Measurement of Cross-Phase Angle Between Turbulent $\tilde{n}$ and $\tilde{T}_e$ and Comparison with Nonlinear GYRO Predictions

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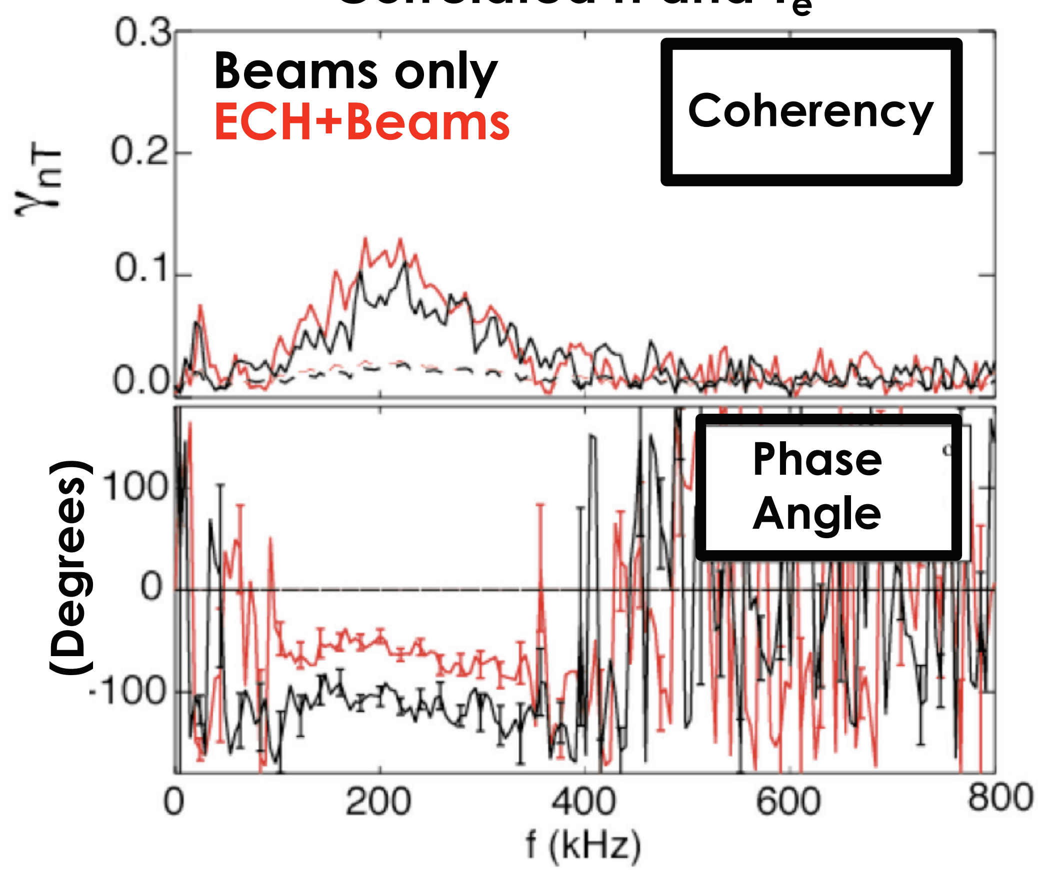
Correlated $\tilde{n}$ and $\tilde{T}_e$



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$\tilde{n}_e$-$\tilde{T}_e$ Cross-Phase Angle has been Measured and is in Good Agreement with Nonlinear Gyrokinetic Simulations

•Nonlinear GYRO simulations used to design experiments, study changes in cross-phase angle between $\tilde{n}_e$ and $\tilde{T}_e$

•$\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle has been measured successfully using combined Correlation Electron Cyclotron Emission (CECE) and Reflectometry Diagnostics

•Density and electron temperature fluctuations are out of phase, But become more in phase as temperature is increased

•GYRO is used to model experimental discharges to qualitatively and quantitatively compare with trend in $\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle

Outline

- $\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle in theory and simulations
- $\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle via Reflectometry and CECE
- Experimental Results
- Comparison with local, nonlinear GYRO simulations
- Conclusions and Future Work

Cross-Phase Angle is Important for Understanding Physics of Turbulence-Driven Transport

- Turbulence-driven transport is believed to be well-described by models of drift-wave instabilities

- Direct comparisons between experiment and nonlinear turbulence simulations are possible

