Measurement of Electron Temperature Fluctuations on DIII-D

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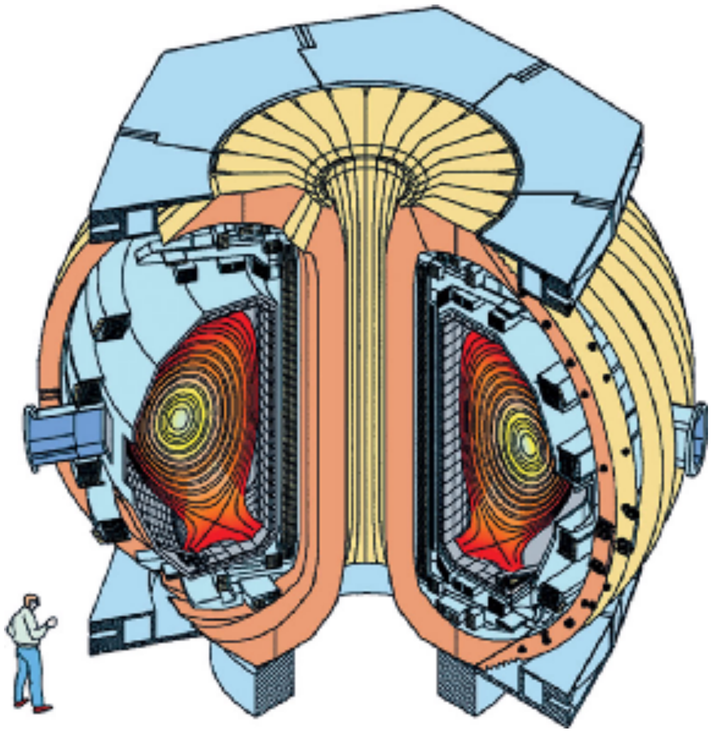
PSFC

Turbulence plays a central role in cross-field transport of energy, particles and momentum in magnetically-confined plasmas

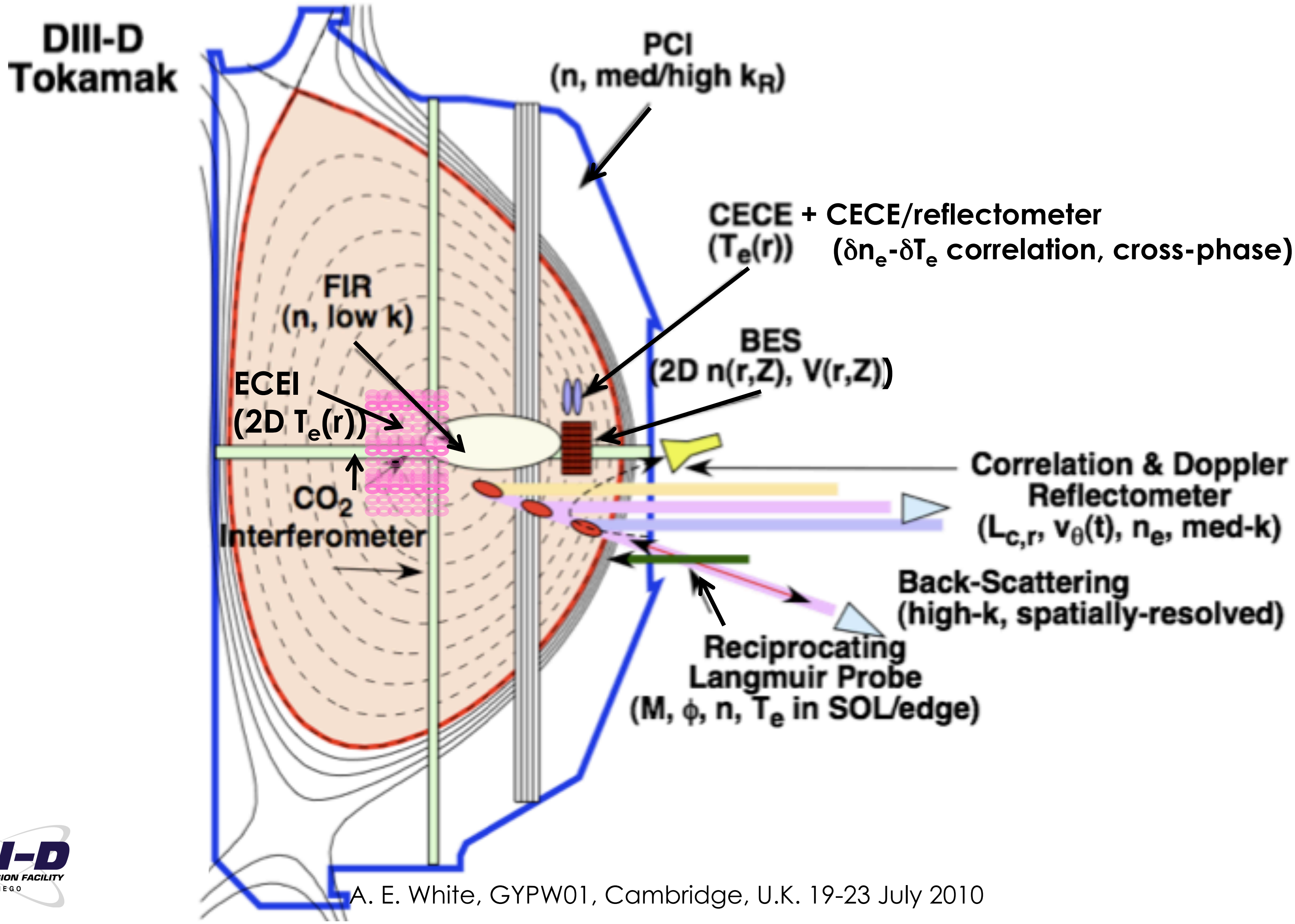
DIII-D Tokamak

R = 1.66 m
a = 0.67 m
B_T = 2.1 T
I_P = 1.2 MA
n ~ 4×10^{19} m^{-3}

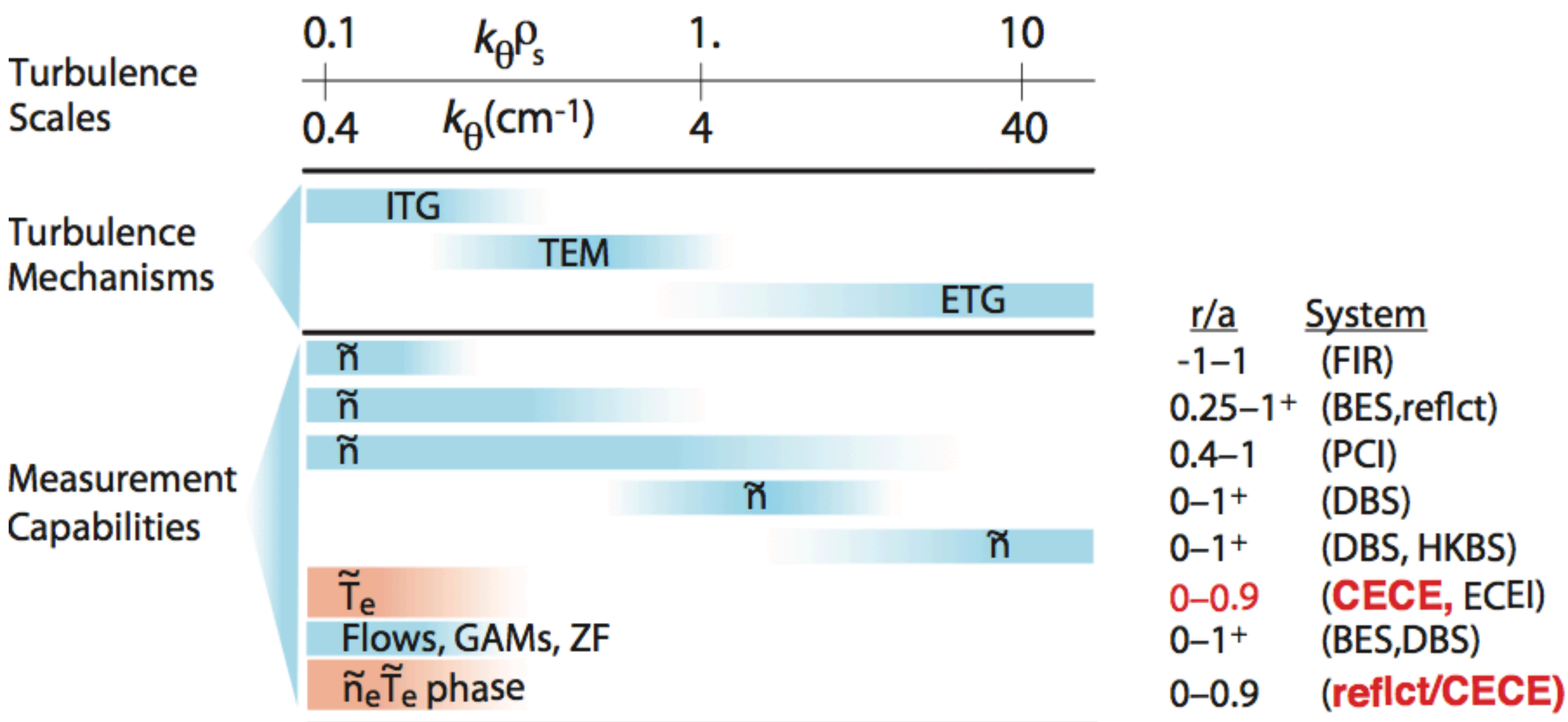


c_s/a	(kHz)	200-400
γ_{ExB}	(c_s/a)	0.03-0.08
ν_{ei}	(c_s/a)	0.1 – 0.5
β_e		0.001
ρ^*		0.001-0.003

DIII-D Employs Suite of Fluctuation Diagnostics to Measure Wide Range of Turbulence Scales and Characteristics



Fluctuation diagnostics at DIII-D cover a wide range of spatial scales, relevant for ITG, TEM and ETG turbulence



Cannot measure turbulent flux

$$Q_e^{fl} = 3/2 n k_B T_e / B_t (< (\tilde{T}_e/T)\,\tilde{E}_\theta > + < (\tilde{n}/n)\,\tilde{E}_\theta >)$$

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Summary of Results

•In ITG-dominant L-mode plasmas, long wavelength ($k_\theta\rho_s < 0.5$) $\tilde{T}_e/T_e$ are similar to amplitude to long wavelength $\tilde{n}/n$ (0.5-2.0%, increasing with radius)

•After H-mode transition, core electron temperature fluctuations are significantly reduced; increased ExB shearing of ITG turbulence

•In experiments where TEM drive/thermal transport increased using ECH to modify plasma profiles, $\tilde{T}_e/T_e$ and $\tilde{n}/n$ respond differently

- •$\tilde{T}_e/T_e$ increases (50-60%), $\tilde{n}/n$ little to no change (< 5-10%)

