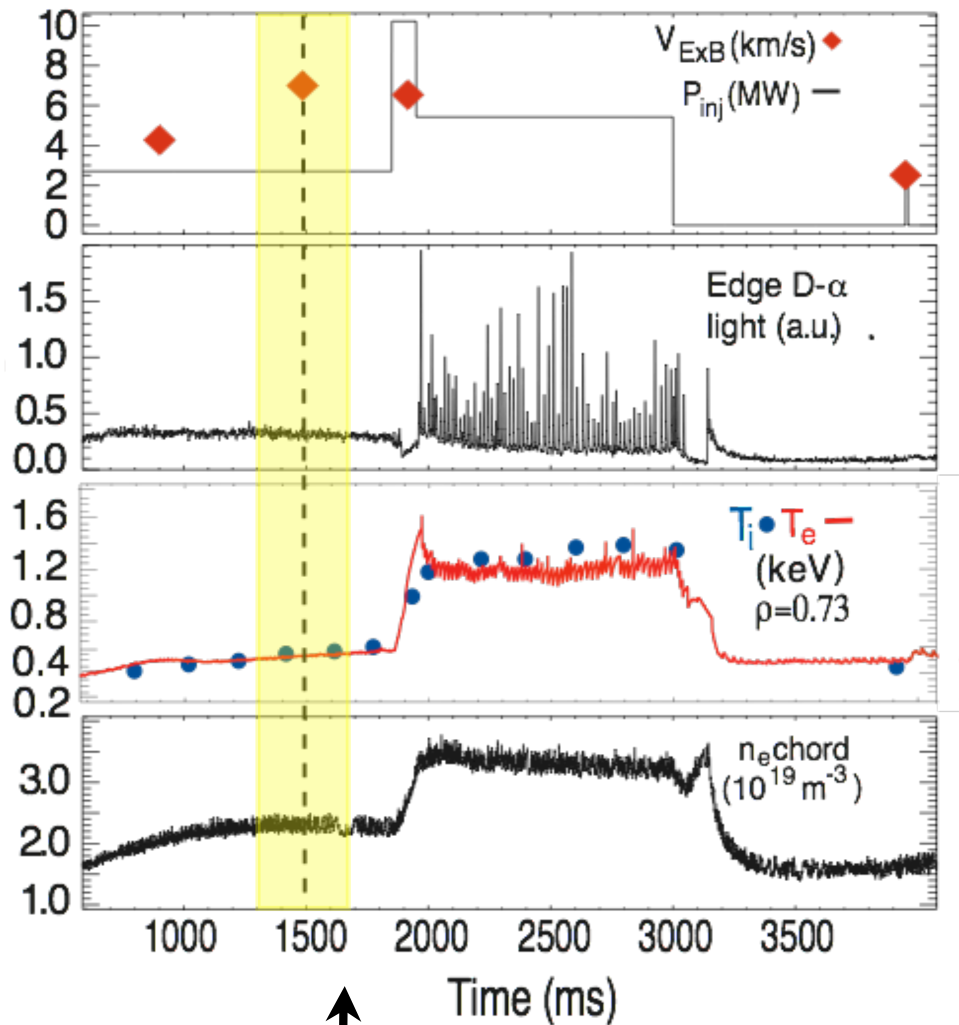
The Profile of Temperature Fluctuations in L-mode Is Compared to the Profile of Density Fluctuations



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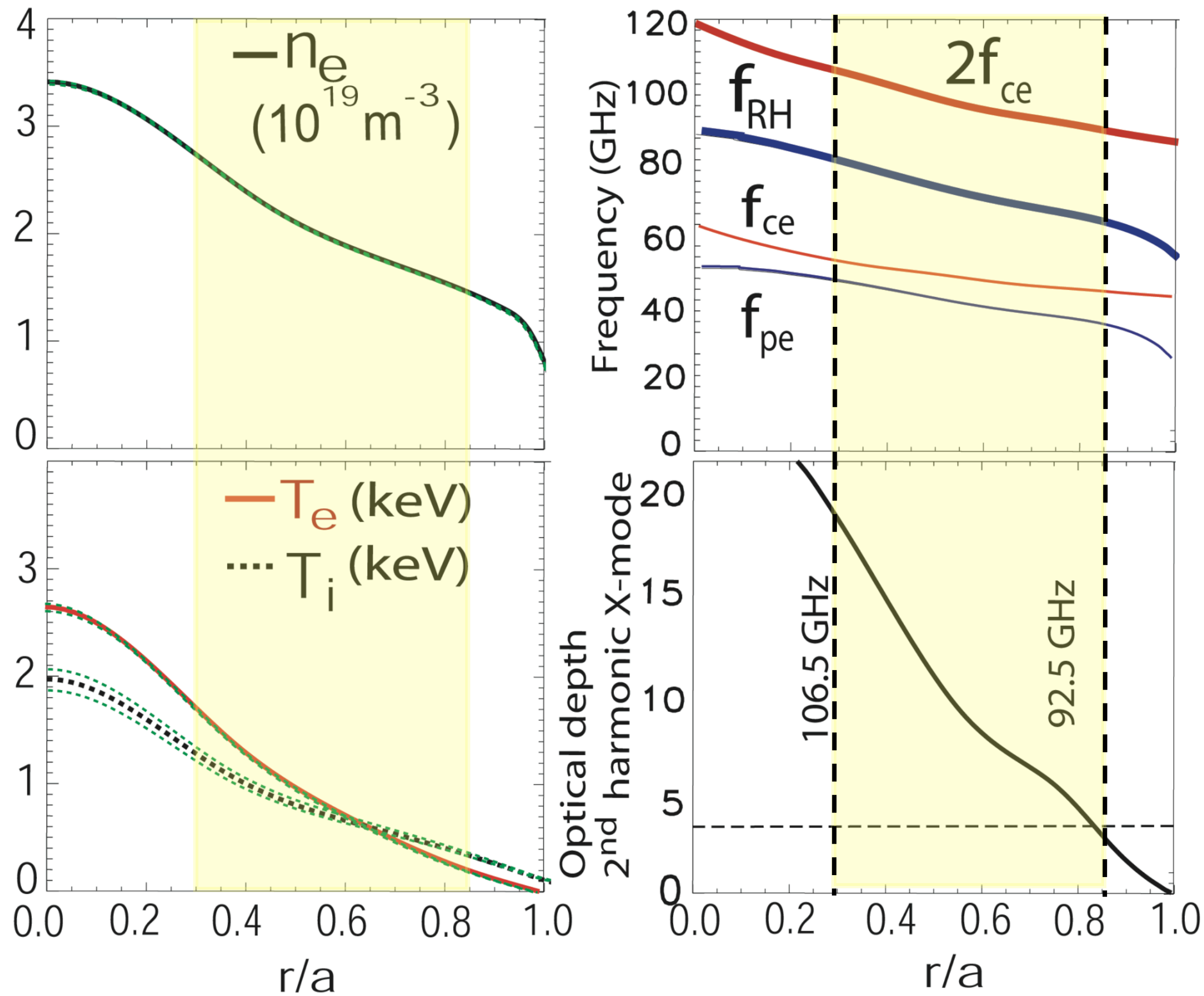
Plasma Profiles, Plasma Frequencies, and Optical Depth in L-mode Plasma of Interest