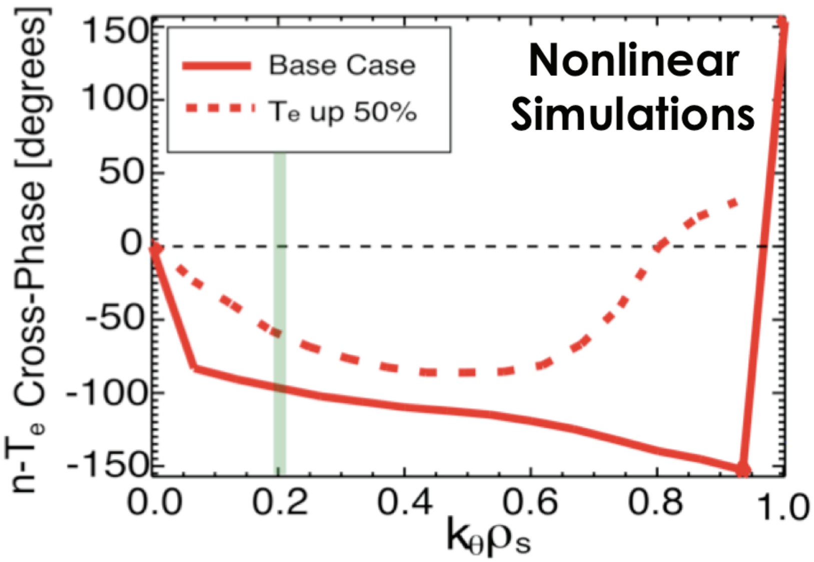
- Electrostatic electron energy flux expression expanded to show dependence on cross-phase angles and fluctuation levels

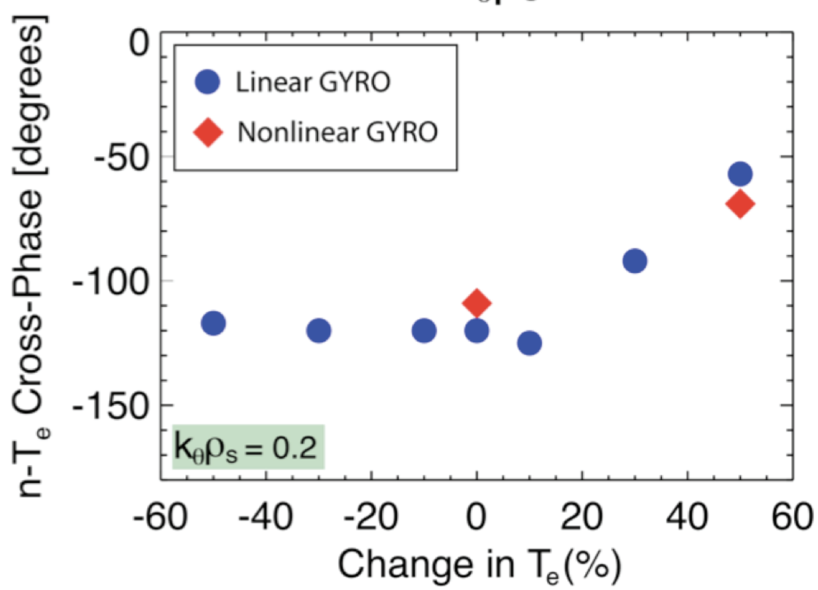
$$Q^{ES} = \frac{3}{2B} n_0 T_0 k_\theta (\tilde{n}_{rms} \tilde{\phi}_{rms} |\gamma_{n\phi}| \sin(\alpha_{n\phi}) + \tilde{T}_{rms} \tilde{\phi}_{rms} |\gamma_{T\phi}| \sin(\alpha_{T\phi}))$$

- Finite phase differences arise due to dissipation of parallel electron motion collisions and magnetic trapping effects

- Several types of instabilities can 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 ($k_\theta \rho_s > 2$)

GYRO: Predict a Change in $\tilde{n}_e$-$\tilde{T}_e$ Phase Angle Using Nonlinear Simulations of Experimentally Accessible Conditions





•Nonlinear *GYRO runs* are performed *before* an experiment to aid in design

1)Base case:
Beam heated L-Mode DIII-D plasma parameters,
ITG-dominant

2) High T_e case:
L-mode plasma with 50% increase in T_e (a/L_{Te} fixed);
electron mode drive increases at low-k