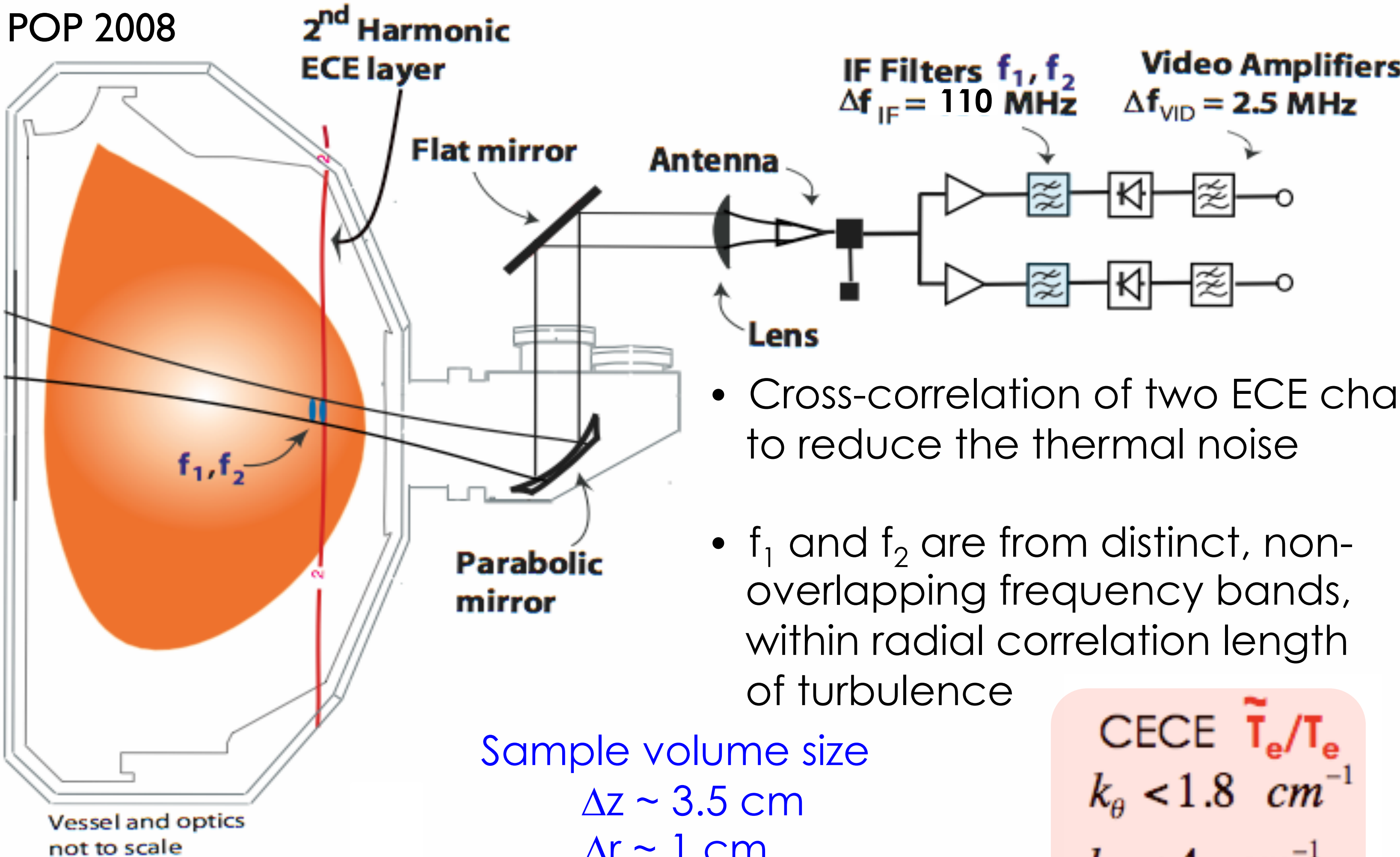
•Nonlinear GYRO simulations predict increases in transport as TEM drive increases associated with

- **•Large change in $\tilde{T}_e/T_e$, smaller changes in $\tilde{n}/n$**
- **•Change in cross-phase angle between $\tilde{n}$-$\tilde{\phi}$**

•The change $\tilde{n}$-$\tilde{T}$ phase angle is measured and is in good agreement with predictions from GYRO; ongoing modeling effort required

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

Sattler PRL 1994,
Cima POP 1995,
White POP 2008



- Cross-correlation of two ECE channels to reduce the thermal noise
- f_1 and f_2 are from distinct, non-overlapping frequency bands, within radial correlation length of turbulence

Sample volume size
$\Delta z \sim 3.5$ cm
$\Delta r \sim 1$ cm

CECE $\tilde{T}_e/T_e$
$k_\theta < 1.8 \ cm^{-1}$
$k_r < 4 \ cm^{-1}$

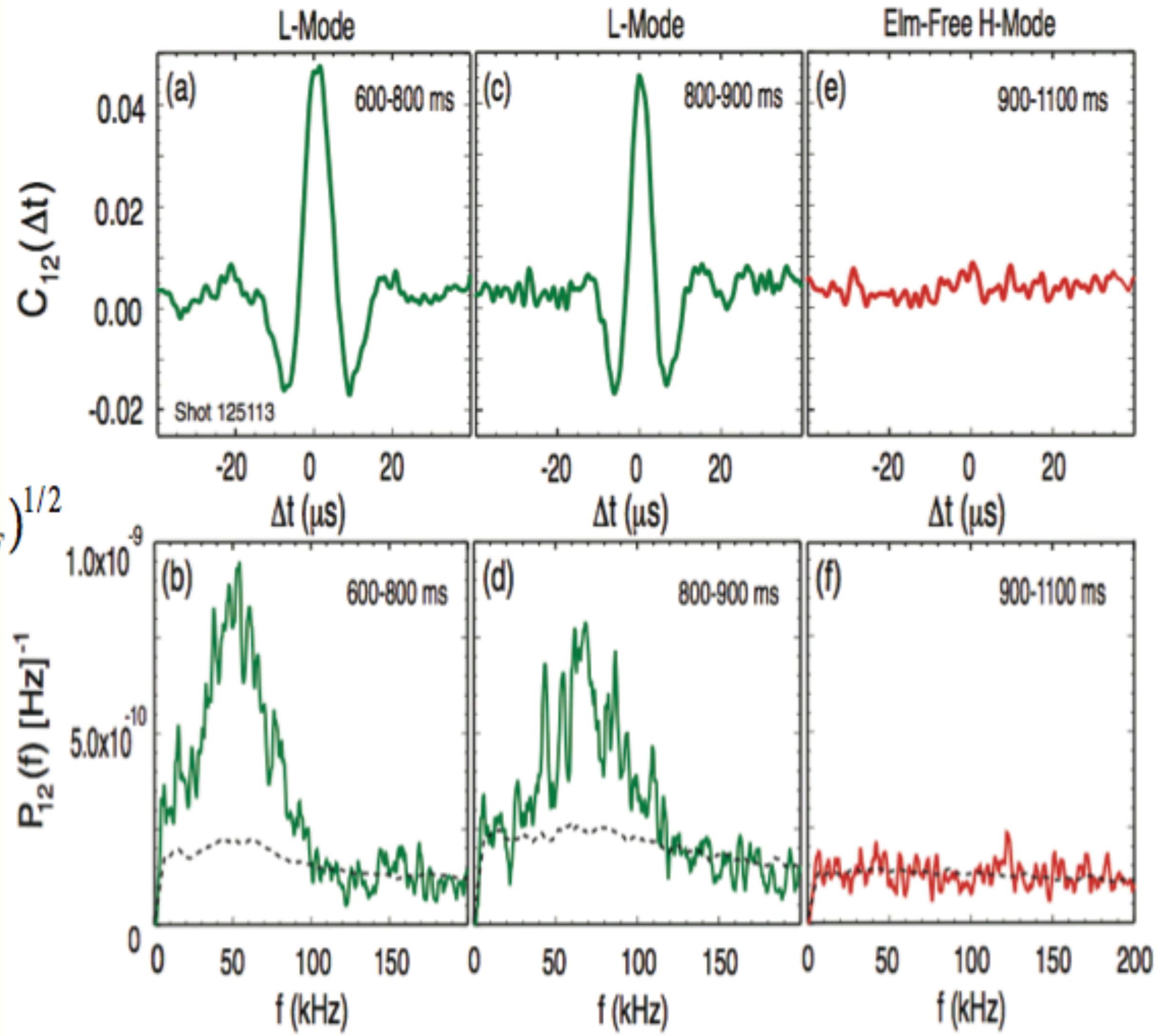
CECE measures power spectrum and fluctuation levels $\tilde{T}_e/T_e$ with typical time averaging δt = 50-400 ms

$\tilde{T}_e/T_e$ **is directly determined from the correlation coefficient:**

$$\tilde{T}_e/T_e = [C_{12}(0)]^{1/2} \times (\Delta f_{vid}/\Delta f_{IF})^{1/2}$$

Spectral shape is dominated by ExB speed:

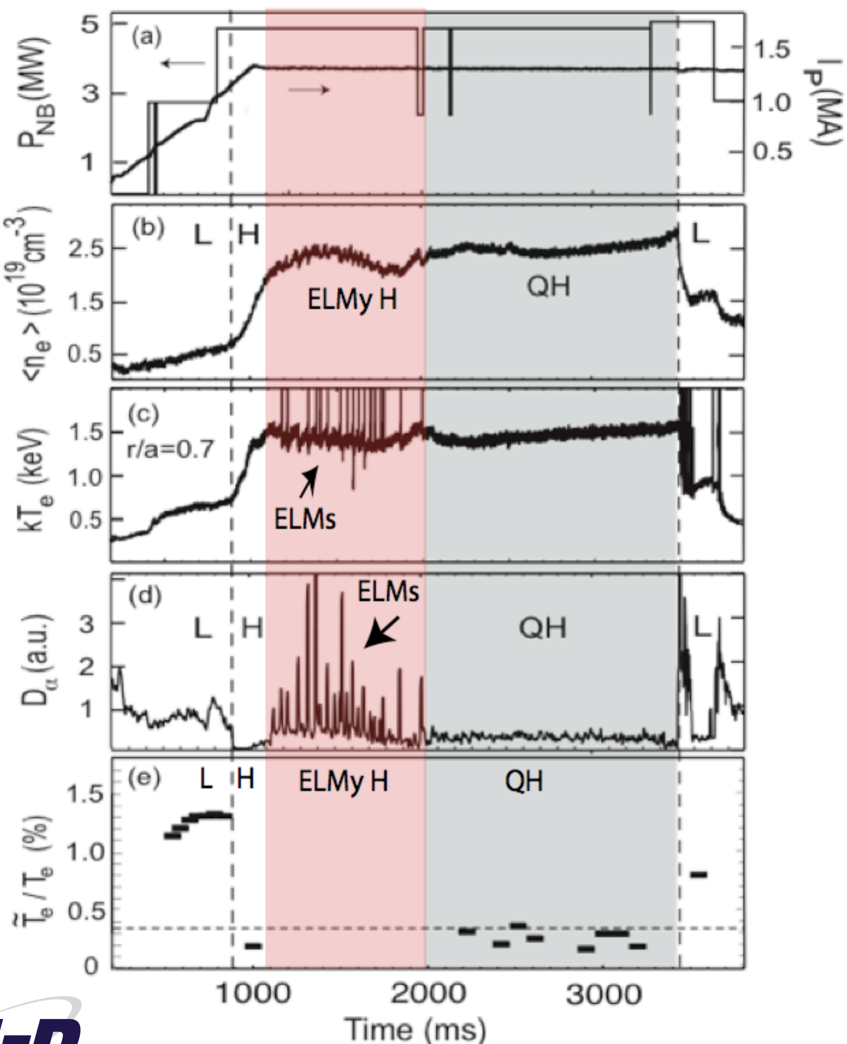
$$f_{max} \sim v_{E\times B} < k_\theta > /2\pi$$

