Correlation ECE Measurements of Turbulent Electron Temperature Fluctuations in the Core of DIII-D Plasmas

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

- **Several types of instabilities contribute to electron thermal transport**
  - Ion temperature gradient (ITG) mode ($k_\theta \rho_s < 1$),
  - Trapped electron mode (TEM) ($k_\theta \rho_s < 2$)
  - Electron temperature gradient (ETG) mode ($k_\theta \rho_s > 2$)

- **Cross-phase angles and fluctuation levels are important**

$$Q^{ES} = \frac{3}{2B} k_\theta (T_0 \tilde{n}_{rms} \tilde{\phi}_{rms} |\gamma_{n\phi}| \sin(\alpha_{n\phi}) + n_0 \tilde{T}_{rms} \tilde{\phi}_{rms} |\gamma_{T\phi}| \sin(\alpha_{T\phi}))$$

- **Finite phase differences lead to transport. These arise due to dissipation of parallel electron motion (e.g. collisions, magnetic trapping, etc.)**

- **In the core of tokamak plasmas, typically focus on $\tilde{n}$**

  - **Measurements of $\tilde{T}_e$ provide important information about physics of turbulence, constrain nonlinear gyrokinetic turbulence simulations and support validation efforts**

Outline of Talk

- Motivation and summary
- Correlation radiometry of ECE (CECE)
- Comparisons with simultaneously measured density fluctuations
- n-T cross phase angle measurements using coupled reflectomery and CECE systems
- Summary and Conclusions

Correlation Radiometry of ECE is Needed for Measurements of Turbulent Temperature Fluctuations

- **Single ECE radiometer channel sensitivity limited by the thermal noise level given by radiometer equation** (Bekefi, 1966)

$$\left(\tilde{T}/T\right)^2 \geq \frac{B_{vid}}{B_{if}}$$

B_{if} ~ 110 MHz , B_{vid} ~ 2.5 MHz : sensitivity $\tilde{T}_e/T_e > 15\%$

Correlation ECE has been used on tokamaks and stellarators for turbulence studies

W7-AS (Sattler 1994, Hartfuss 1996, Watts 2004), TEXT (Cima 1995, Deng 1998), RTP (Deng 2001), DIII-D (Rettig 1997, White 2008), Review article (Watts 2007)

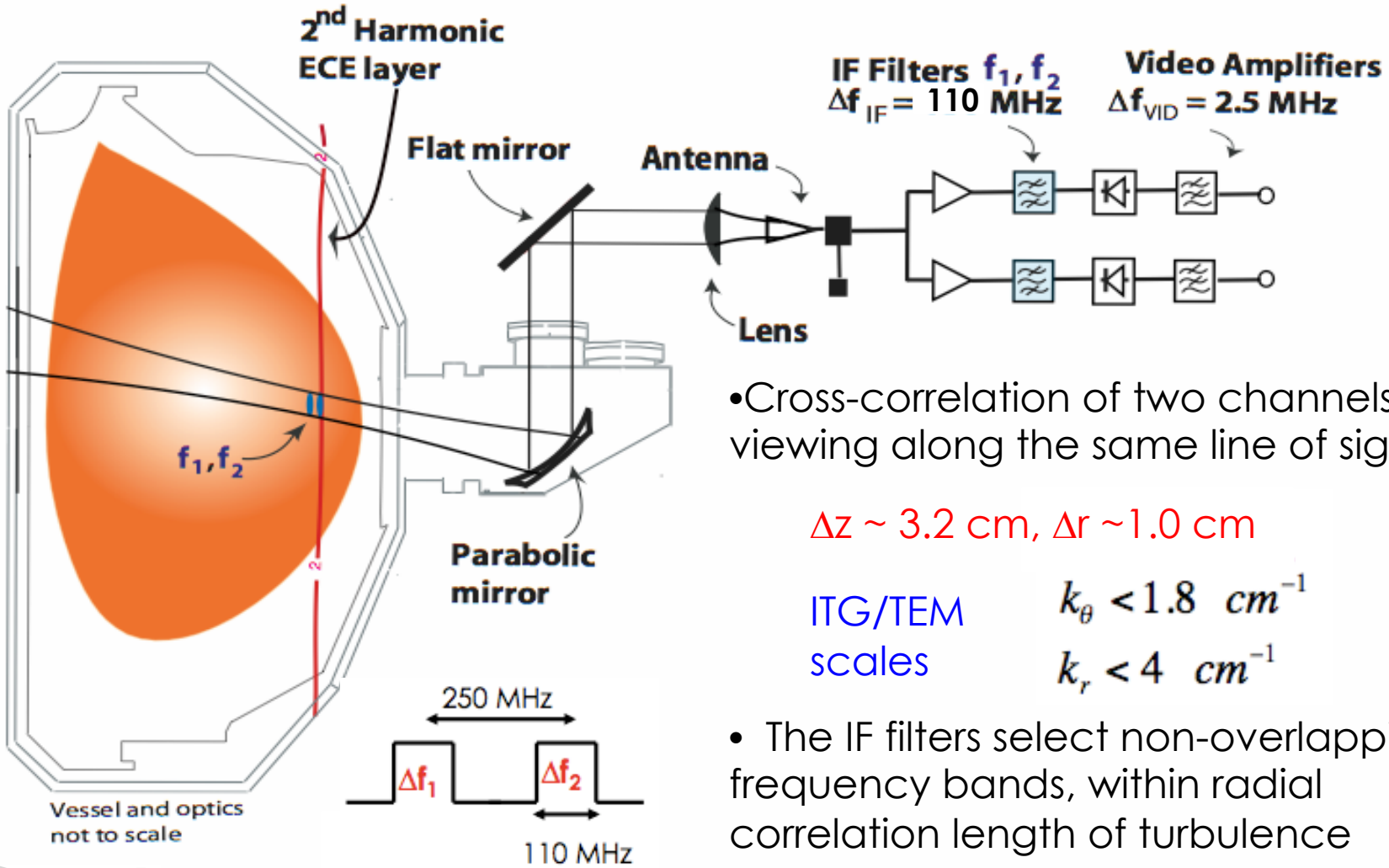
- **Standard cross-correlation techniques are used to improve sensitivity to turbulent fluctuations** (Sattler 1994, Cima 1995)

$$\left(\tilde{T}/T\right)^2 \geq \frac{1}{\sqrt{N_s}}\frac{B_{vid}}{B_{if}}$$

$$N_s = \sqrt{2\Delta t B_{vid}}$$

Sensitivity improves $\tilde{T}_e/T_e > 0.2\%$

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



- Cross-correlation of two channels viewing along the same line of sight

$\Delta z \sim 3.2$ cm, $\Delta r \sim 1.0$ cm

ITG/TEM scales $k_\theta < 1.8 \ cm^{-1}$

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

- The IF filters select non-overlapping frequency bands, within radial correlation length of turbulence

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

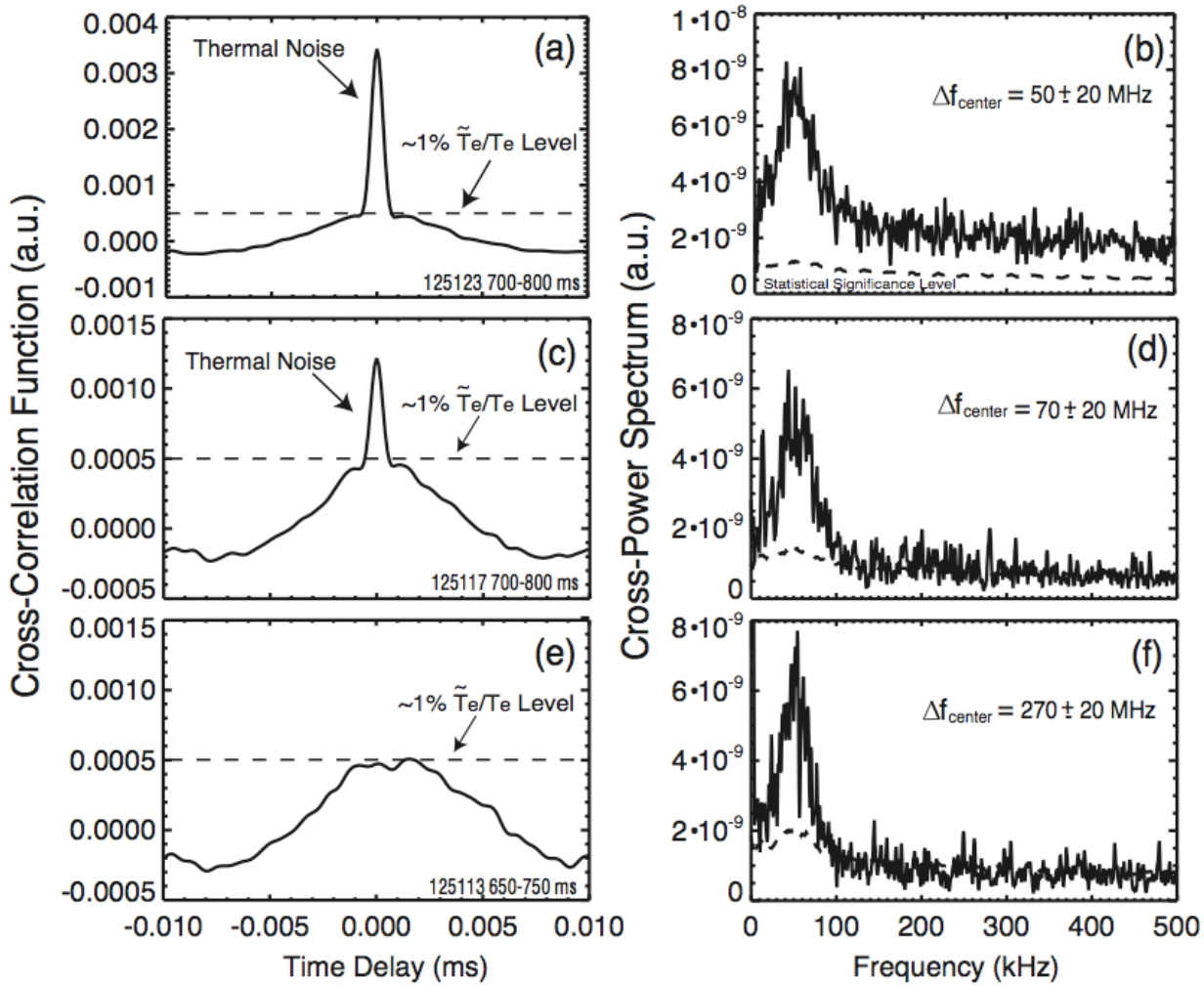
- The thermal noise feature is broadband in frequency