•Qualitatively compare predicted trend with experiment

•Perform post-experiment GYRO simulations to quantitatively compare with experiment

Outline

- $\tilde{n}$-$\tilde{T}$ cross-phase angle in theory and simulations
- **$\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle via Reflectometry and CECE**
- Experimental Results
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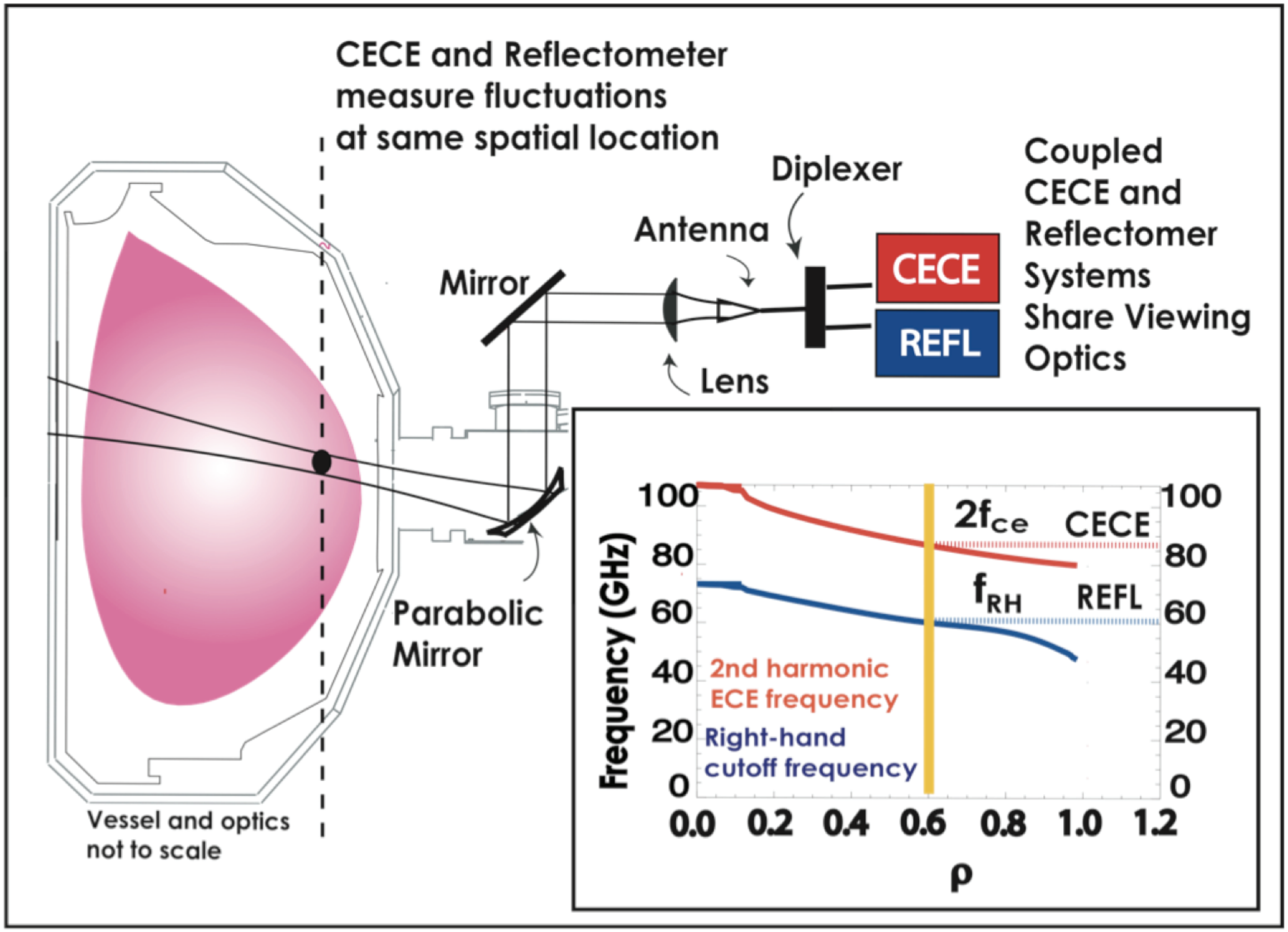
Coupled Correlation Electron Cyclotron Emission (CECE) and Reflectometry for Cross-Phase Angle Measurement