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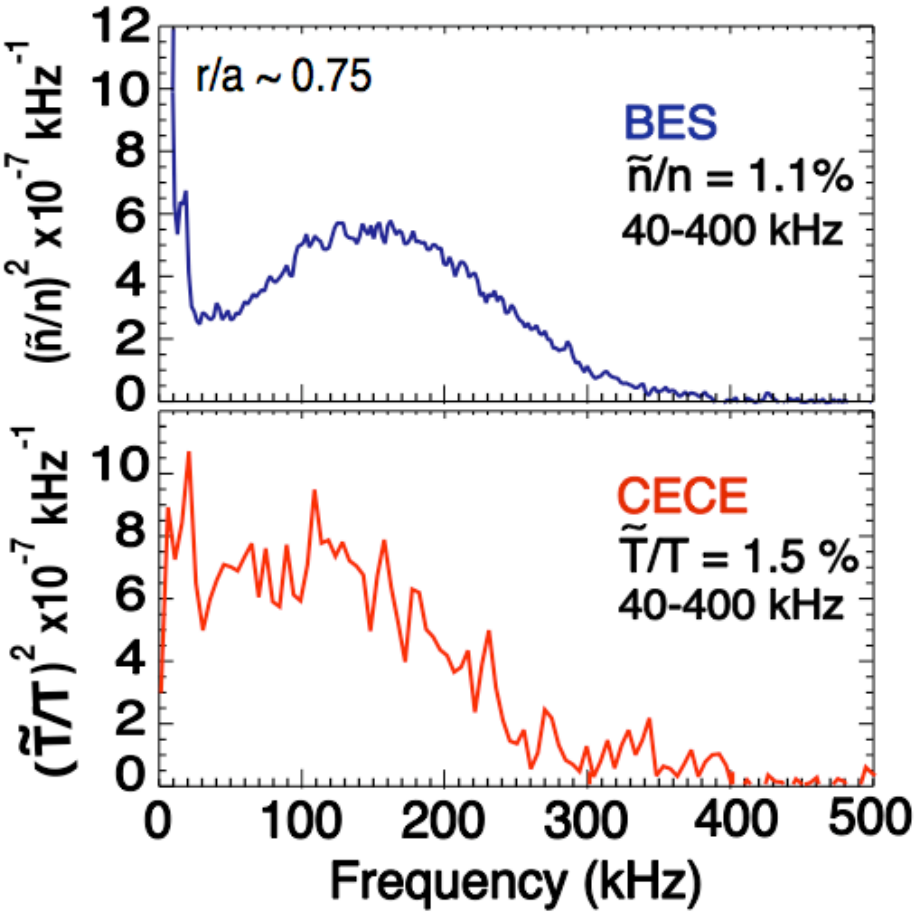
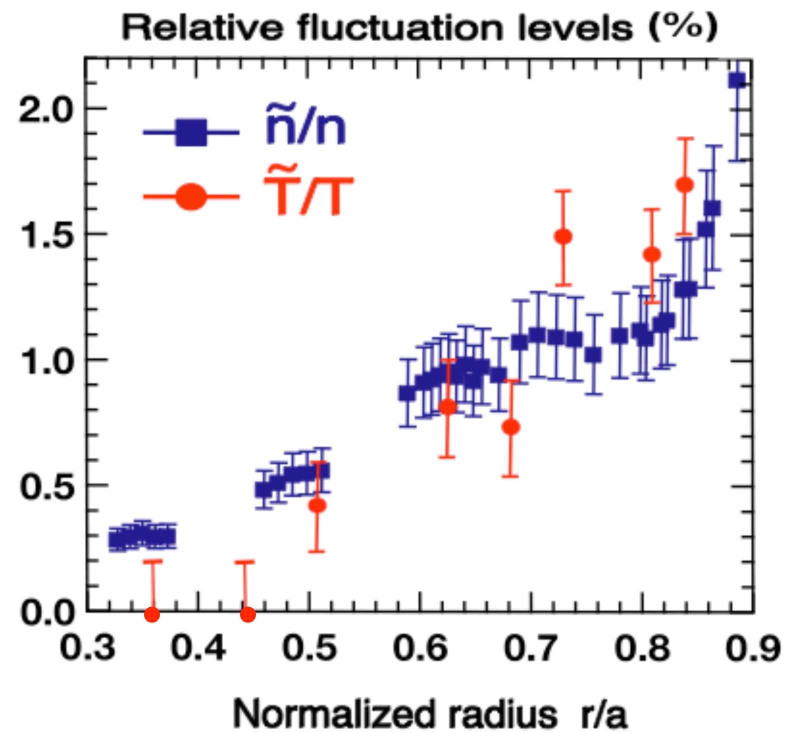
CECE and BES diagnostics scanned between *0.3 < r/a < 0.9*