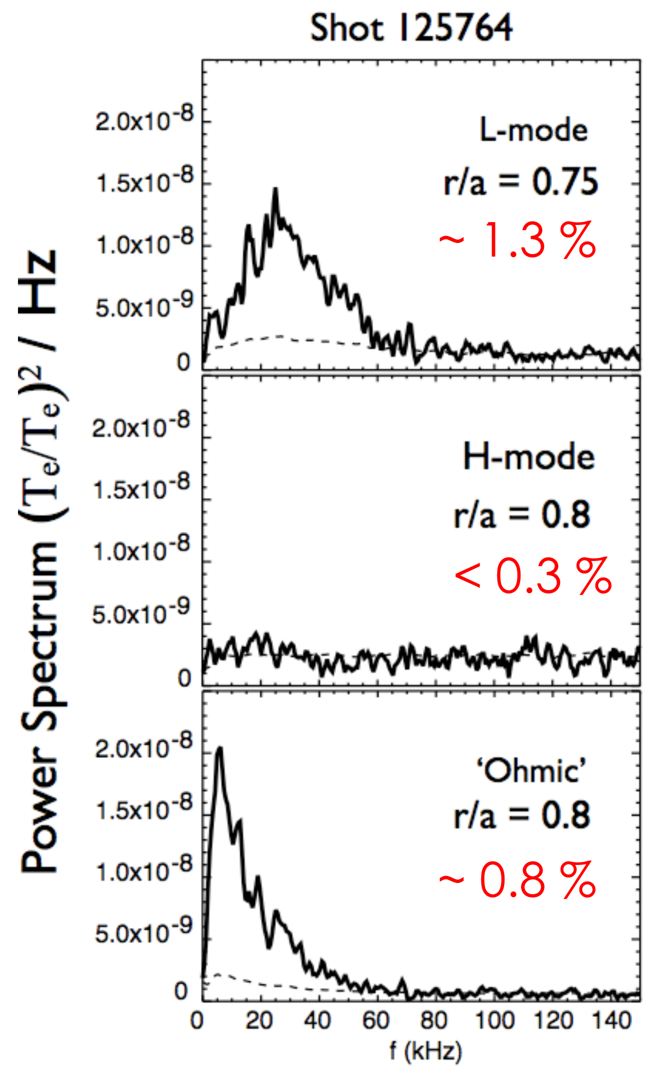


Reduction of electron temperature fluctuations in H-mode

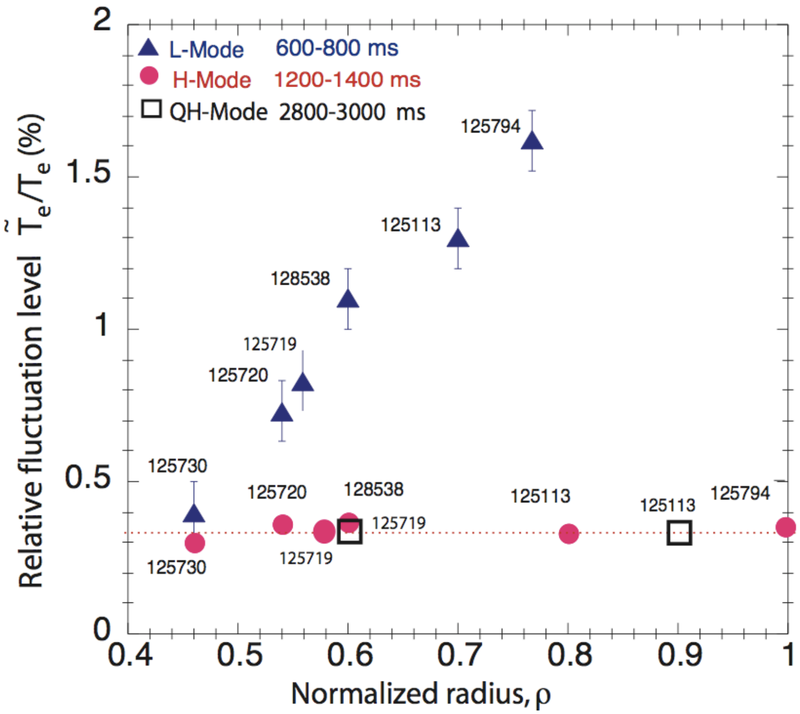
Quiescent H-mode Experiments Show Reduction in Core Electron Temperature Fluctuations

- QH-mode experiments: Bt~ -2 T, Ip ~1.2 MA, counter beams





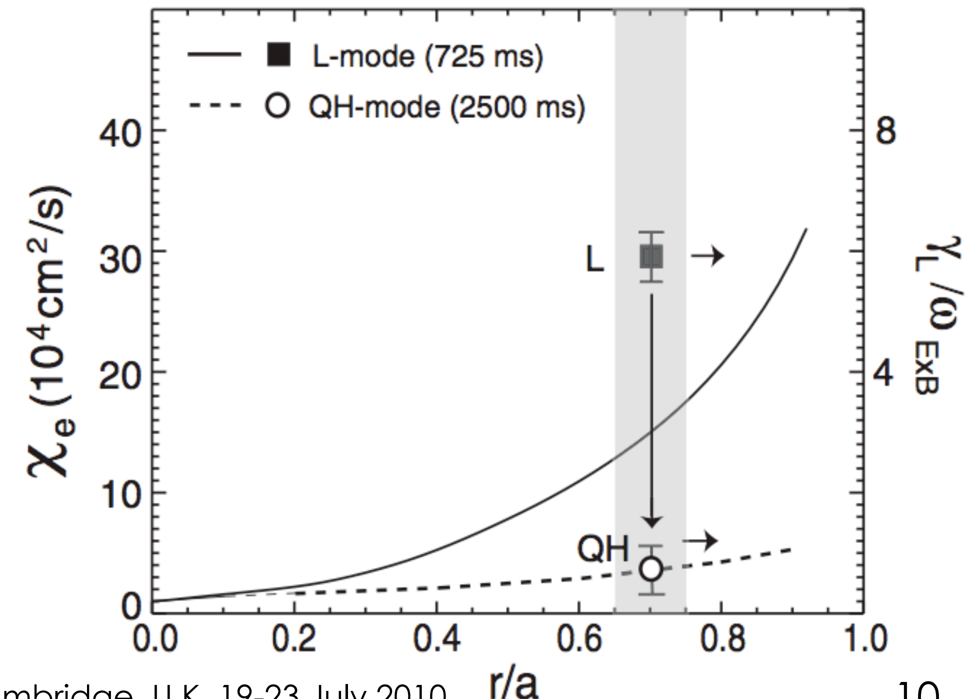
Core Turbulence Reduction in Quiescent H-mode Experiments Suggests Contribution to Heat Flux in L-mode



Diagnostic scan over many similar QH-mode plasmas

Core reduction in H-mode observed between 0.4< ρ < 1.0

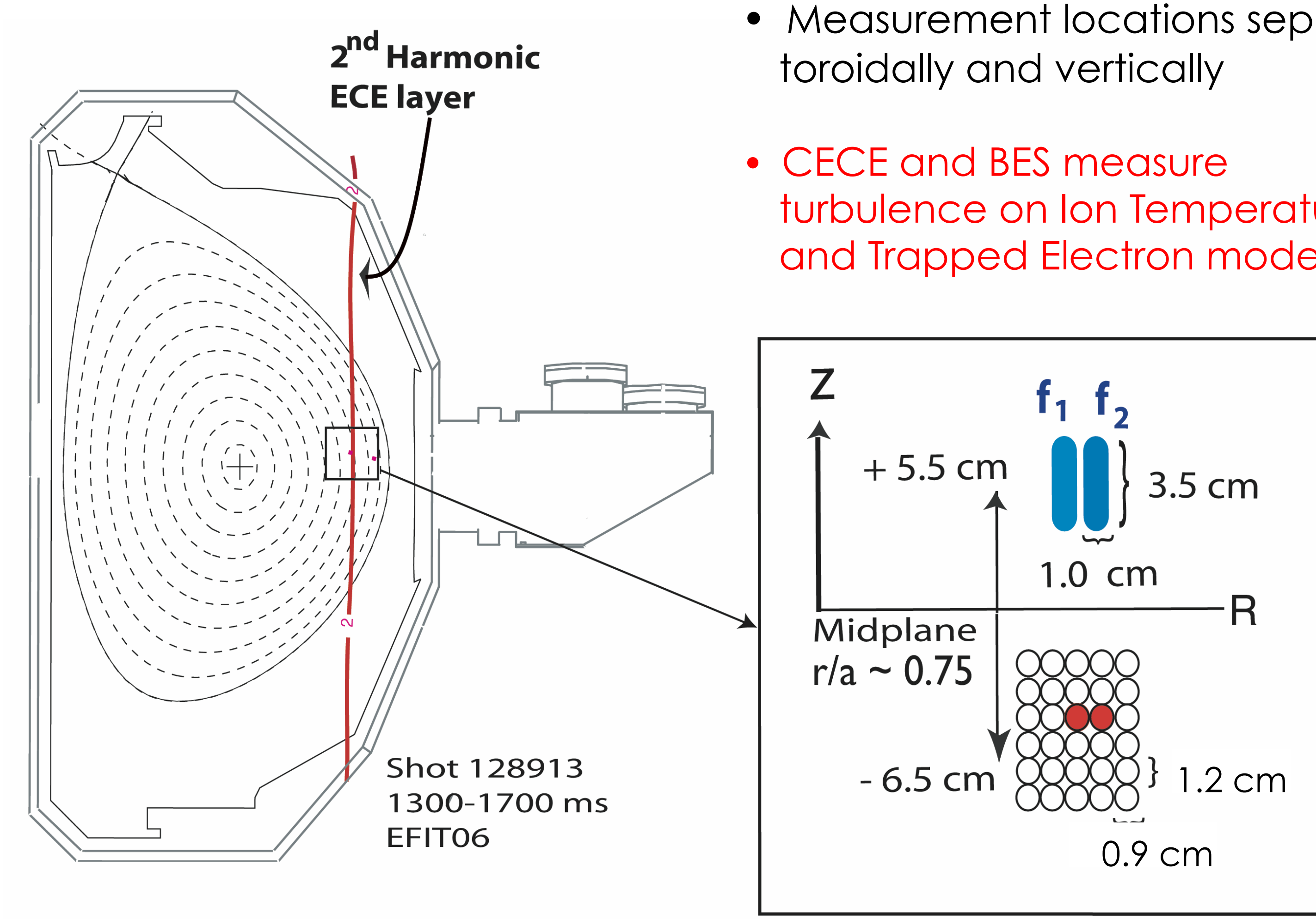
Electron temperature fluctuations in L-mode attributed to ITG modes that are sheared apart (EXB flows) in core of H-mode
Schmitz, PRL, 2008