- Turbulence: $B_{sig} \sim B_{vid}$

Long time averaging is needed to measure fluctuations (200-400 ms)

- Shorter integration times are needed in cases of moderate filter overlap when $B_{sig} < B_{vid}$

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

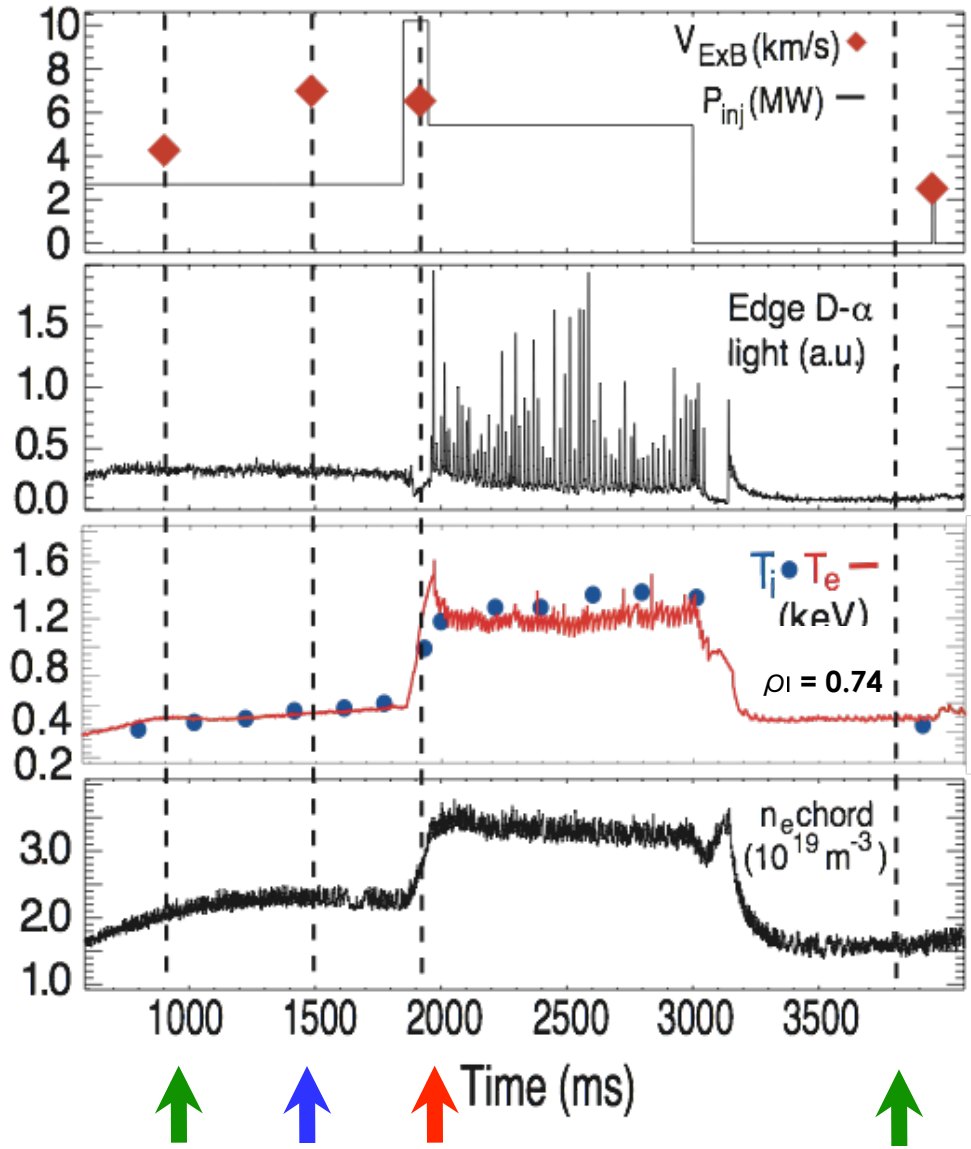


Temperature Fluctuations Are Measured in L-mode, H-mode and Ohmic Plasmas in a Single Discharge

- 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 ρ = 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 $\tilde{T}e/Te$ After L-H Transition

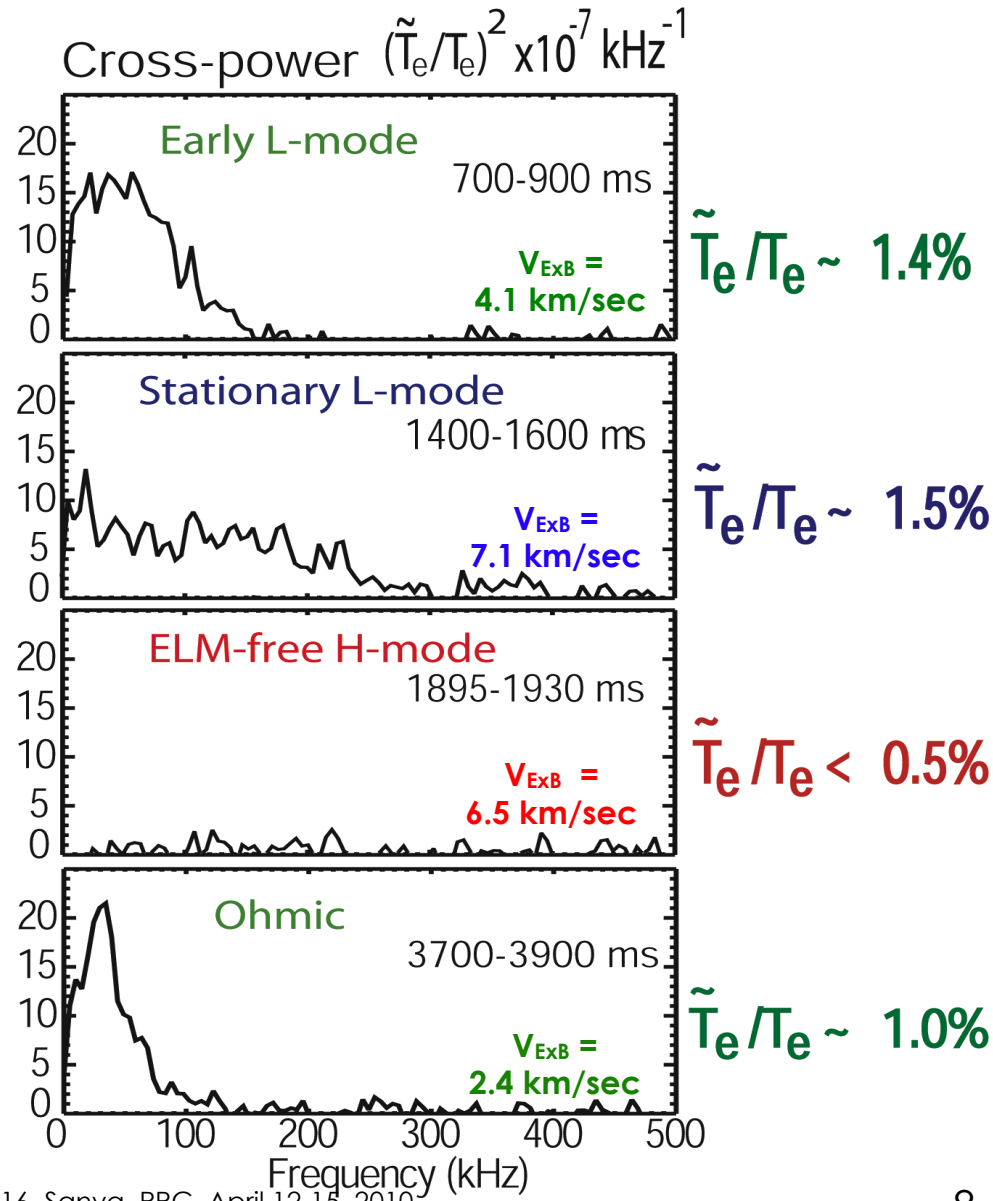
- **Typical cross-power spectra of $\tilde{T}_e/T_e$ at ρ = *0.75***

  - 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)

-- Consistent with Schmitz PRL 2008 reduction seen in QH-mode plasmas



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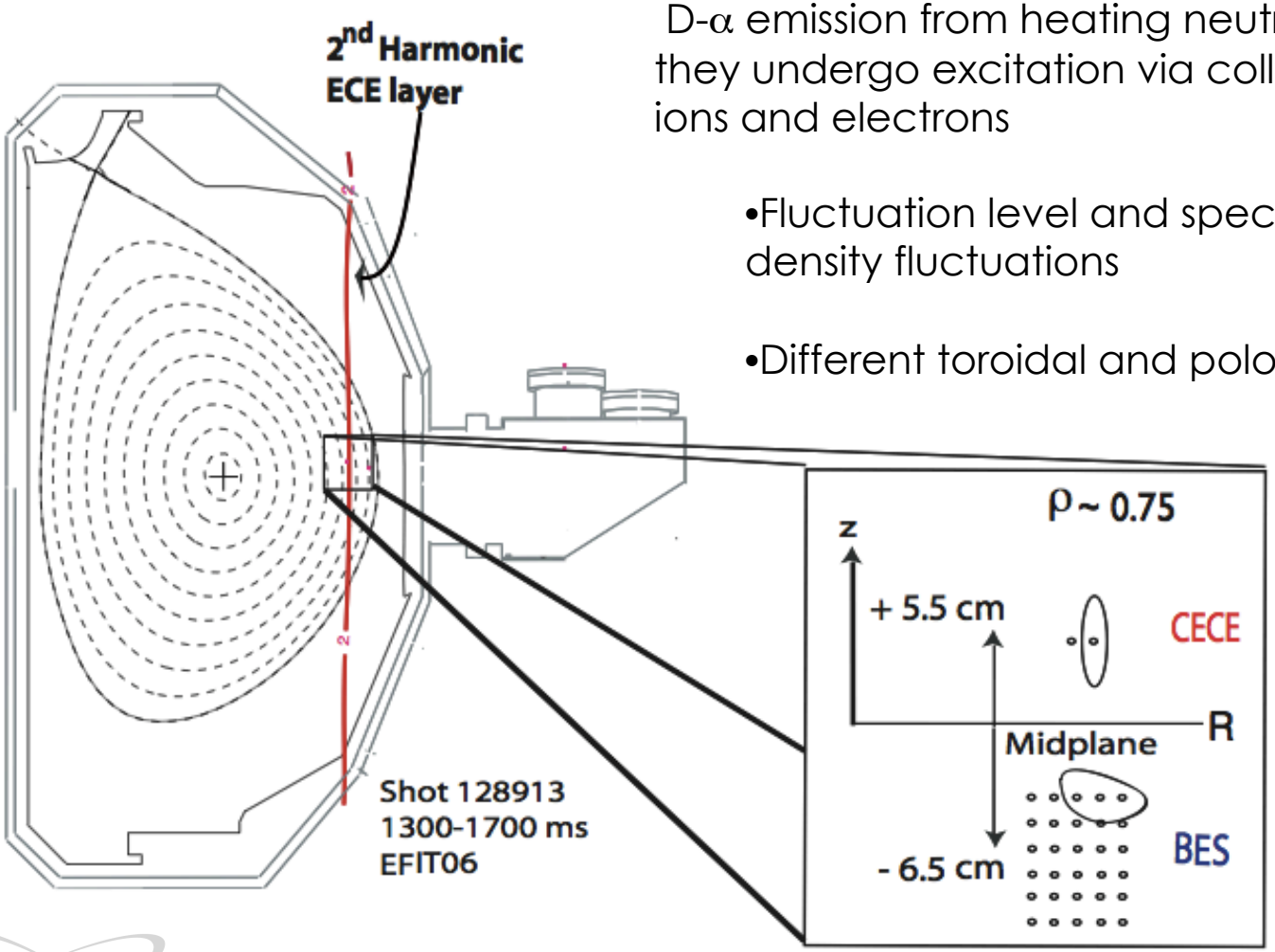
Beam Emission Spectroscopy (BES) Diagnostic Measures Local Density Fluctuations at Same Radius as CECE