Temperature and Density Fluctuations Have Similar Spectra and Normalized Fluctuation Amplitude Profiles





- $\tilde{T}_e/T_e$ and ñ/n measured between 0.3< r/a < 0.9

Outline

- Temporal evolution of temperature fluctuations
- Comparison between temperature and density fluctuations in beam heated L-mode plasmas
- Comparison with nonlinear simulations
- Comparison of temperature and density fluctuations in ECH experiment

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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, electromagnetic effects
  - Take experimental profiles (T_e, T_i, n_e, E_r) as input

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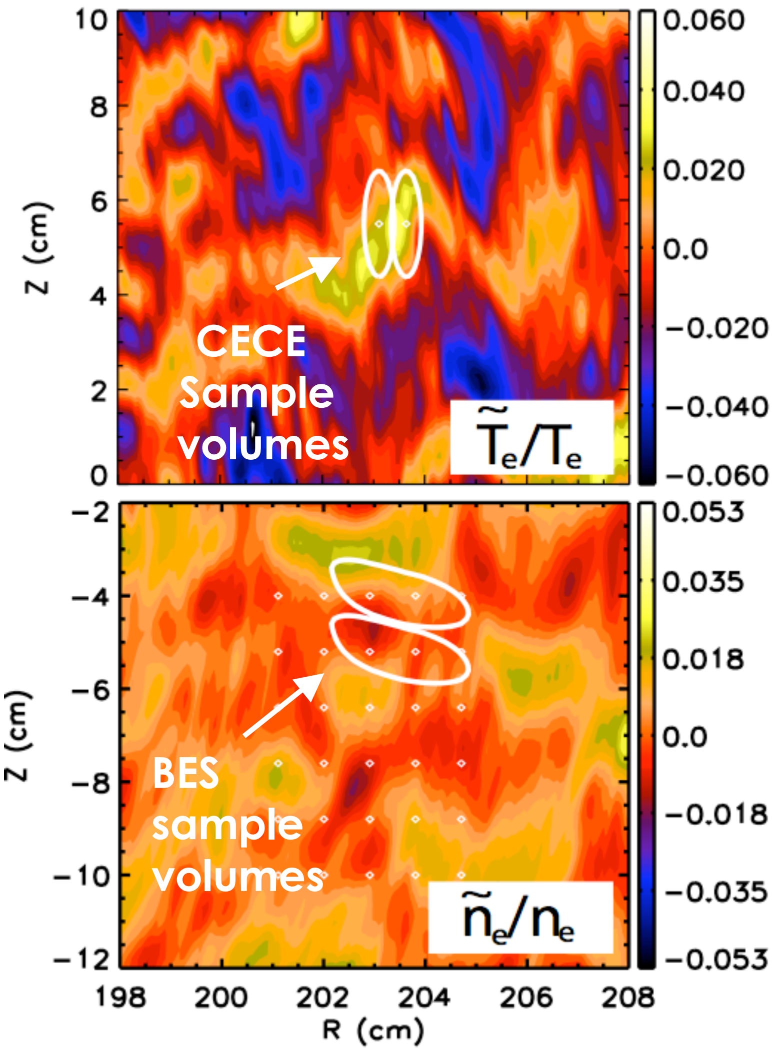
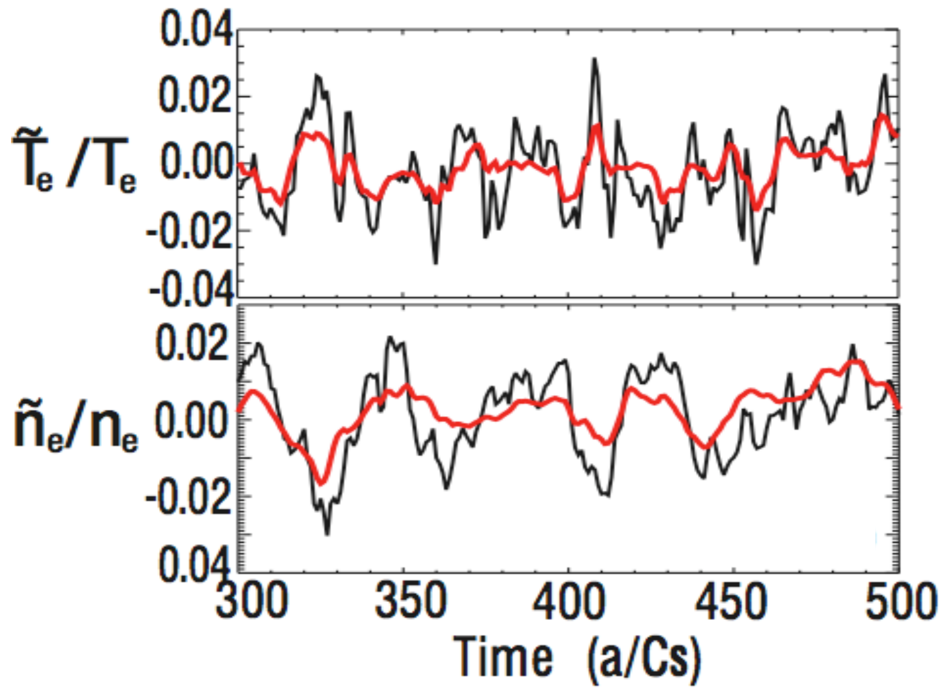
Synthetic Diagnostics That Model the BES and CECE Sample Volumes are Used to Spatially Filter the Raw GYRO Data