X-mode Correlation ECE radiometer

- Low-k $\tilde{T}_e$ ($k_\theta \rho_s < 0.3$)
- **Spot-Size**
  - $\Delta z \sim 3.2$ cm
  - $\Delta r \sim 1.0$ cm

X-Mode quadrature Reflectometer

- Low-k $\tilde{n}_e$ ($k_\theta \rho_s < 0.5$)
- **Spot-size**
  - $\Delta z \sim 3.5$ cm
  - $\Delta r \sim 1.0$ cm

ρ_s =2-3 mm in plasmas of interest

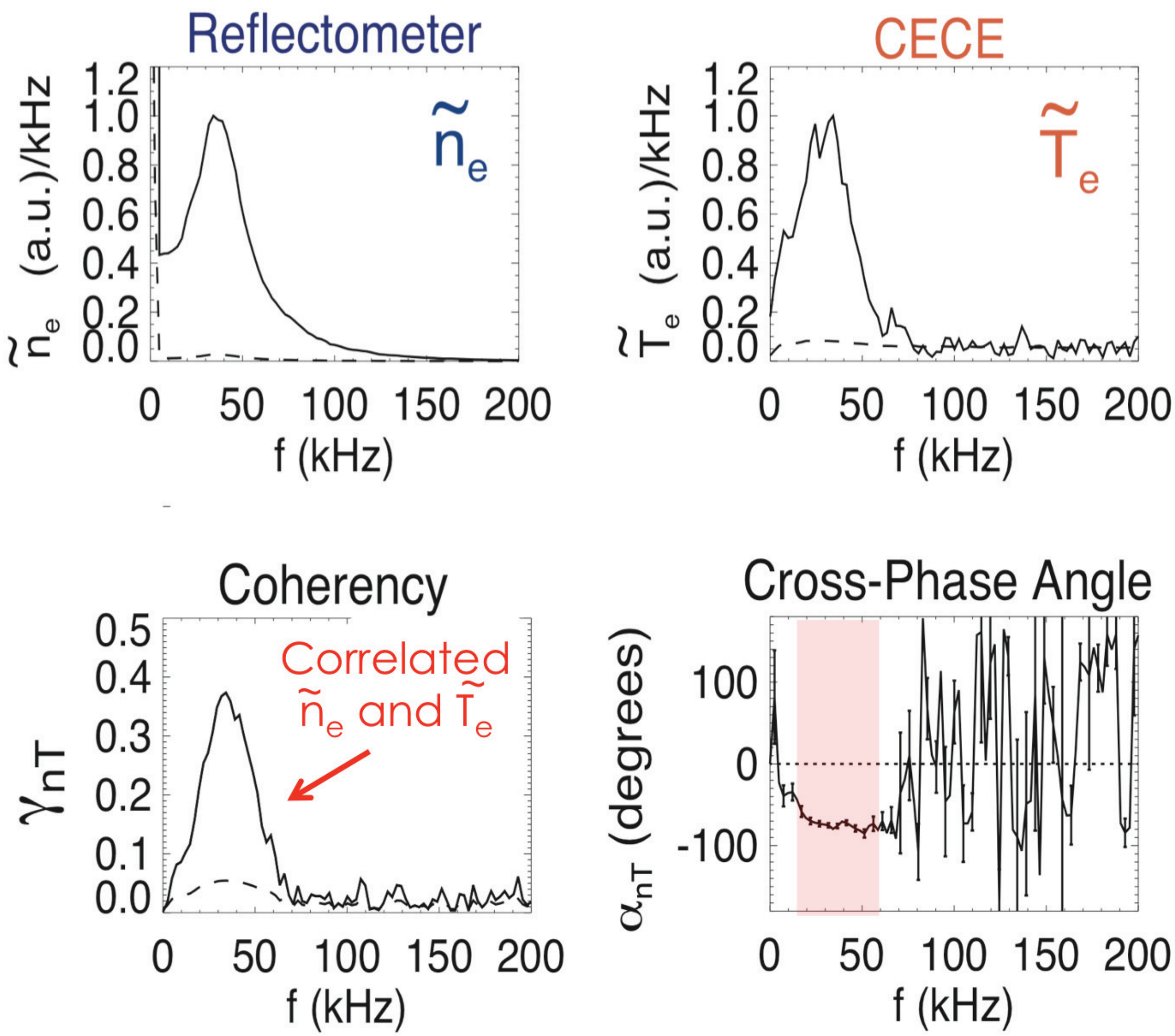
Coupled CECE and Reflectometry: Standard Spectral Correlation Analysis is Used to Measure α_{nT}