Simultaneously measured electron temperature fluctuations (CECE) and density fluctuations (BES)

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 $\tilde{T}_e/T_e$

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

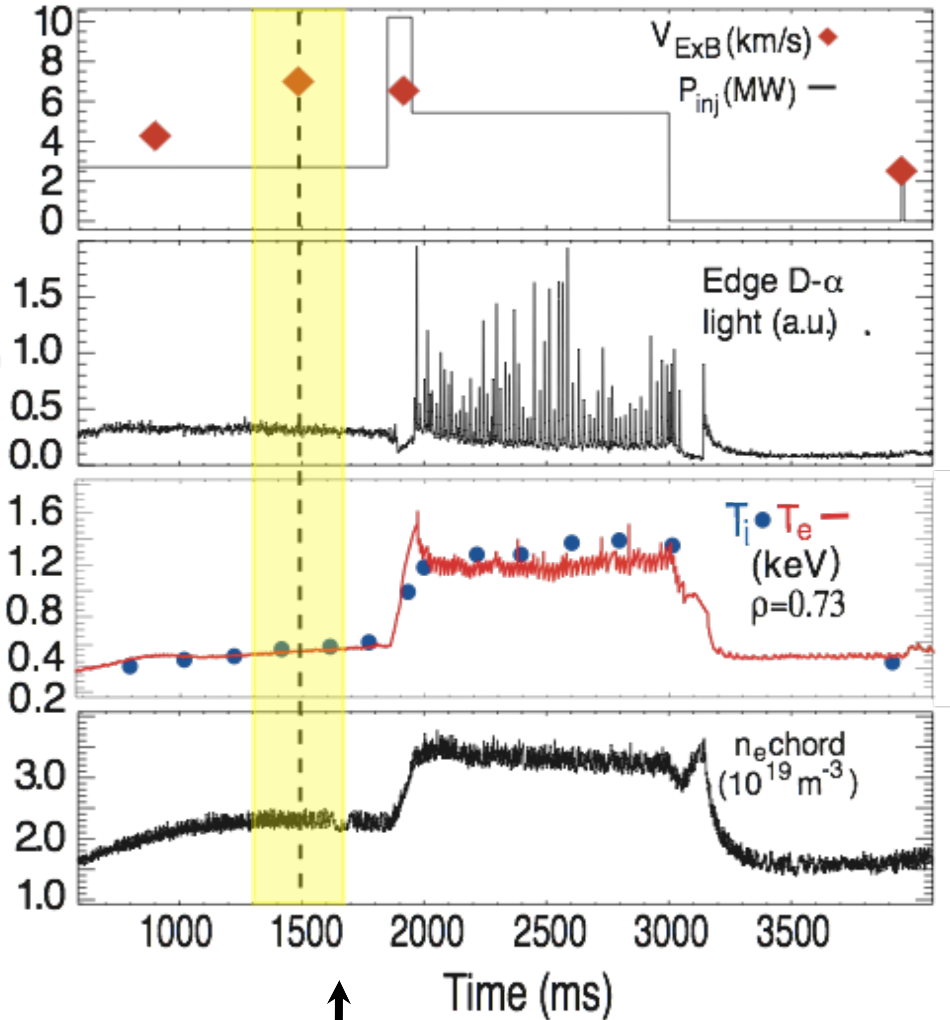
$k_r < 4 \quad cm^{-1}$

BES $\tilde{n}/n$

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

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

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



- Shot parameters, 128913

– I_p = 1 MA
– B_T = 2.1 T,
– 2.5 MW beam power (L-Mode)
– upper single null

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

Stationary, sawtooth-free L-mode

-- The ITG is most unstable mode

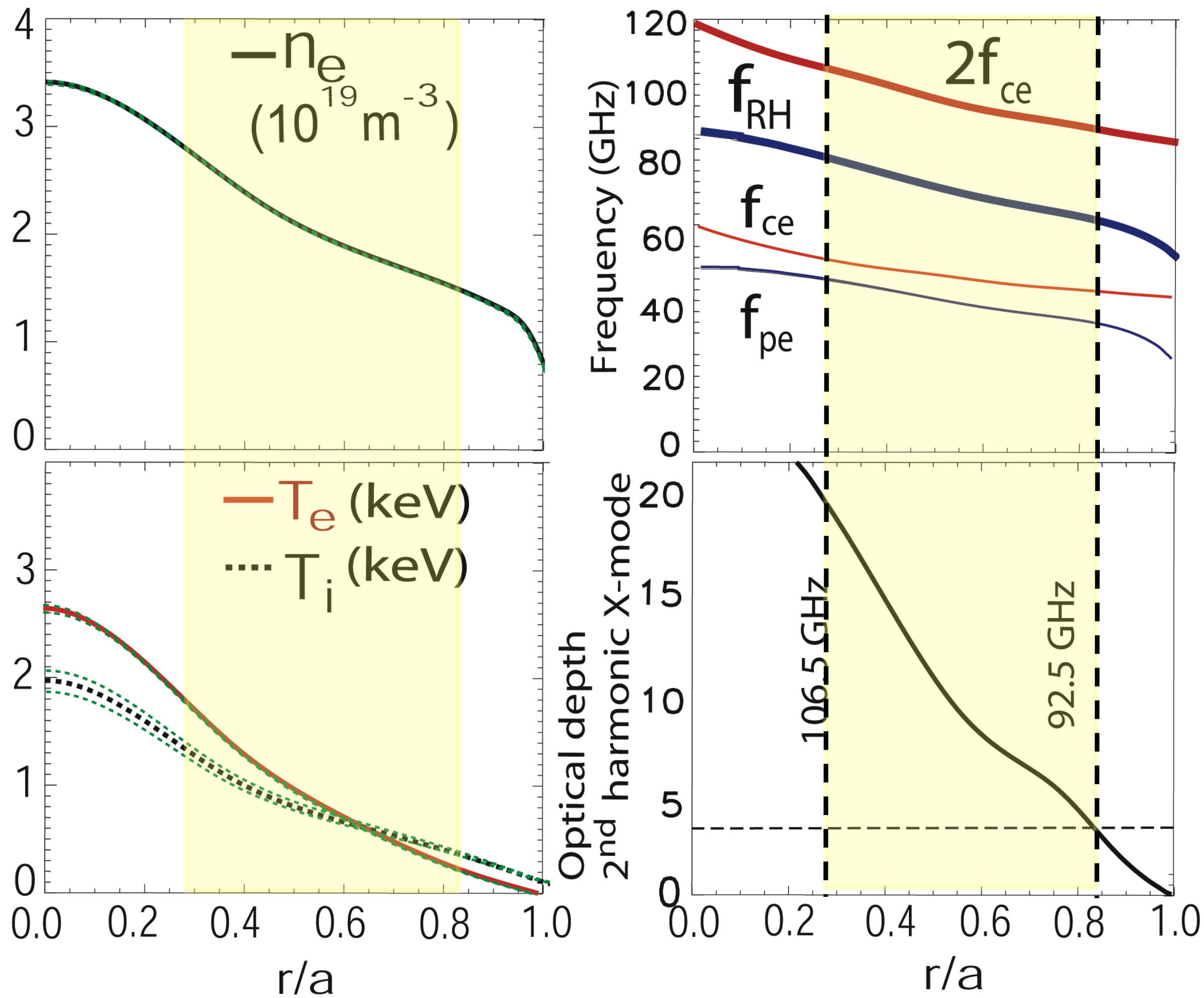
1300-1700 ms used in analysis

Plasma Profiles, Plasma Frequencies, and Optical Depth in a Typical 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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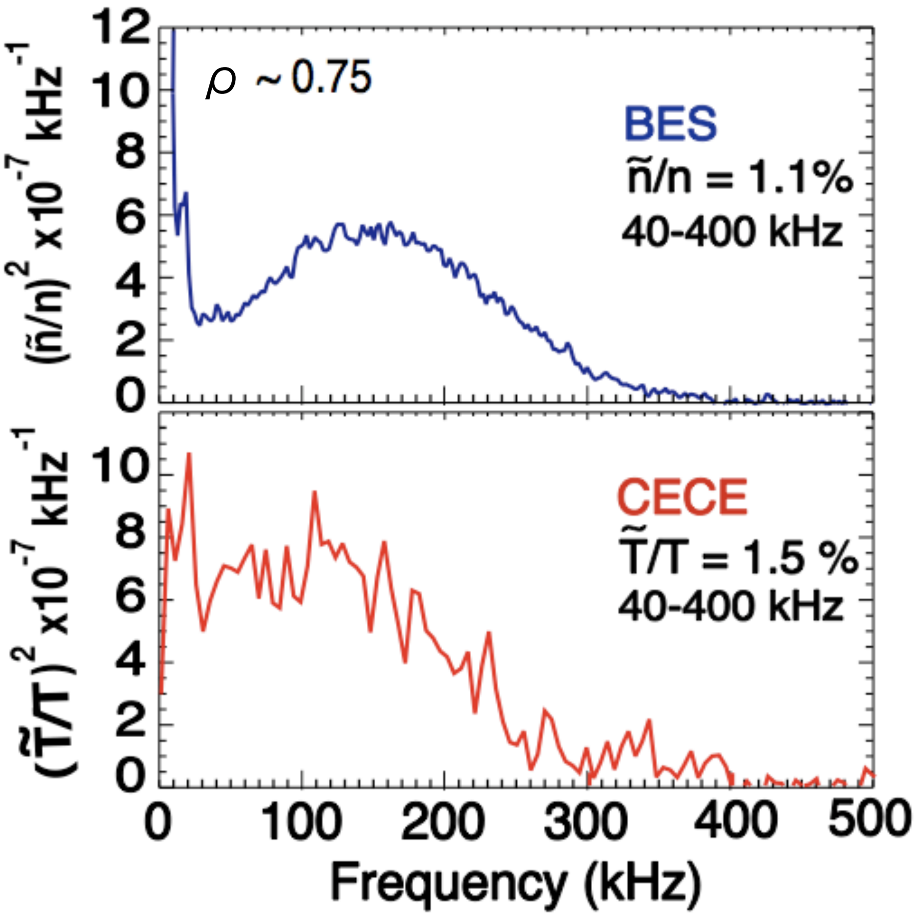
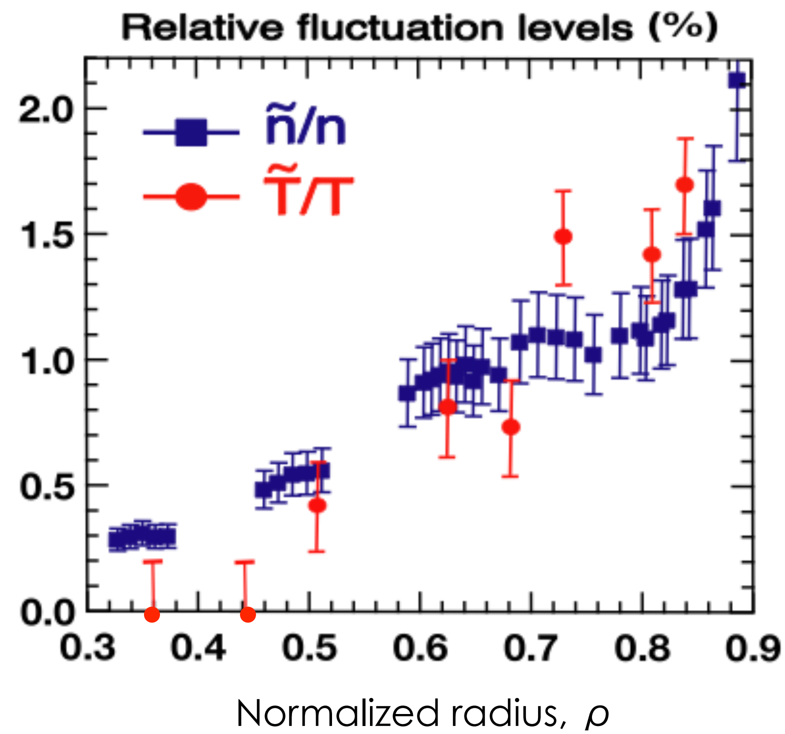
CECE diagnostic scanned between *0.3 < r/a < 0.9*