CECE sample volume: Antenna pattern and natural linewidth

BES sample volume: Collection optics, neutral beam/sight-line geometry, neutral beam cross-section intensity and the finite atomic transition time of the collisionally excited beam atoms [Shafer RSI 2006)

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Shapes of BES and CECE Sample Volumes Result In Different Filtering of the High Frequencies

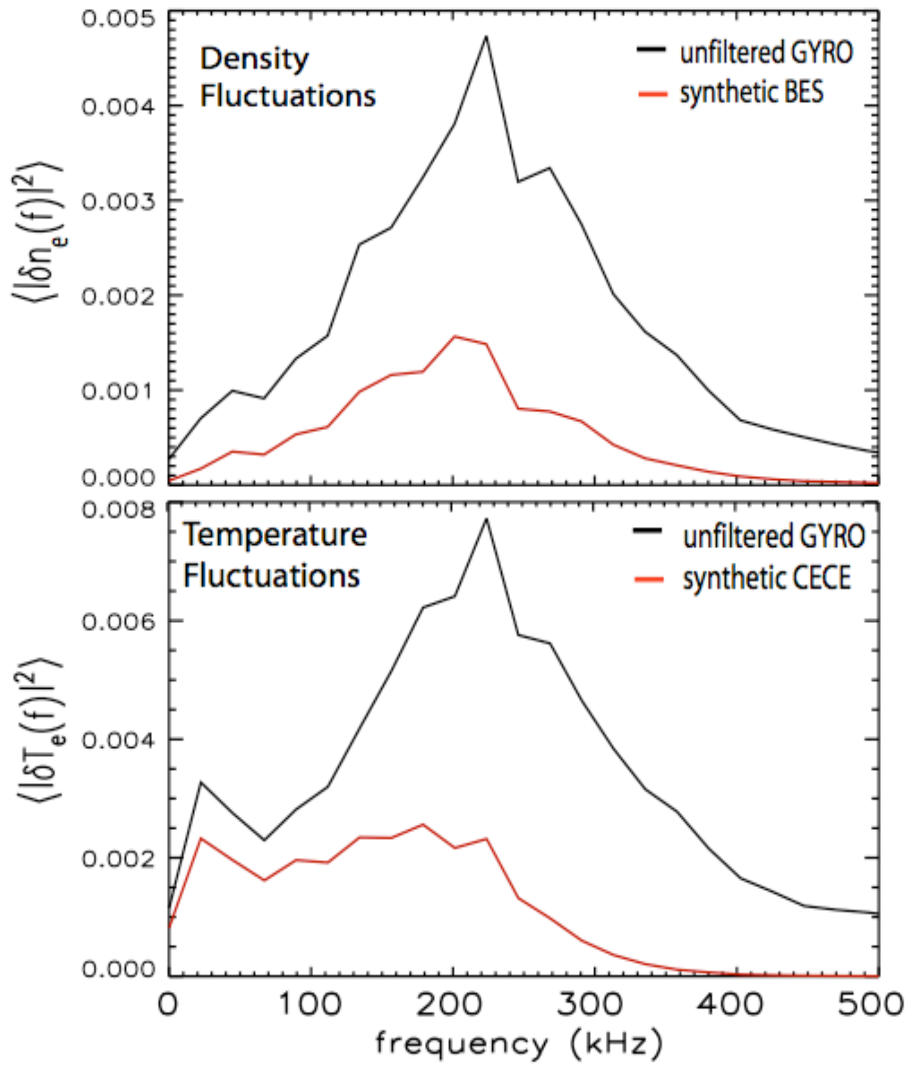
- In measurements, Doppler shift due to ExB plasma rotation dominates Observed spectrum of fluctuations $f \sim k_\theta$

  (McKee, PRL 2000)

- **BES sample volume extended radially ($\Delta r \sim 2$ cm, $\Delta z \sim 1.5$ cm)**
  - Radial extent causes symmetric attenuation of all wavenumbers

- **CECE sample volume extended vertically ($\Delta r \sim 1$ cm, $\Delta z \sim 3.5$ cm)**
  - Poloidal extent causes more attenuation of higher wavenumbers

  (Bravenec, RSI 1995)



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At r/a = 0.75 GYRO Underestimates the Experimental Fluctuation Levels

- Density Fluctuations

GYRO (40-400 kHz)

$\tilde{n}_e/n_e$ = 0.33+-0.007

Experiment (40-400 kHz)