- **BES** measures density fluctuations by detecting D-α emission from heating neutral beam atoms as they undergo excitation via collisions with plasma ions and electrons
  - Fluctuation level and spectrum of low-k density fluctuations
  - Different toroidal and poloidal location



CECE $\tilde{T}_e/T_e$

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

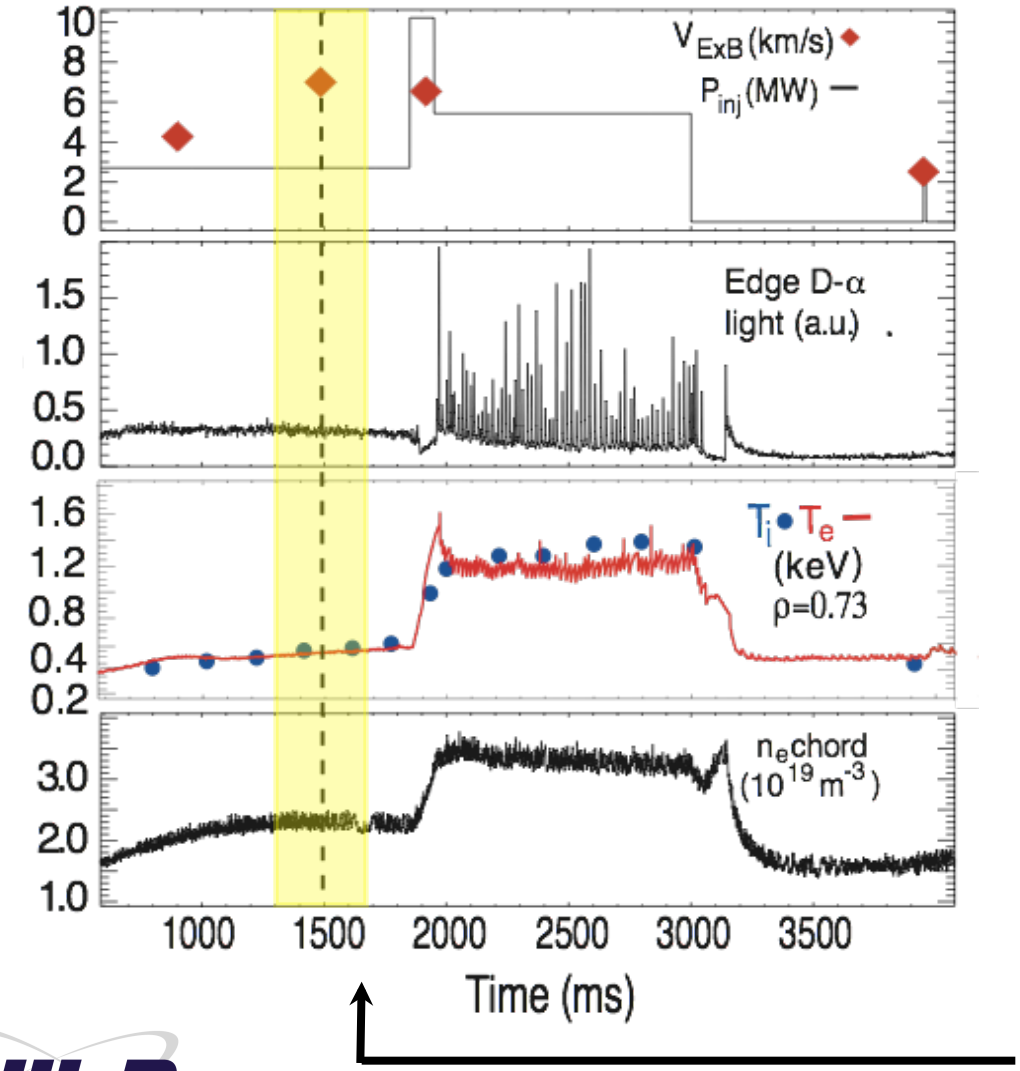
$k_r < 4 \quad cm^{-1}$

BES $\tilde{n}/n$

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

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

L-mode Radial Profile of Temperature Fluctuations 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.

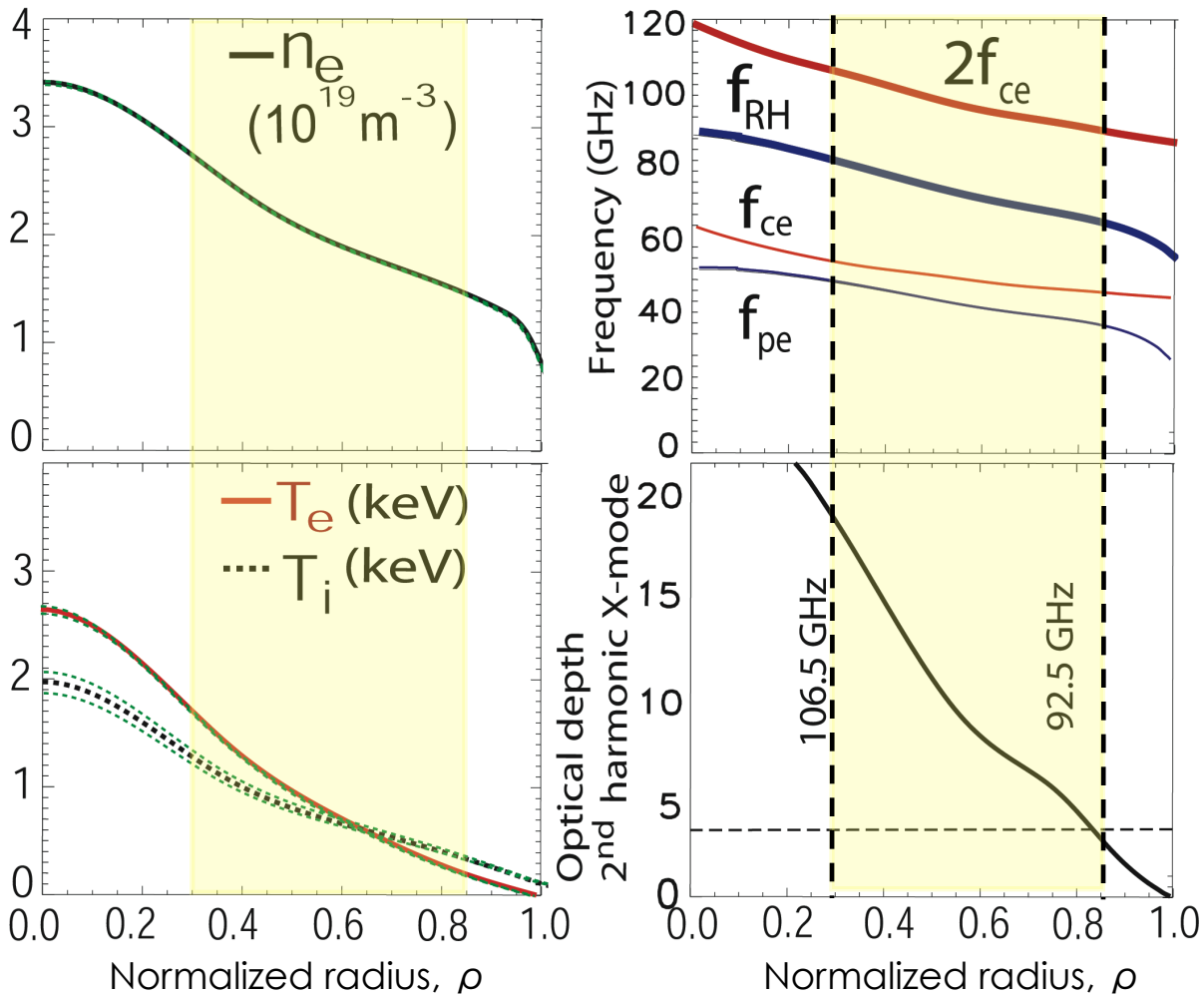
$n_e \sim 2.3 \times 10^{19}\ m^{-3}$
$T_e \sim 450$ eV
$T_i \sim 500$ eV