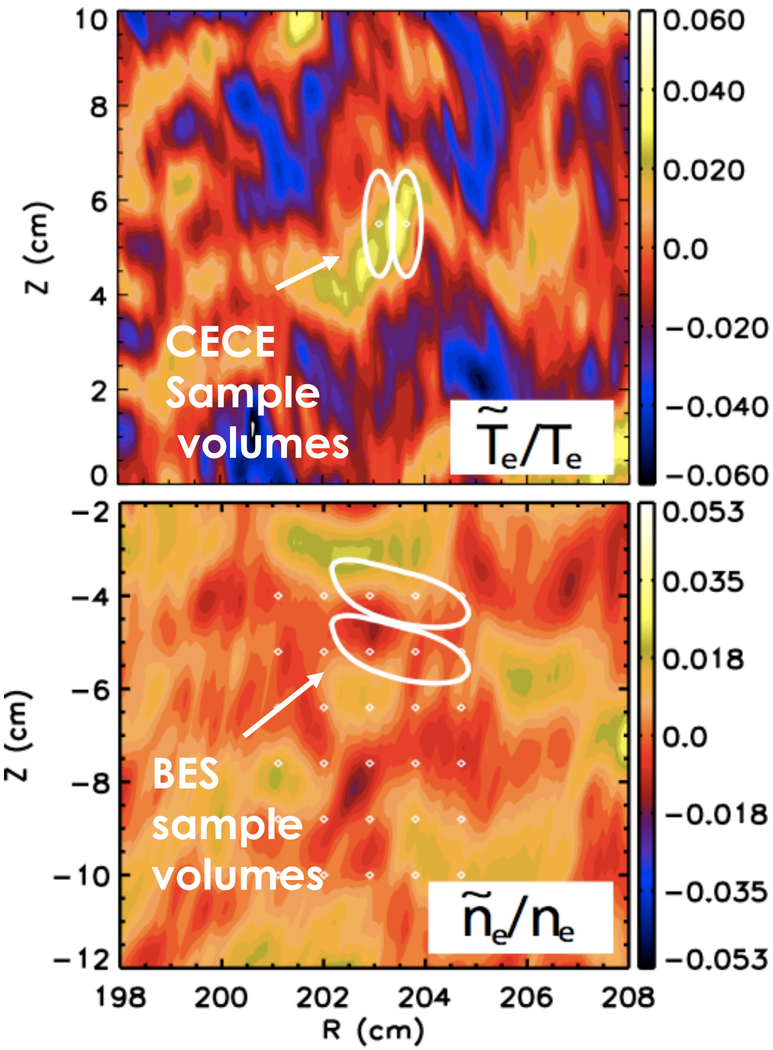
Temperature and Density Fluctuations Have Similar Spectra and Normalized Fluctuation Amplitude Profiles

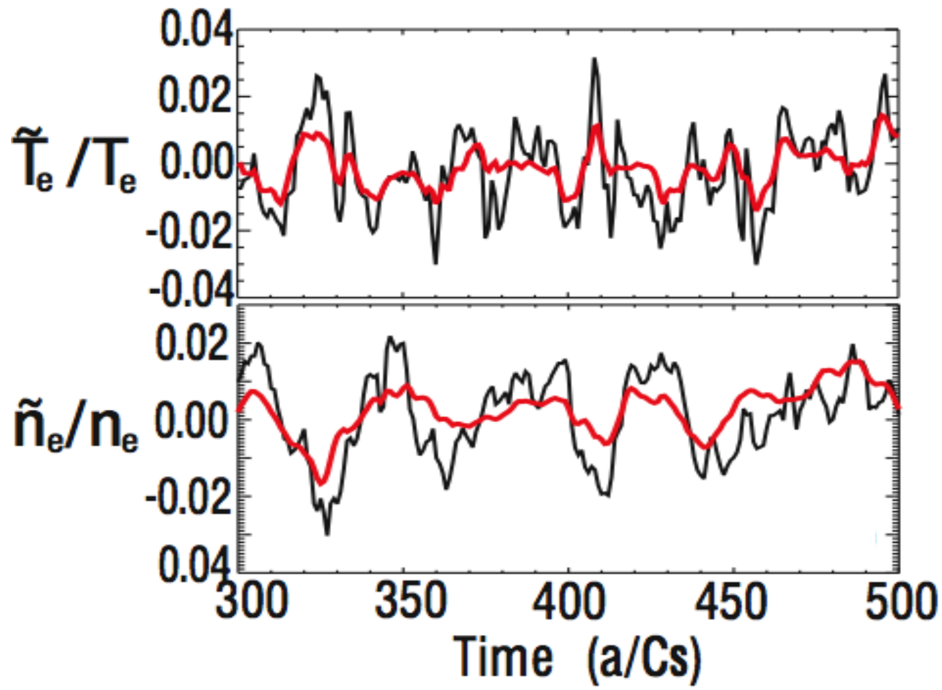




- $\tilde{T}_e/T_e$ and $\tilde{n}/n$ measured between $0.3 < \rho < 0.9$

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

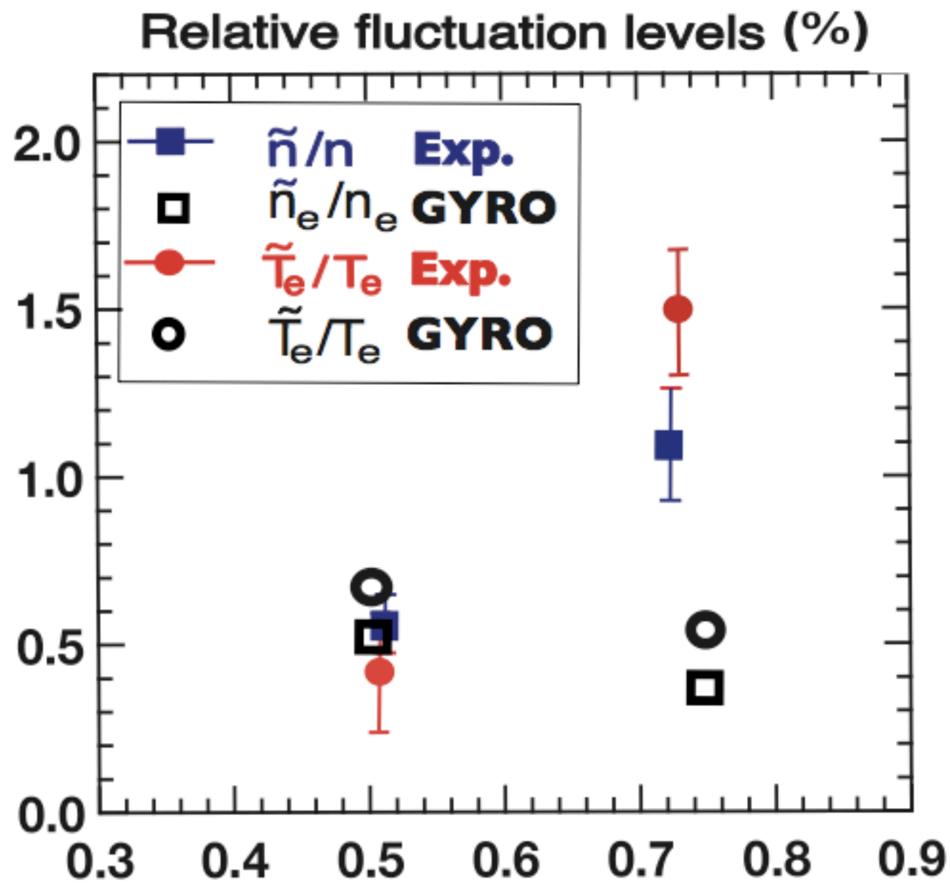




CECE sample volume: Antenna pattern and natural linewidth

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)