$\tilde{n}/n$ = 1.1+-0.2%

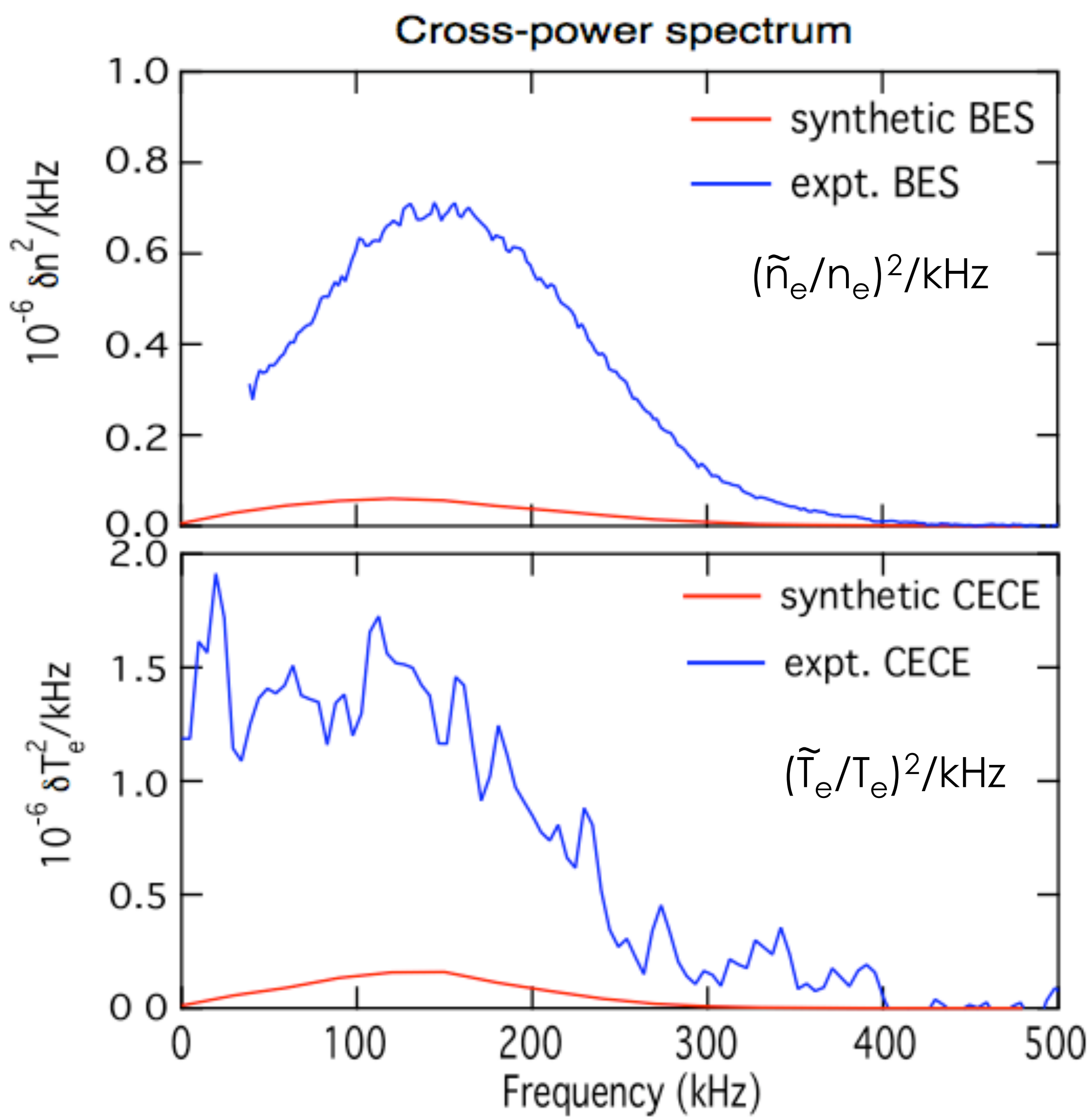
- Temperature Fluctuations

GYRO (40-400 kHz)

$\tilde{T}_e/T_e$ = 0.5+-0.02

Experiment (40-400 kHz)

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



At r/a = 0.5 GYRO Shows Reasonable Agreement With Experimental Fluctuation Levels

- Density Fluctuations

GYRO (40-400 kHz)

$\tilde{n}_e/n_e$ = 0.56+0.008 %

Experiment (40-400 kHz)