1300-1700 ms used in analysis

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

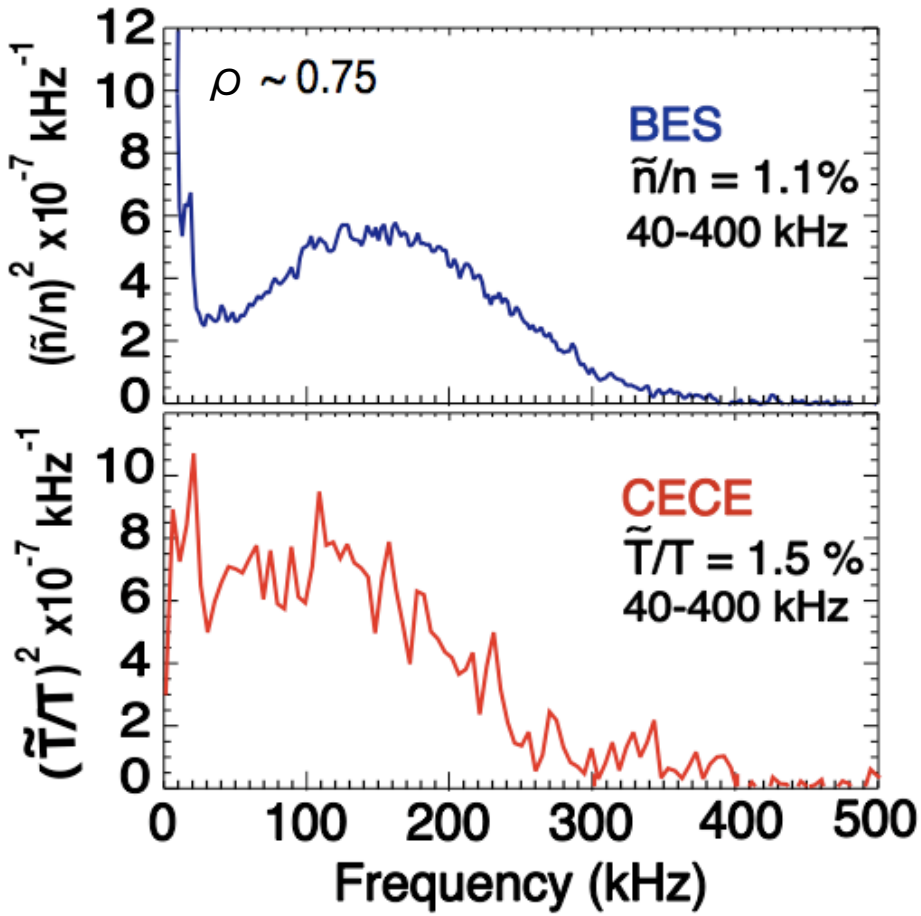
- 2nd Harmonic ECE is far from being cut-off, far from f_{RH}
- Plasma is optically thick ($\tau > 4$)in region of interest
- Density fluctuations not expected to contribute to temperature fluctuation signal

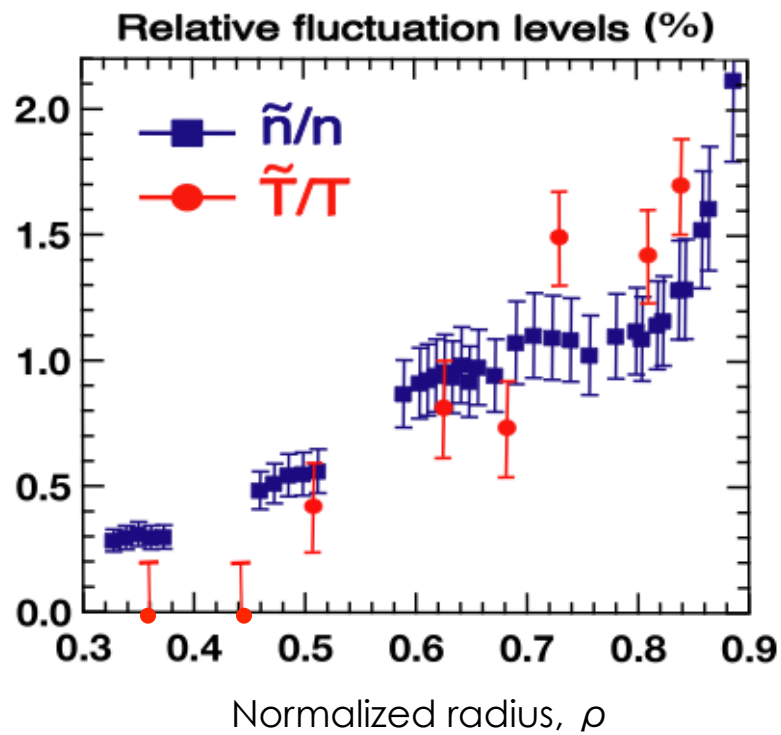
(Sattler PRL 94, Rempel RSI 94)



CECE and BES diagnostics scanned between *0.3 < ρ < 0.9*

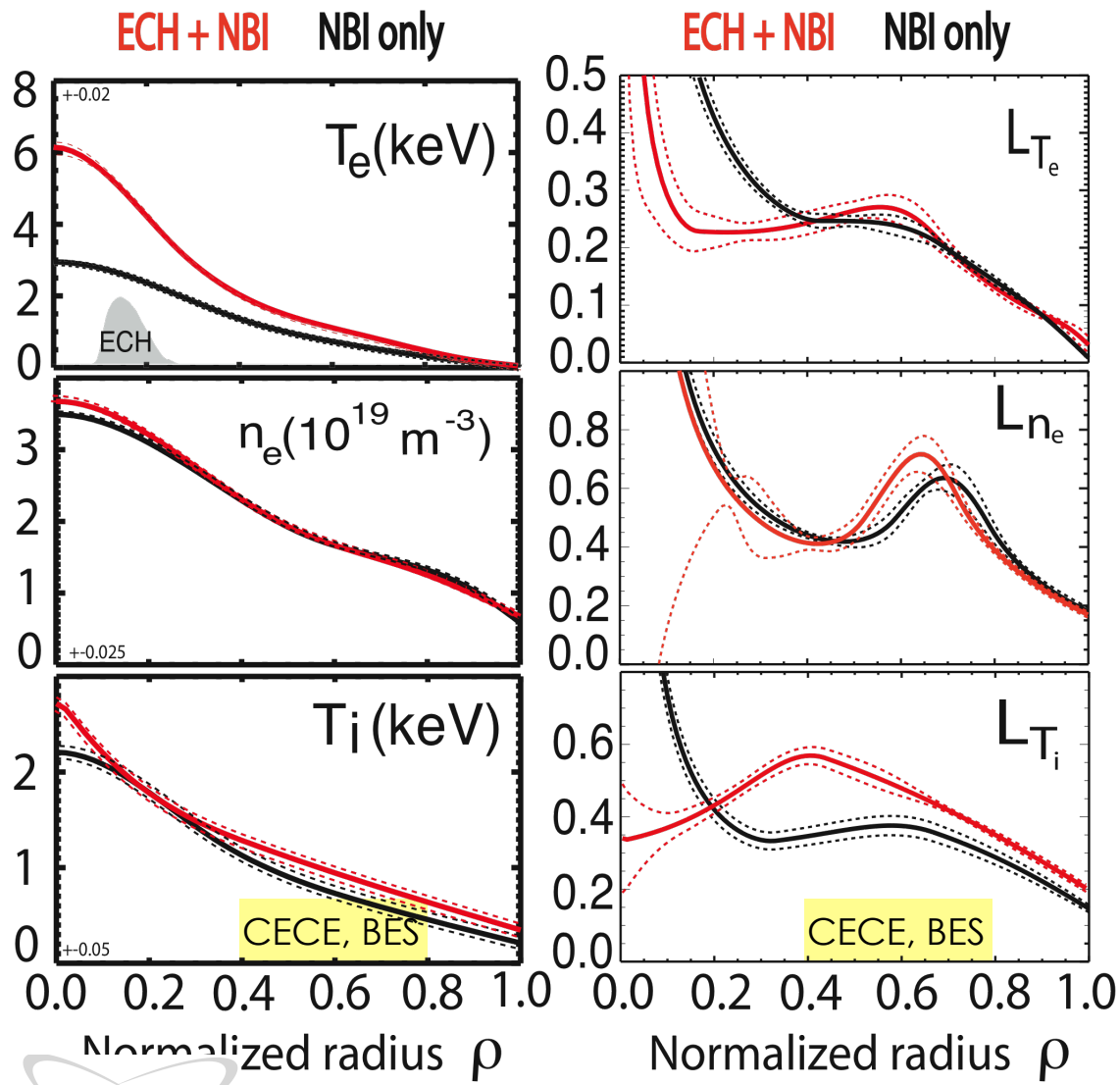
Temperature and Density Fluctuations Have Similar Spectra and Normalized Fluctuation Amplitude Profiles





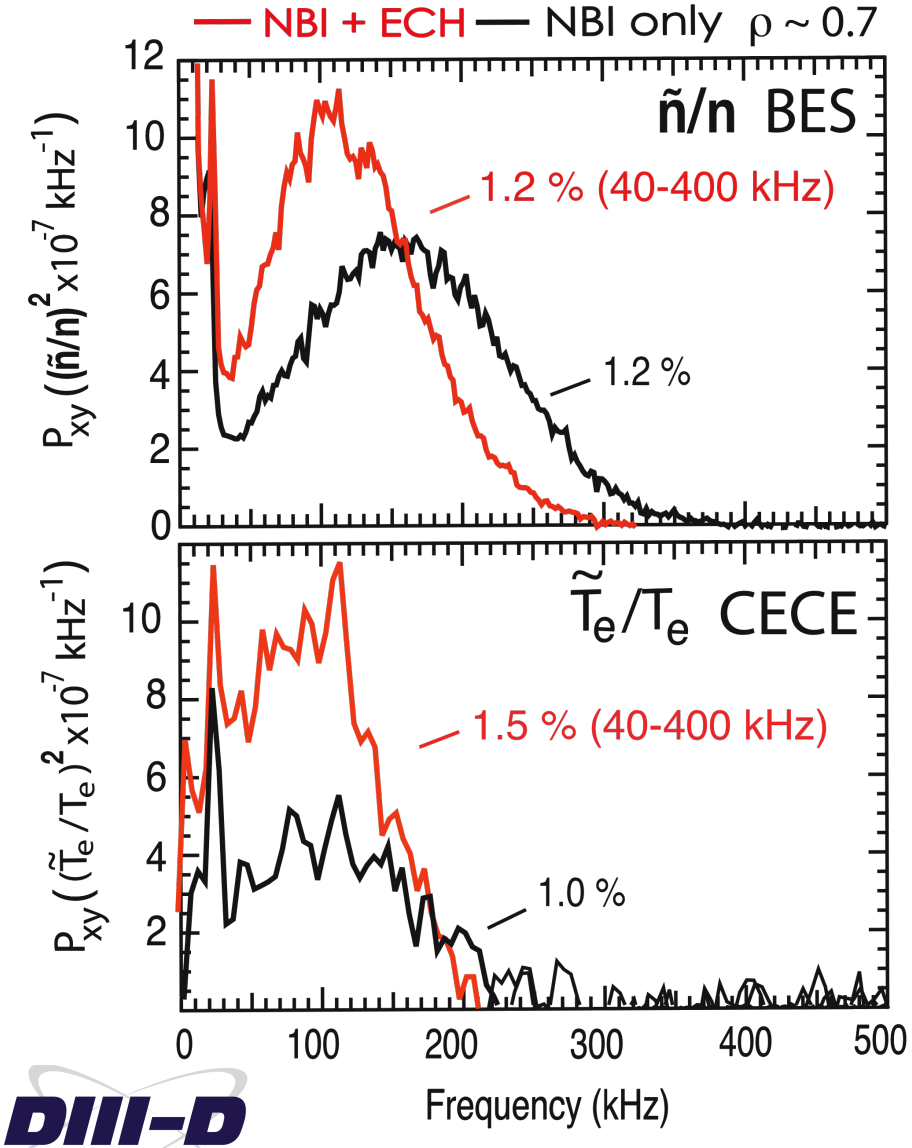
- $\tilde{T}_e/T_e$ and $\tilde{n}/n$ measured between $0.3 < \rho < 0.9$