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



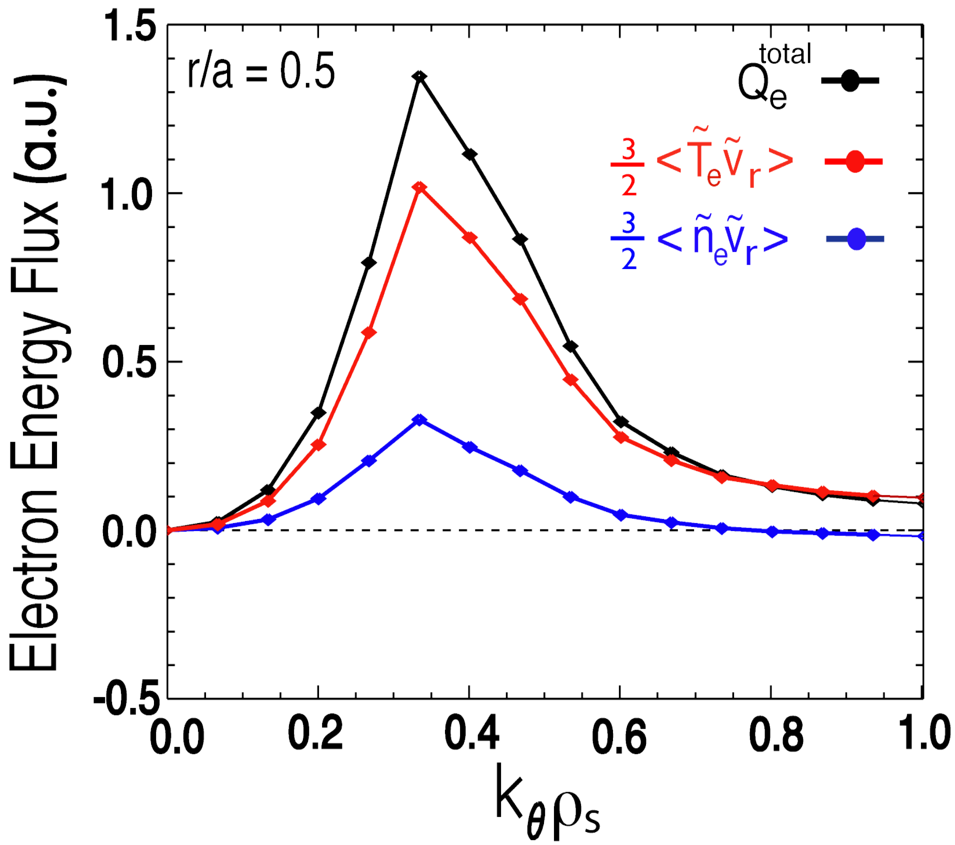
Normalized radius, ρ

- $\tilde{T}_e/T_e \sim \tilde{n}_e/n_e$, consistent with experiment
- At ρ = 0.5, reasonable quantitative agreement
- Trend that fluctuation levels increase with radius not reproduced (White, POP, 2008)

Under-prediction at ρ ~ 0.75 could not be resolved even with extensive GYRO simulations
(Holland, POP, 2009)

Radial trend recovered using gyrokinetic transport modeling, TGYRO
(Candy, POP, 2009)

GYRO Predicts Temperature Fluctuations Drive 80% of Energy Flux at mid radius

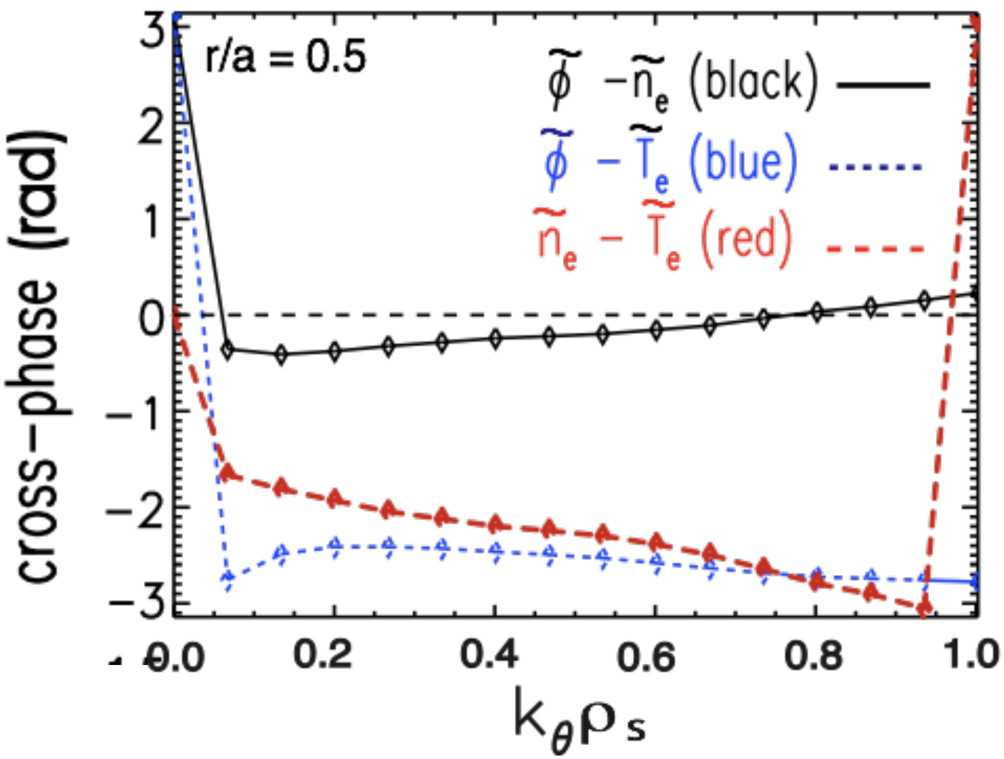


- **GYRO simulations at ρ ~ 0.5 has good quantitative agreement with experiment**
  - fluctuation levels
  - energy fluxes

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

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

GYRO Predicts the Phase Difference Between $\tilde{T}_e$ and $\tilde{n}_e$ in the L-mode Plasma



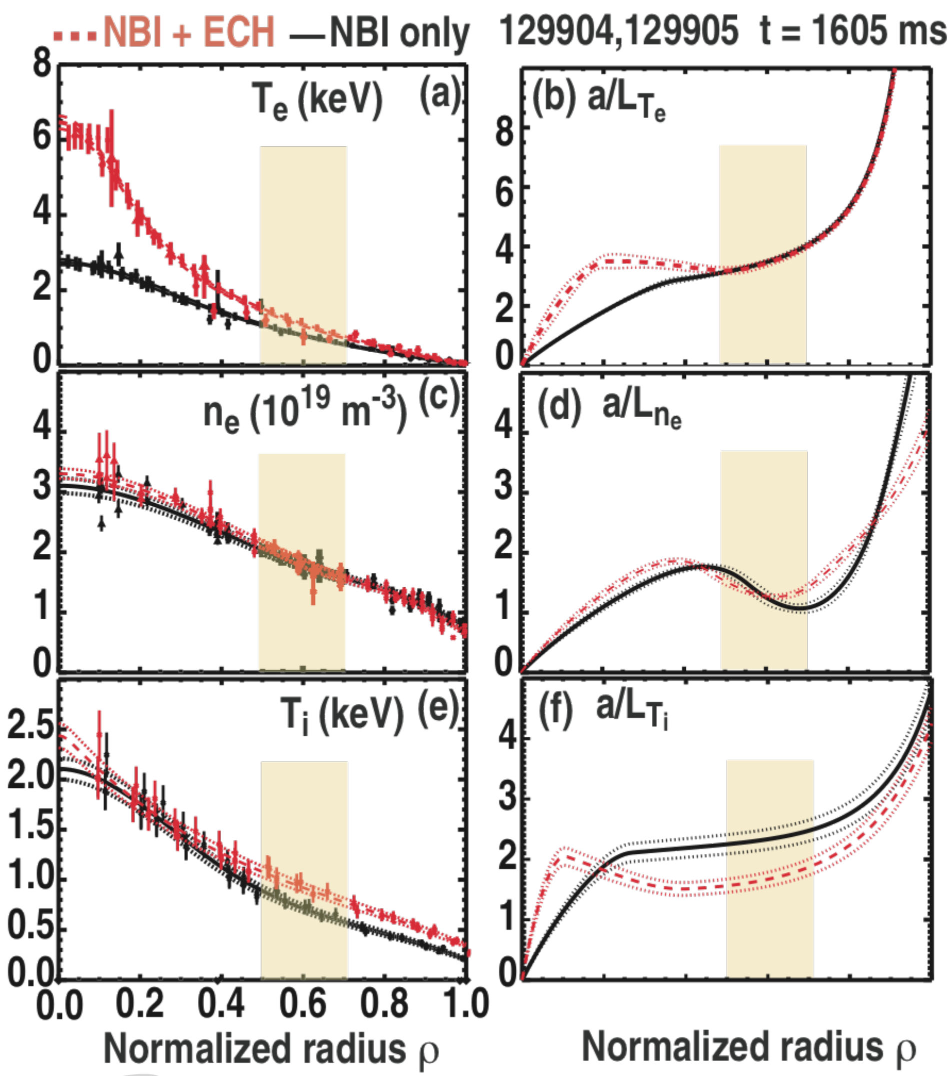
Density and potential fluctuations are ***in phase***
- small transport contribution

Temperature and potential fluctuations are ***out of phase***
- large transport contribution

Phase between $\tilde{n}_e$ and $\tilde{T}_e$ could be measured in experiments using coupled reflectometry and CECE

Different responses of long wavelength density and electron temperature fluctuations to ECH

ECH in Beam Heated L-mode Plasma: Change Profiles and Drives for ITG, TEM Instabilities and Turbulence



- 110 GHz ECH ($\rho \sim 0.17$)
- Small changes in density
- Changes in scale lengths, $L_{Te} = T_e/(dT_e/d\rho)$, L_n are small
- Largest changes overall:
  - **Increase in T_e (x1.5-2)**
  - **Decrease in collisionality**
  - **a/LTi decreases**
- ONETWO Power balance:
  - **Increase in electron thermal diffusivity**
- Linear and nonlinear GYRO: **increase in TEM turbulence, decrease in ITG turbulence**