$\tilde{n}/n$ = 0.55+-0.12%

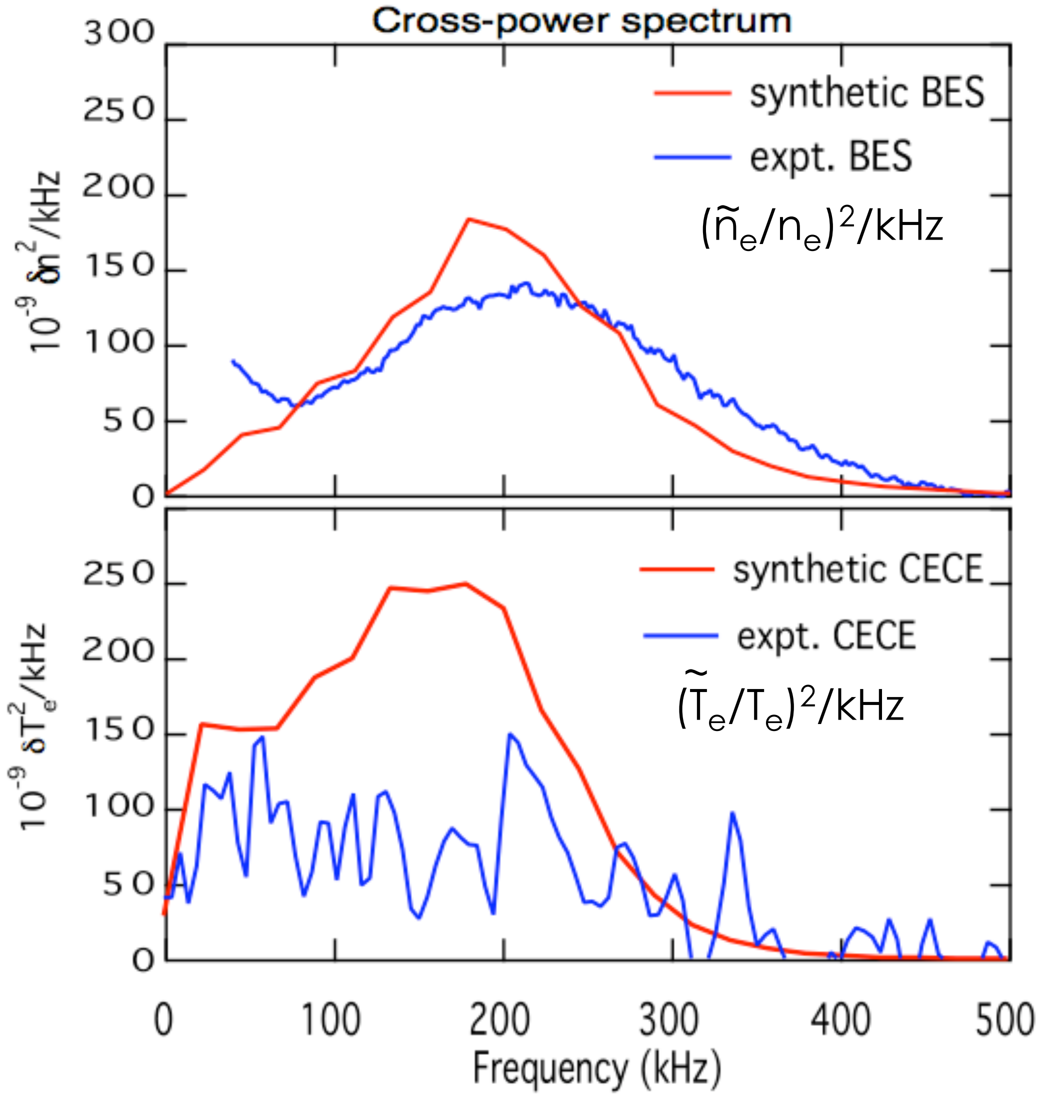
- Temperature Fluctuations

GYRO (40-400 kHz)

$\tilde{T}_e/T_e$ = 0.66+-0.2 %

Experiment (40-400 kHz)

$\tilde{T}_e/T_e$ = 0.4+-0.2%



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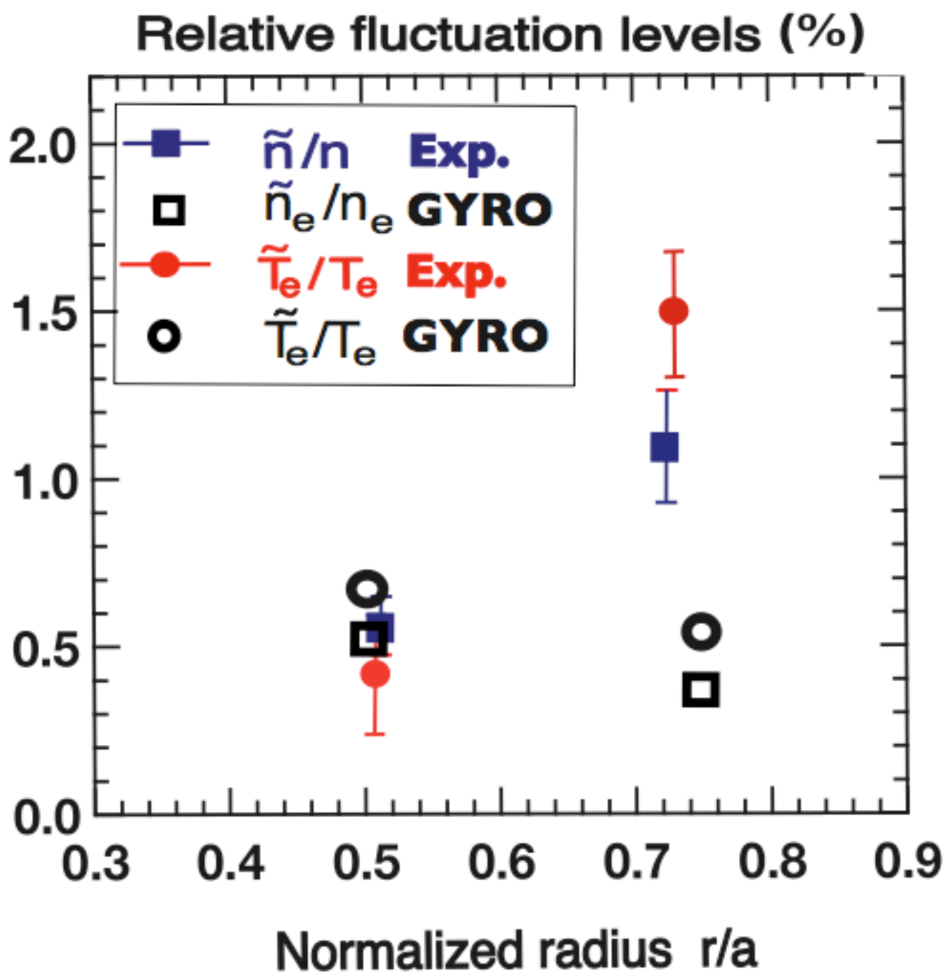
GYRO Predicts $\tilde{T}_e/T_e$ and $\tilde{n}_e/n_e$ are Similar in Amplitude but Radial Profile Trend is not Reproduced