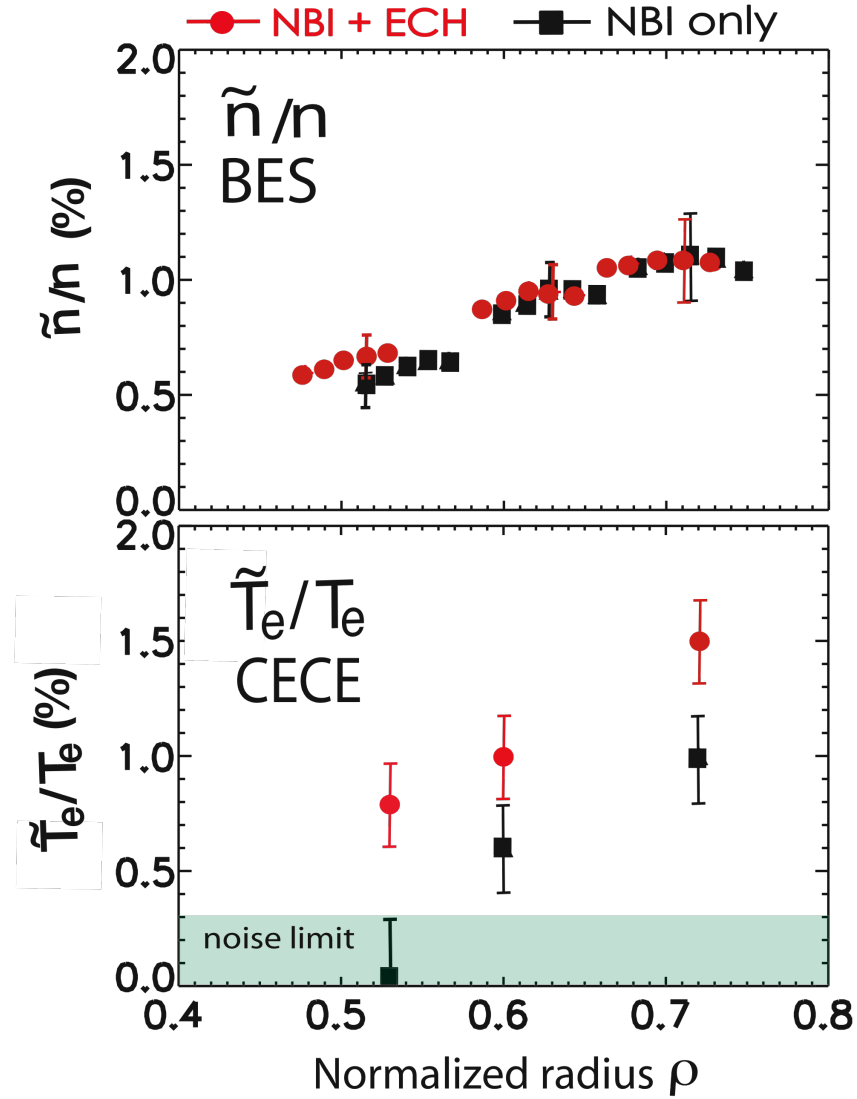
Add ECH to Beam Heated L-mode Plasma, Change Profiles and Drives for Instabilities (ITG, TEM) and Turbulence



- 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**
- Linear stability analysis: **increase in TEM growth rate, decrease in ITG growth rate**
- Power balance:
  - **Increase in electron thermal diffusivity**

In Experiment, Only Fluctuation Levels $\tilde{T}_e/T_e$ Are Correlated with Changes in Electron Heat Transport





Nonlinear GYRO Runs and Synthetic Diagnostics are Used to Directly Compare with Measurements

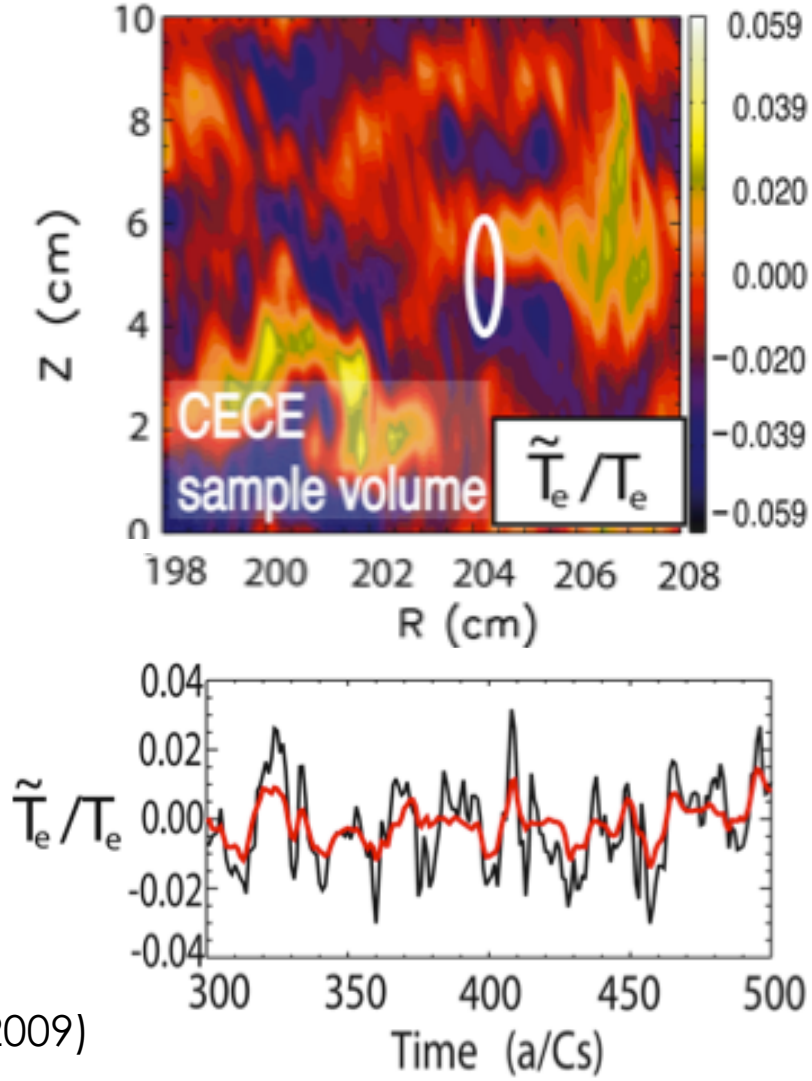
–**GYRO is an initial value, Eulerian (Continuum) gyrokinetic transport code used to simulate core turbulence and transport** (Candy PRL 2003)

– **Model in Simulations**: realistic geometry, drift-kinetic electrons, e-i pitch-angle collisions, mass ratio, equilibrium ExB flow, EM effects

– **INPUT:** experimental profiles (T_e, T_i, n_e, E_r) **OR** experimental fluxes (Q_e, Q_i) (Candy APS 2009, TGYRO)

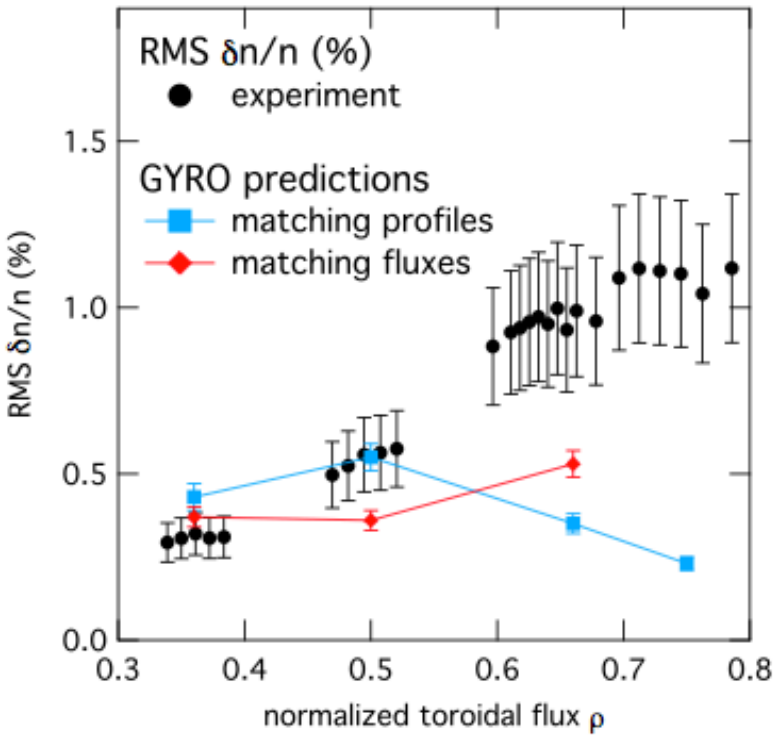
–**GYRO outputs must be filtered** to take into account wavenumber sensitivity limits of diagnostics