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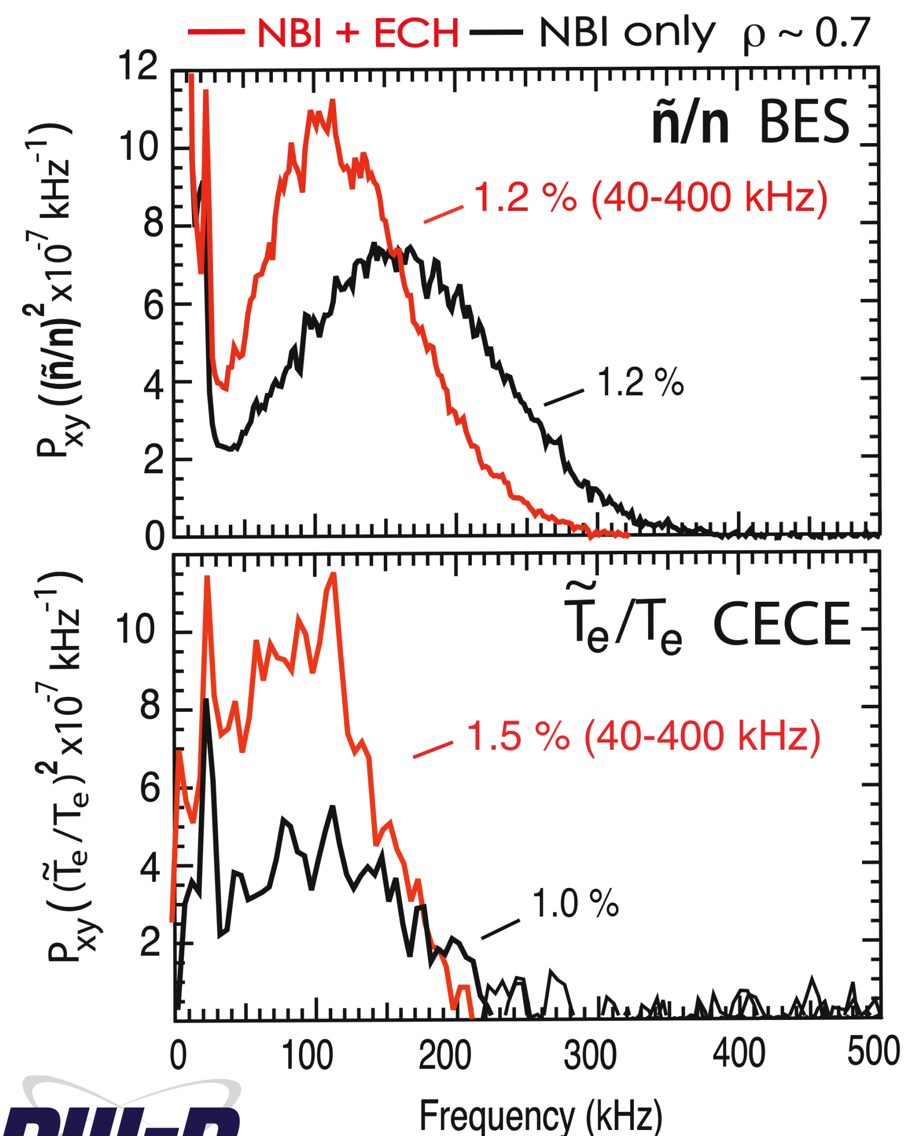
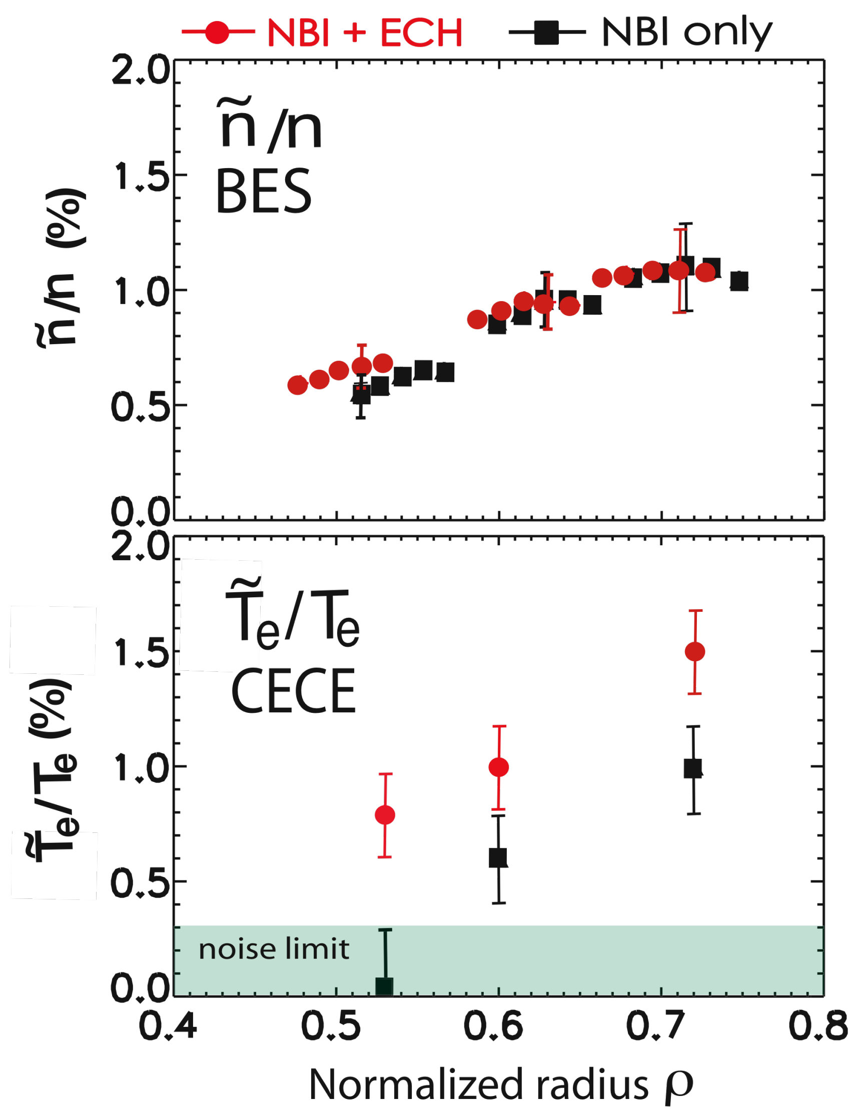
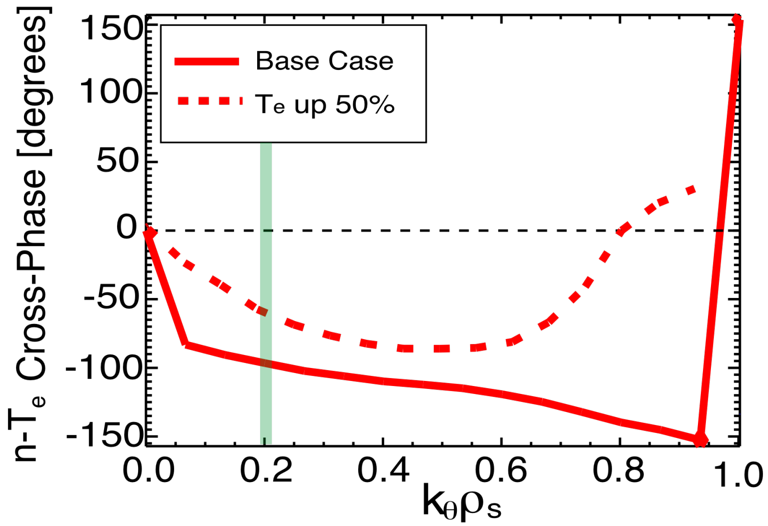
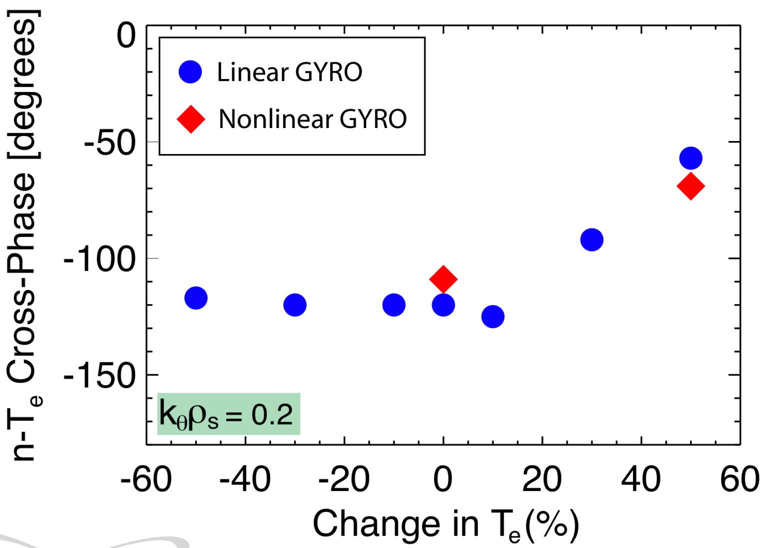
In Experiment, Fluctuation Levels $\tilde{T}_e/T_e$ Are Correlated with Changes in Electron Heat Transport, $\tilde{n}/n$ are not





GYRO results are used to predict change in $\tilde{n}_e$-$\tilde{T}_e$ phase angle as T_e is increased, TEM drive increased





Nonlinear GYRO scans:
Start with inputs from ITG L-mode plasma

Increase T_e by 50%, no change in a/L_{Te}
Accomplished with ECH in experiment

In case with increased TEM turbulence, GYRO predicts:
Increase in heat transport,
Increase in $\tilde{n}/n$ and $\tilde{T}_e/T_e$
Increase in $\tilde{n}$-$\tilde{\phi}$ phase angle,
no change in ***$\tilde{T}$-$\tilde{\phi}$*** *phase angle*

Expect to measure a reduced $\tilde{n}$-$\tilde{T}$ phase angle as T_e increases with ECH

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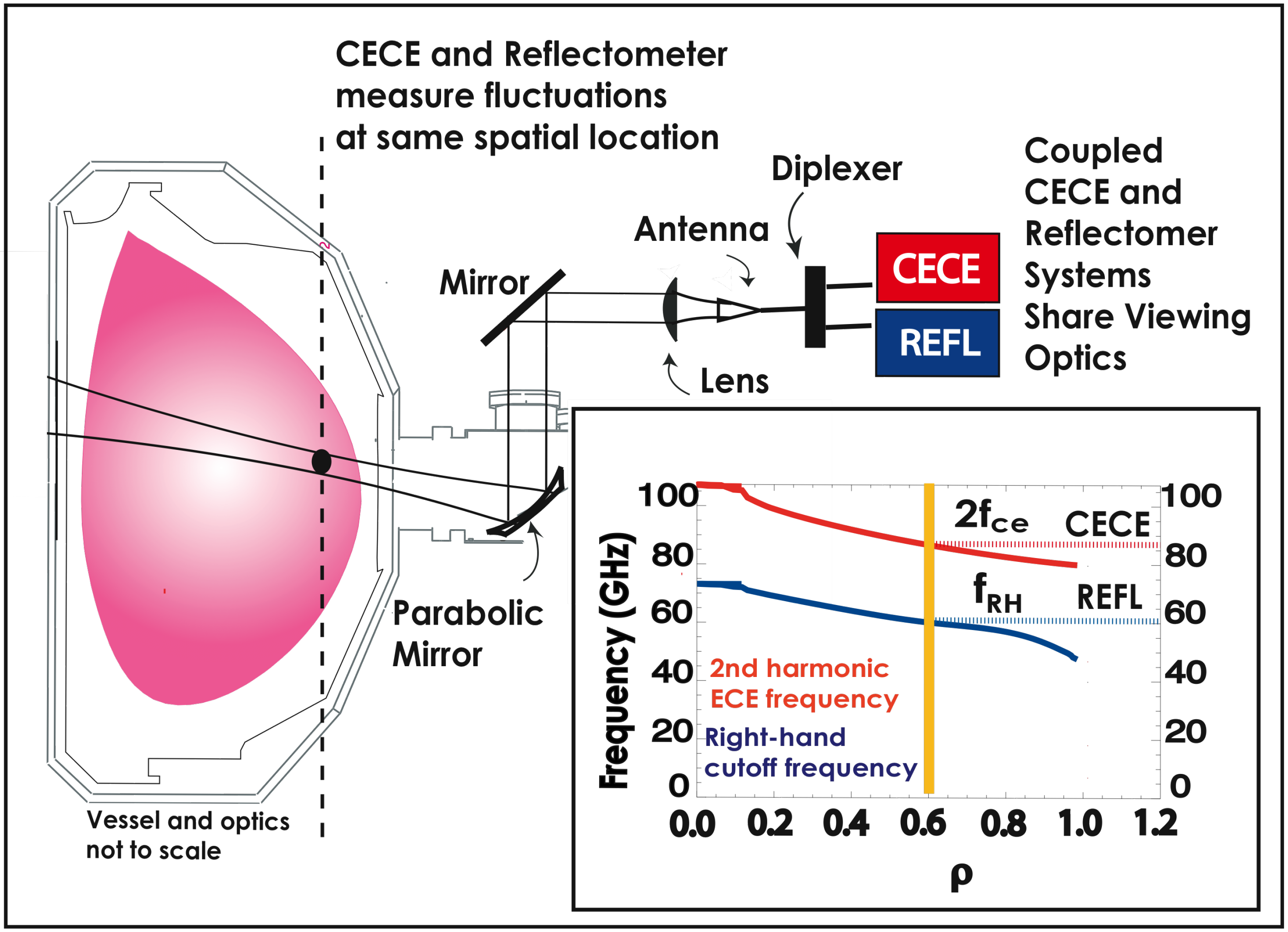
Change in cross-phase angle between density and electron temperature fluctuations in response to ECH