- $\tilde{T}_e/T_e \sim \tilde{n}_e/n_e$, consistent with experiment
- At r/a = 0.5, reasonable 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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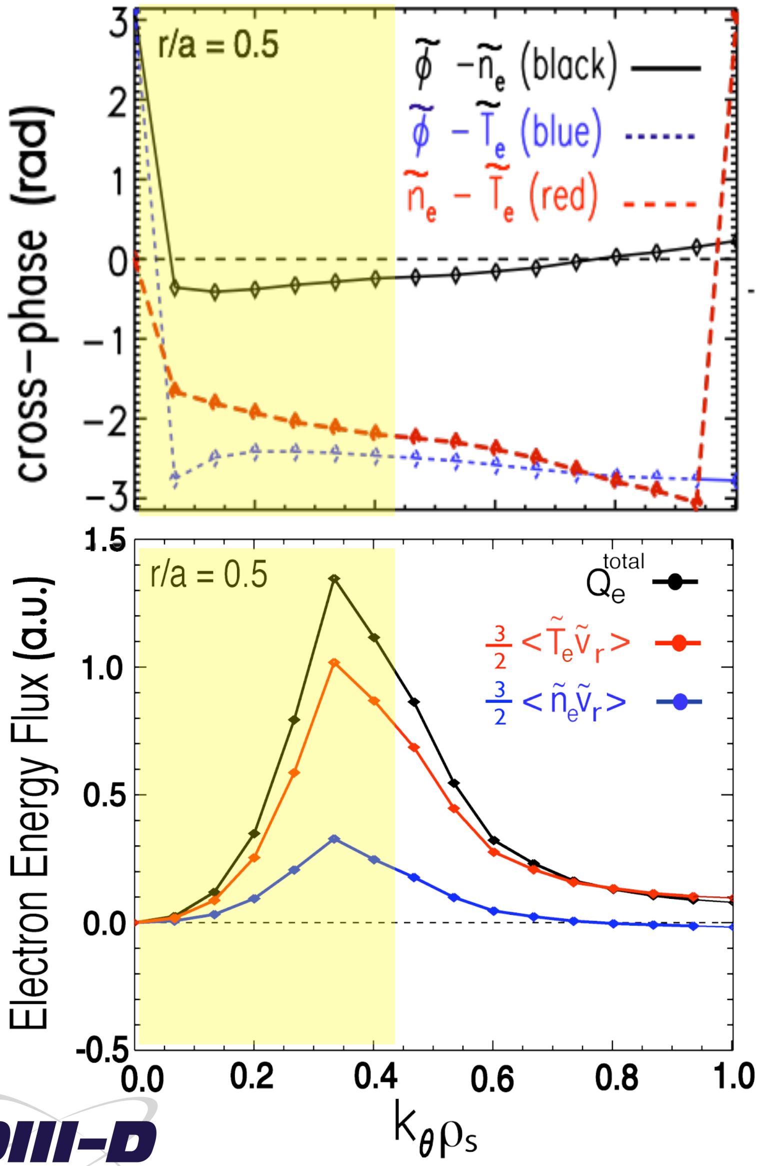
GYRO Predicts Temperature Fluctuation Contribution to Energy Flux at r/a = 0.5



- **GYRO flux-tube simulation at r/a = 0.5 has good quantitative 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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Outline

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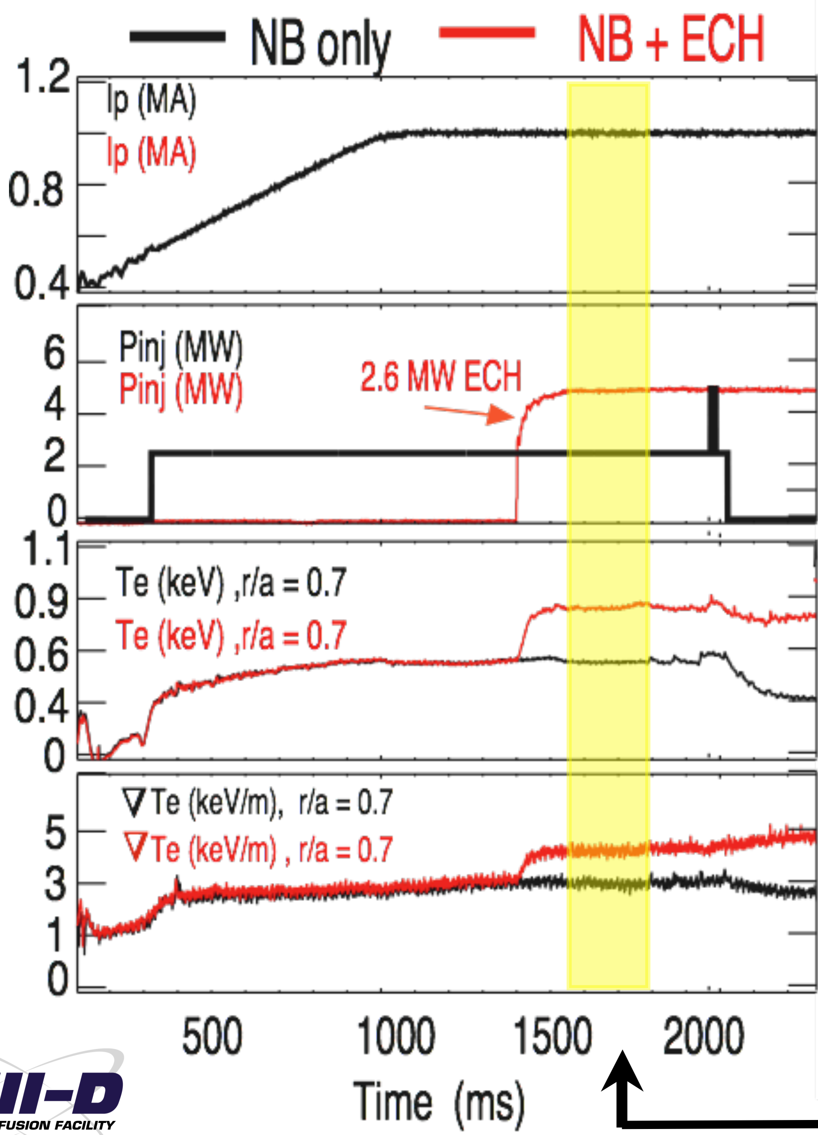
Experiment Using Local ECH to Change Local T_e Gradient and Turbulence Drives