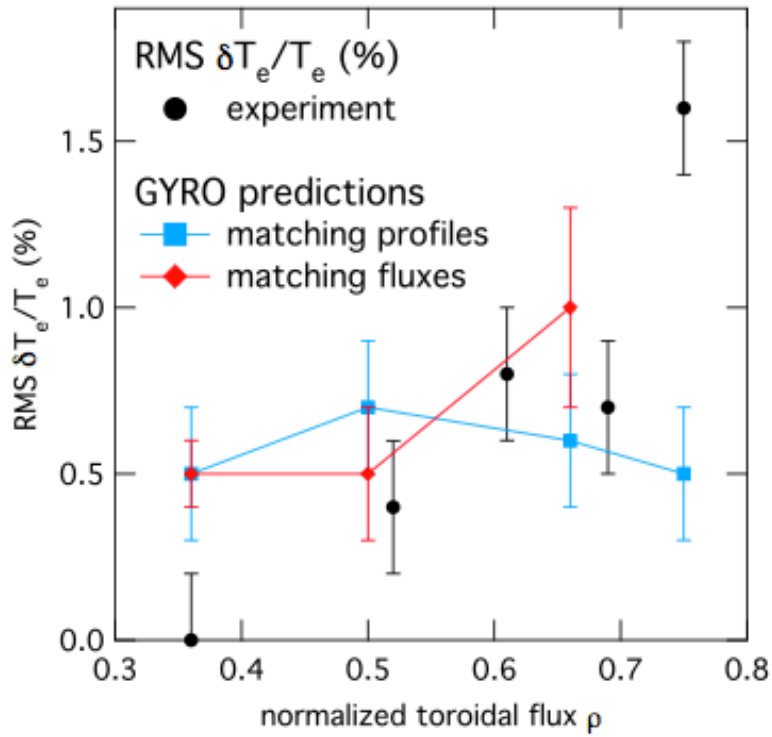
→ **Synthetic Diagnostics** (Bravenec RSI 2006, Holland POP 2009)



GYRO Can Match Profiles Reasonably Well Using New Flux-Matching Simulations, Resolving Past Disagreements

Fluctuation level sensitive to instability threshold





DIII-D 128913-23 1300-1700 ms

Disagreement with **both** BES n-tilde and CECE Te-tilde profiles in "matching profiles" case (White POP 2008, Holland POP 2009) stimulated interest, effort on the "matching fluxes" (Candy APS 2009)

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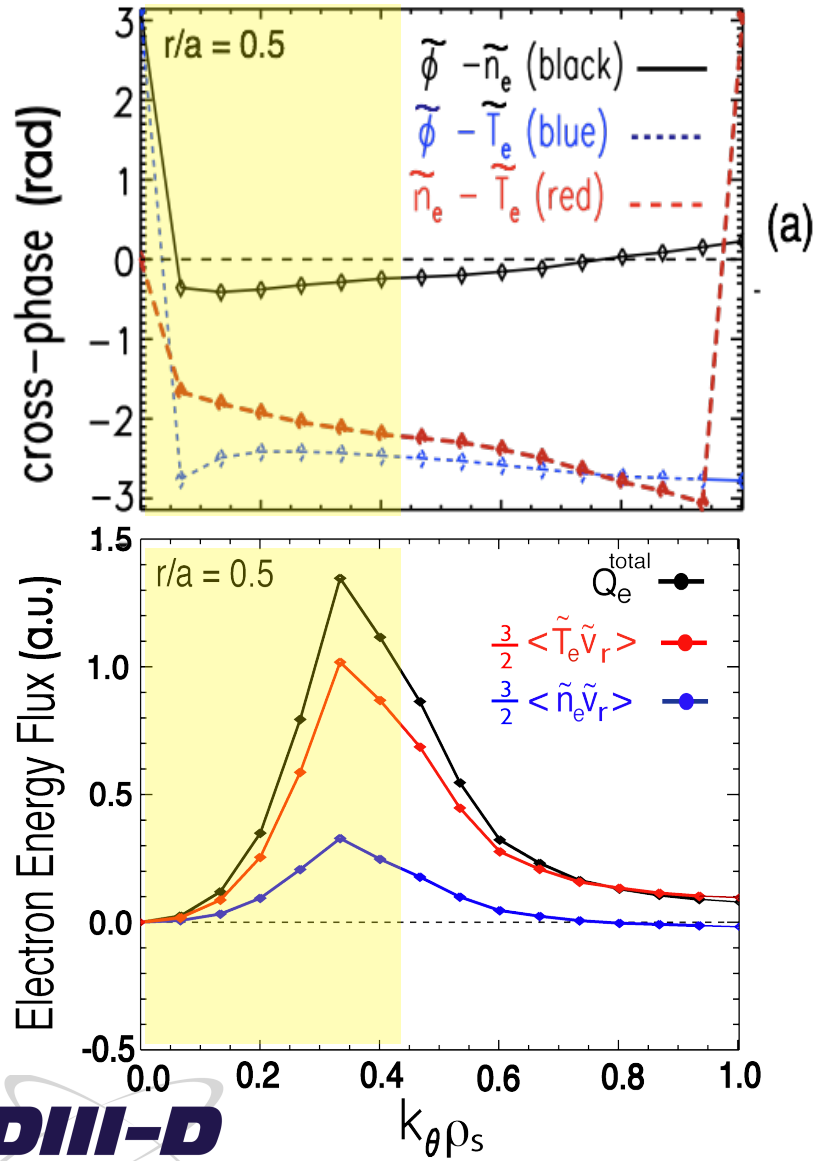
- **Measurement of the n-T cross phase angle using coupled reflectomery and CECE**
- Conclusions

Beam Heated L-mode: $\tilde{T}_e$ are Associated with ITG Turbulence, Drive Majority of Heat Transport



- **GYRO simulations in L-mode**
  ρ = 0.5 (White 2008, Holland 2009)

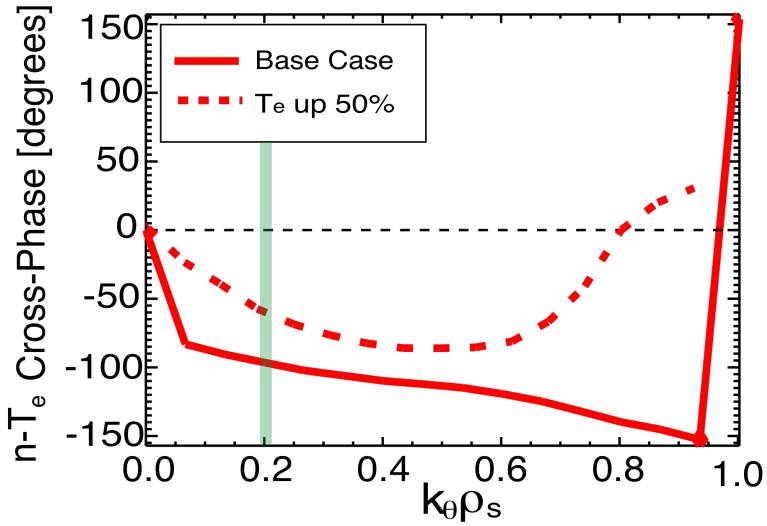
Good agreement with experiment
- fluctuation levels
- energy fluxes

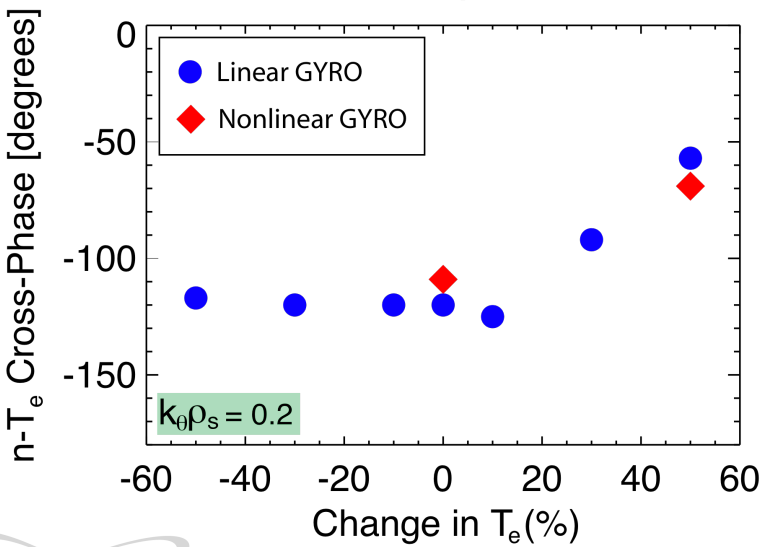
– **Nonlinear simulations show dominant ITG turbulence**

– GYRO predicts
T_e drives 80% of energy transport
n_e drives 20% of energy transport

–T-tilde amplitude as n-tilde shows **phase angle is important**

GYRO Results Indicate that Phase Angle Between Density and Electron Temperature Fluctuations Changes in ECH case





Nonlinear GYRO scans:
increase T_e as was done in experiment

GYRO shows increased TEM turbulence

GYRO: increased electron heat transport is due to changes in underlying turbulence