Coupled Reflectometry and Correlation Electron Cyclotron Emission (CECE) for Cross-Phase Angle Measurement

White POP 2010



X-mode Correlation ECE radiometer

- Low-k $\tilde{T}_e$ ($k_\theta \rho_s < 0.3$)

X-Mode quadrature Reflectometer

- Low-k $\tilde{n}_e$ ($k_\theta \rho_s < 0.5$)

Multi-channel systems are frequency-tuned to overlap sample volumes radially

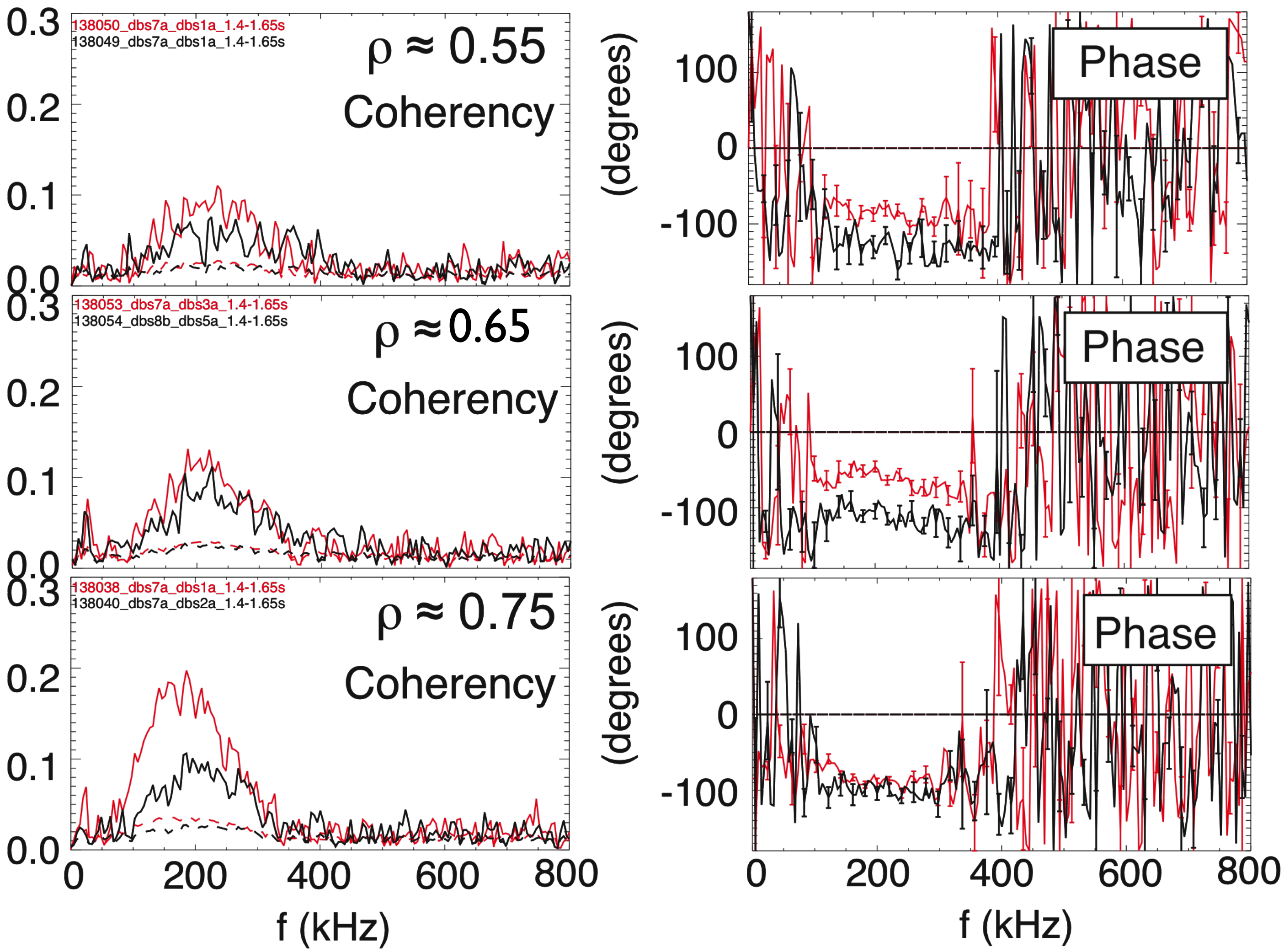
- **Spot-Sizes are similar**

  $\Delta z \sim 3.0\text{-}3.5$ cm

  $\Delta r \sim 1.0$ cm

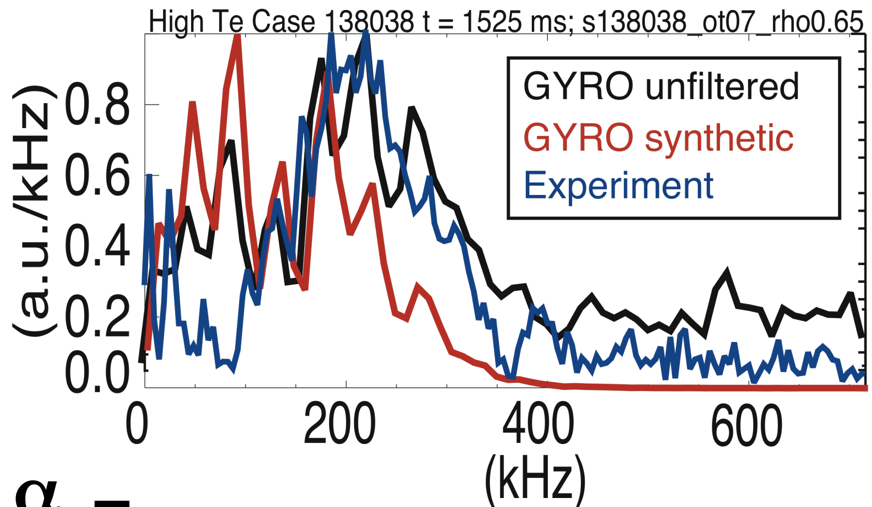
Predicted Trend is Observed at ρ = 0.55 and 0.65 but not At ρ = 0.75 in the High T_e Case

Base Case **High T_e Case**

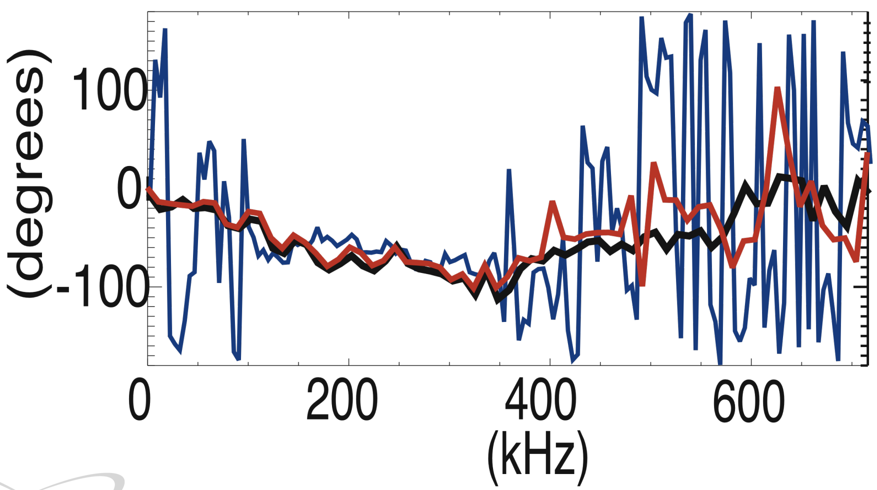


Measured n-T Phase Angle in NBI+ECH L-mode Agrees Quantitatively with Nonlinear GYRO Results; Questions Remain

$|\langle \tilde{n}_e \tilde{T}_e \rangle|^2$



α_{nT}



- **Nonlinear GYRO results**
  - Local Simulation at r/a = 0.65
  - High T_e Case only

GYRO raw Phase = -70°+-2°
GYRO syn. Phase = -71°+-1°
Exp. n_e-T_e phase = -61°+-12°

- **Cross-phase angle *does depend sensitively* on spacing between CECE and reflct sample volumes**

- Need more modeling of reflectometer data – how is phase of fluctuations in reflectometer signals related to underlying phase of density turbulence?

Summary of Results

- In ITG-dominant L-mode plasmas, long wavelength ($k_\theta \rho_s < 0.5$) $\tilde{T}_e/T_e$ are similar to amplitude to long wavelength $\tilde{n}/n$ (0.5-2%, increasing with radius)

- **After H-mode transition, core electron temperature fluctuations are significantly reduced; increased ExB shearing of ITG turbulence**

- **In experiments where TEM drive/thermal transport increased using ECH to modify plasma profiles, $\tilde{T}_e/T_e$ and $\tilde{n}/n$ respond differently**
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- **Nonlinear GYRO simulations predict increases in transport as TEM drive increases associated with**
  - **Large change in $\tilde{T}_e/T_e$, smaller changes in $\tilde{n}/n$**
  - **Change in cross-phase angle between $\tilde{n}$-$\tilde{\phi}$**

- **The change $\tilde{n}$-$\tilde{T}$ phase angle is measured and is in good agreement with predictions from GYRO; ongoing modeling effort required**