- 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
  - Density is held constant
  - Heat fluxes and heat diffusivities increase
  - TGLF indicates increase in TEM growth rate

Times used in analysis 1500-1700 ms

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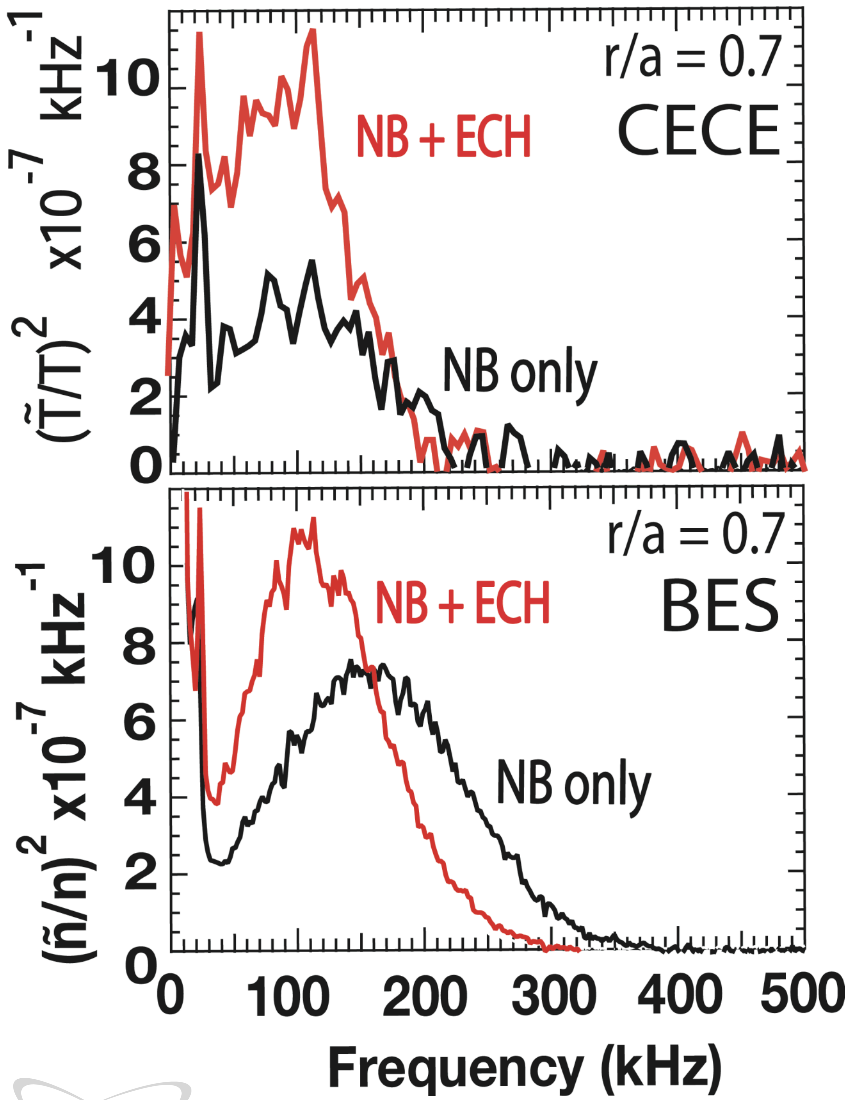
Increases in Heat Flux and TEM Growth Rate Correlate With Increase in $\tilde{T}_e/T_e$, but $\tilde{n}/n$ Does Not Change



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

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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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Future Work

- GYRO predicts phase between $\tilde{T}_e$ and $\tilde{n}_e$, measure phase between $\tilde{T}_e$ and $\tilde{n}_e$ using CECE and reflectometry (Haese 1997)
- Dimensionless parameter scans and comparison of $\tilde{T}_e/T_e$ and $\tilde{n}/n$
- Simulations of results where $\tilde{T}_e/T_e$ and $\tilde{n}/n$ respond differently to ECH
- Flux-matched profiles, TGLF transport model (J. E. Kinsey POP May, 2008)

Simultaneous measurements of multiple fluctuating fields improve understanding of turbulence and transport, provide the opportunity for challenging comparisons with nonlinear gyrokinetic simulations

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