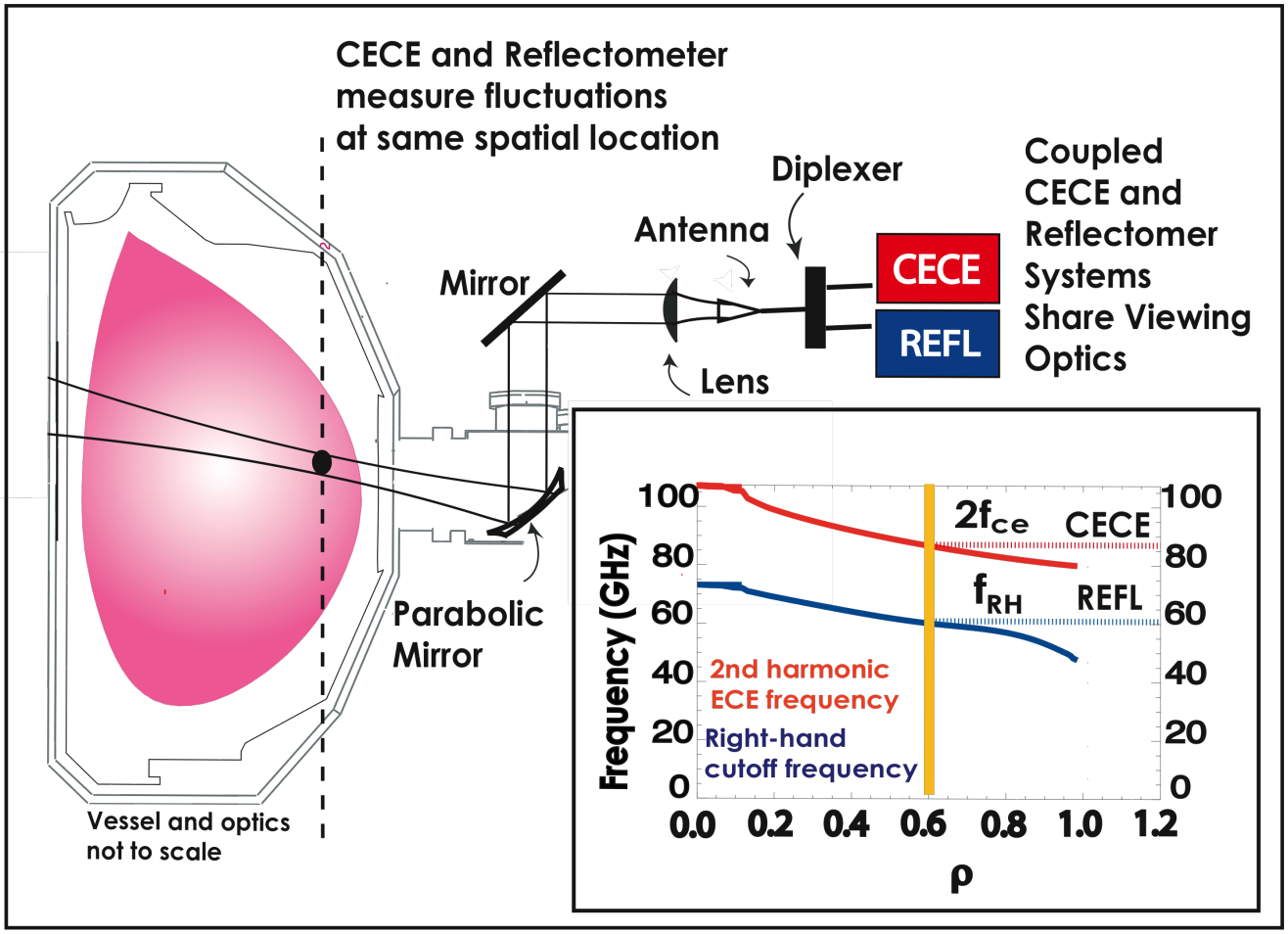
1. large increases in T_e/T_e (50-60%)
2. **Increase in n-phi phase angle,**
   no change in T-phi phase angle

$$Q^{ES} = \frac{3}{2B} k_\theta (T_0 \tilde{n}_{rms} \tilde{\phi}_{rms} |\gamma_{n\phi}| \sin(\alpha_{n\phi}) + n_0 \tilde{T}_{rms} \tilde{\phi}_{rms} |\gamma_{T\phi}| \sin(\alpha_{T\phi}))$$

Cannot measure n-phi phase angle,
But **we can measure n-T phase angle**

Expect to measure a decrease in n-T phase angle as T_e increases with 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**
  - $\Delta z \sim 3.2$ and 3.5 cm
  - $\Delta r \sim 1.0$ cm

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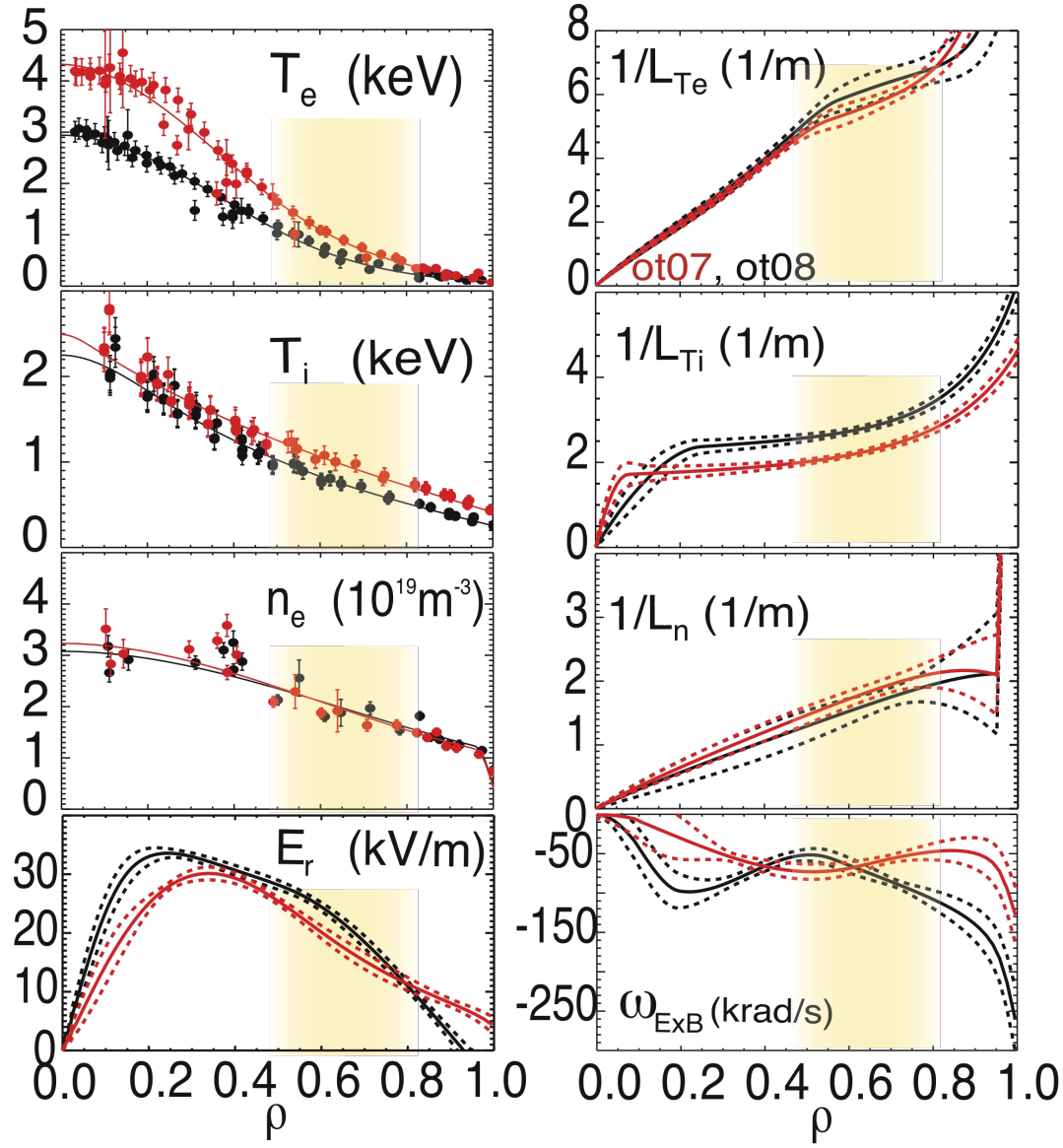
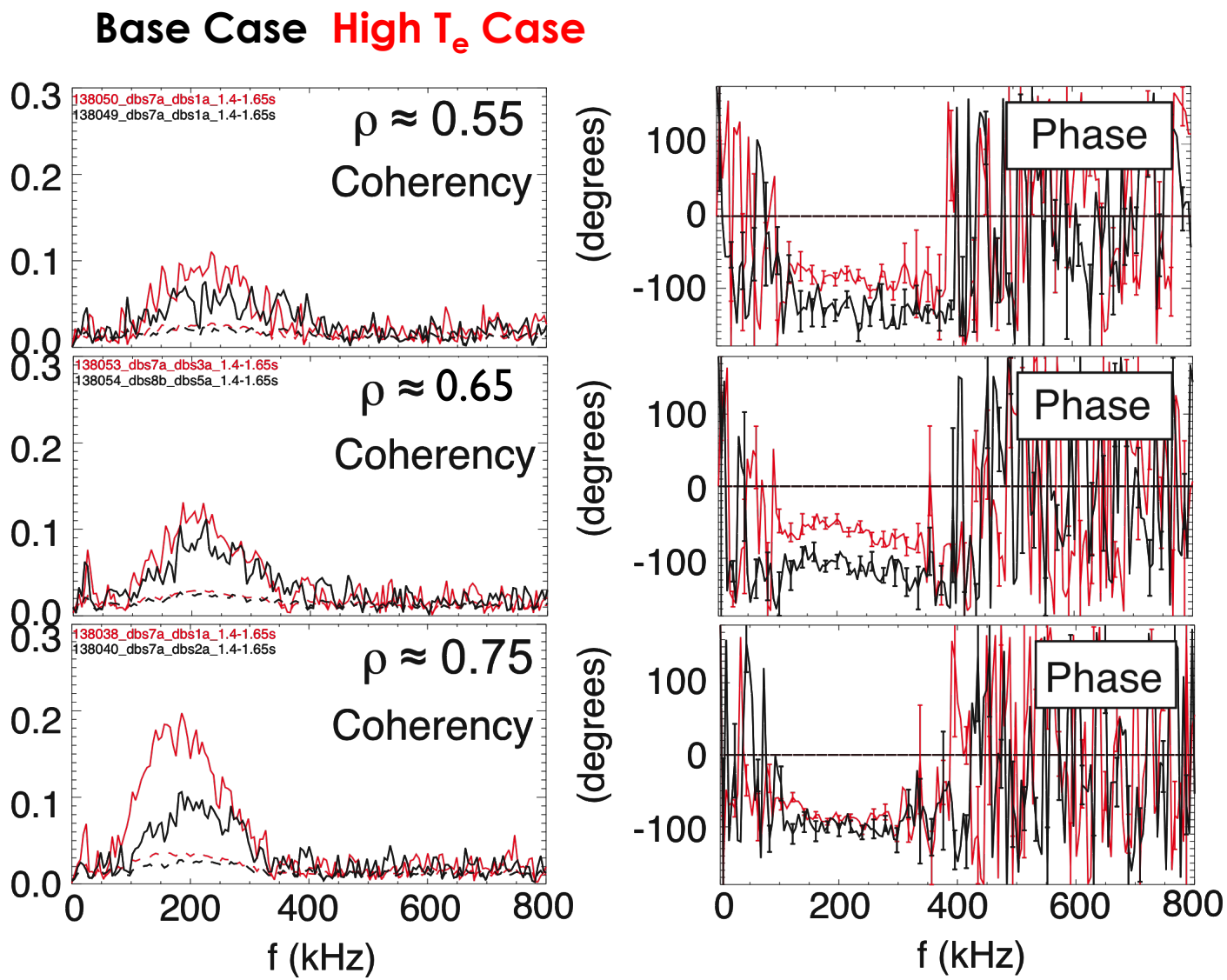
A Pair of Shots is Used to measure the phase angle and compare with GYRO Predictions

- **Cross-Phase Angle Measured During Sawtooth Free, Quasi-Stationary L-Mode Plasmas**
  - I_p = *1* MA, B_T = *2.0* T
  - upper single null
  - **First shot:** 2.5 MW co-injected neutral beam (NBI)
  - **Second shot:** NBI+ 2.4 MW ECH at r = 0.4
    → Increase T_e by 50%
  - Turbulence data averaged t = 1400-1650 ms

•Base Case (NBI only)
•High T_e Case (NBI + ECH)

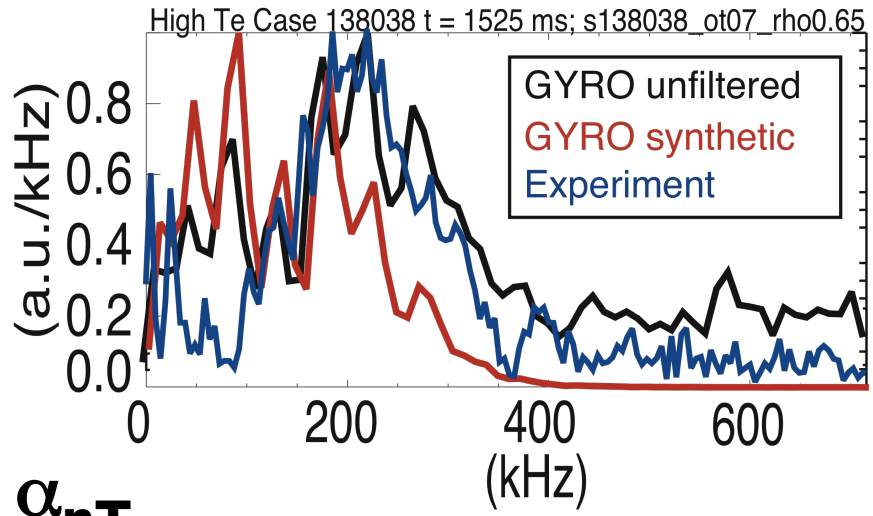


The $\tilde{n}_e$-$\tilde{T}_e$ Cross-Phase is Resolved at ρ = 0.55, 0.65 and 0.75 In the Base Case and the High T_e Case

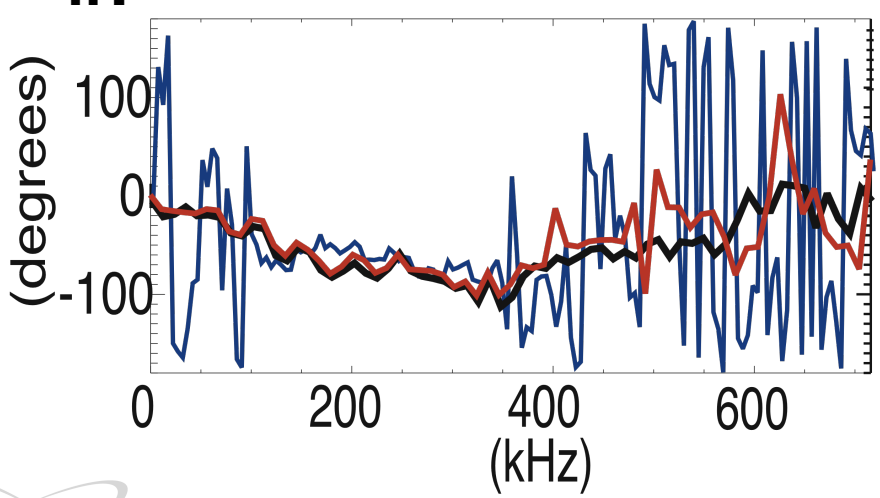


Measured n-T Phase Angle in NBI+ECH L-mode Agrees Quantitatively with Nonlinear GYRO Results

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



α_{nT}



- **Nonlinear GYRO results**
  - Local Simulation at r = 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°

- **Shape of cross-power spectrum not matched (similar for BES &CECE)**
  - **Synthetic spot-size has little effect on cross-phase**

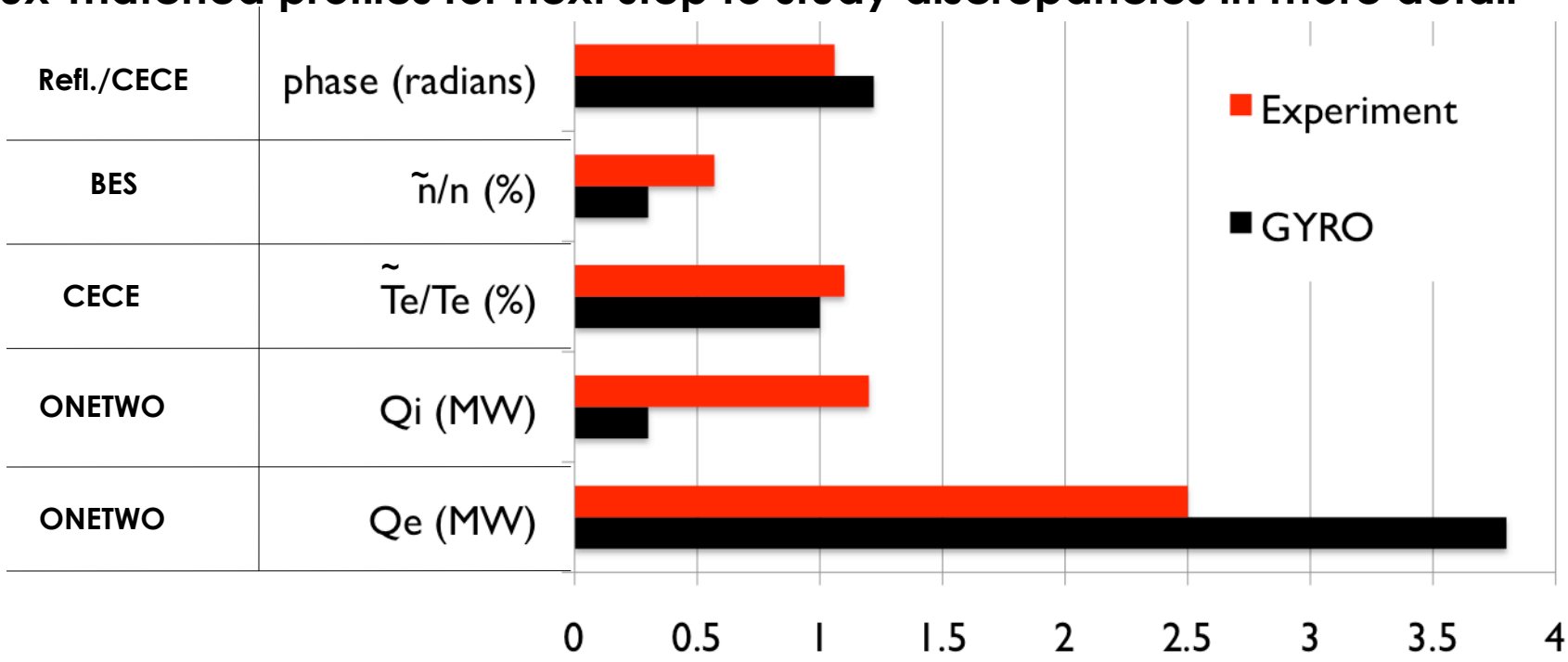
Ray-tracing used to map sample volume locations/separation

Δz = 0.3 cm Δr ~ 0.0 cm

Quantitative Comparisons With Phase Angle, Fluctuation Amplitudes, and Transport Can Test GYRO at Multiple Levels

- **Nonlinear GYRO results compared with experiment**
  - Local Simulation at r = 0.65
  - NBI + ECH sawtooth free, L-mode plasmas
  - Agreement with some quantities, disagreement with others

- **New data set will be useful for testing and validating turbulence simulations**
- **Flux-matched profiles for next step to study discrepancies in more detail**



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Experimental and Simulation Results Highlight Importance of CECE for Understanding Turbulence and Transport

- **Density and electron temperature fluctuations are similar in amplitude and spectrum in a NBI, ITG-dominant L-mode**
  - GYRO predicts 80% contribution to Q_e from T_e-tilde in L-mode

- **Core electron temperature fluctuations are strongly reduced in H-mode**

- **With ECH + NBI in L-mode, increases in heat transport correlate with increases in Te-tilde, but n-tilde stays constant**
  - Changes in TEM/ITG drive can explain these different responses
  - GYRO shows change in n-phi phase angle is important
  - GYRO n-T phase angle agrees with measurements
    - **Supports interpretation that changes Te-tilde and n-phi phase angle important for observed changes in transport**

- **CECE data are being in validation efforts to address outstanding issues and difficulties in experiment-simulation comparisons**
  - **Gyrokinetic simulations very sensitive to input profiles** (Candy PRL 2003 DIII-D, Casati PRL 2009 TORESUPRA)
  - **Flux-matched simulations (Candy APS 2009)** can be used to self-consistently approach issue of sensitivity to input profiles, resolving disagreements previously reported (White POP 2008, EC-15 2008)

Conclusions

▪**Nonlinear turbulence simulation codes are used to develop theory based transport models, which are then used to predict profiles in ITER and next-generation devices**

e.g. DEMO physics studies use GLF23 and Weiland transport models to predict profiles. These are turbulence-transport based transport models.

Measurements of electron temperature fluctuations and new measurements of the phase angle are combined with density fluctuation measurements

- **Used to constrain nonlinear turbulence simulations**
- **Contribute to validation efforts**
- **Improve confidence in transport model predictions**

▪**Important role of CECE measurements in validation efforts at DIII-D highlights how this community via history of well-established EC theory and well-developed EC measurement techniques is important to increased understanding of physics of turbulence-transport**