- **Example of correlated $\tilde{n}$ and $\tilde{T}_e$ in core, $\rho = 0.6$**
- **Shot 133626, Ohmic heating and ECH (no beams)**
- **Turbulence data averaged *t = 1600-1900* ms**

$$G_{nT} = \langle S^{*}_{REFL} S_{ECE} \rangle$$

$$\alpha_{nT} = \arctan(Im(G_{nT})/Re(G_{nT}))$$

- ***Density fluctuation signal is taken as reference***



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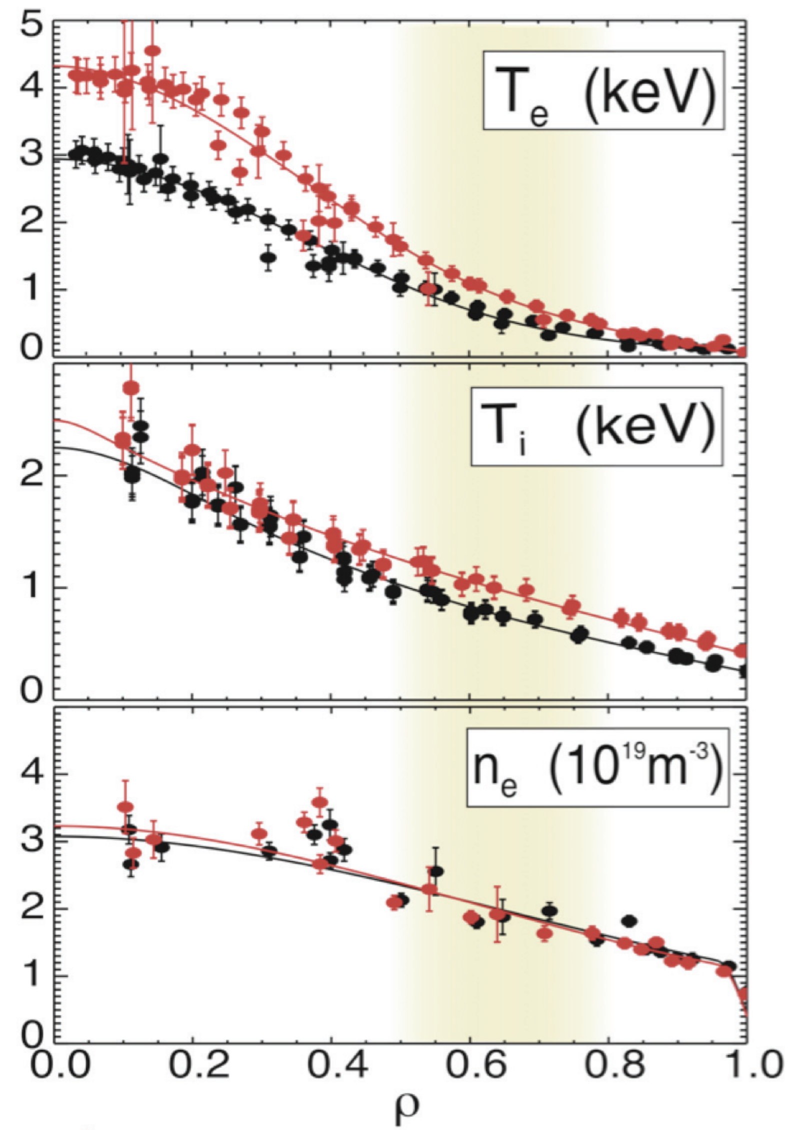
n_e-T_e Cross-Phase Angle Measured During Sawtooth Free, Quasi-Stationary L-Mode Plasmas

Compare *predicted change in phase angle* with experiments

- **Base Case (NBI only)**
  - I_p = 1 MA, B_T = 2.0 T
  - upper single null
  - Early 2.5 MW co-injected NBI
- **High T_e Case (NBI + ECH)**
  - Add 2.4 MW ECH at $\rho = 0.4$

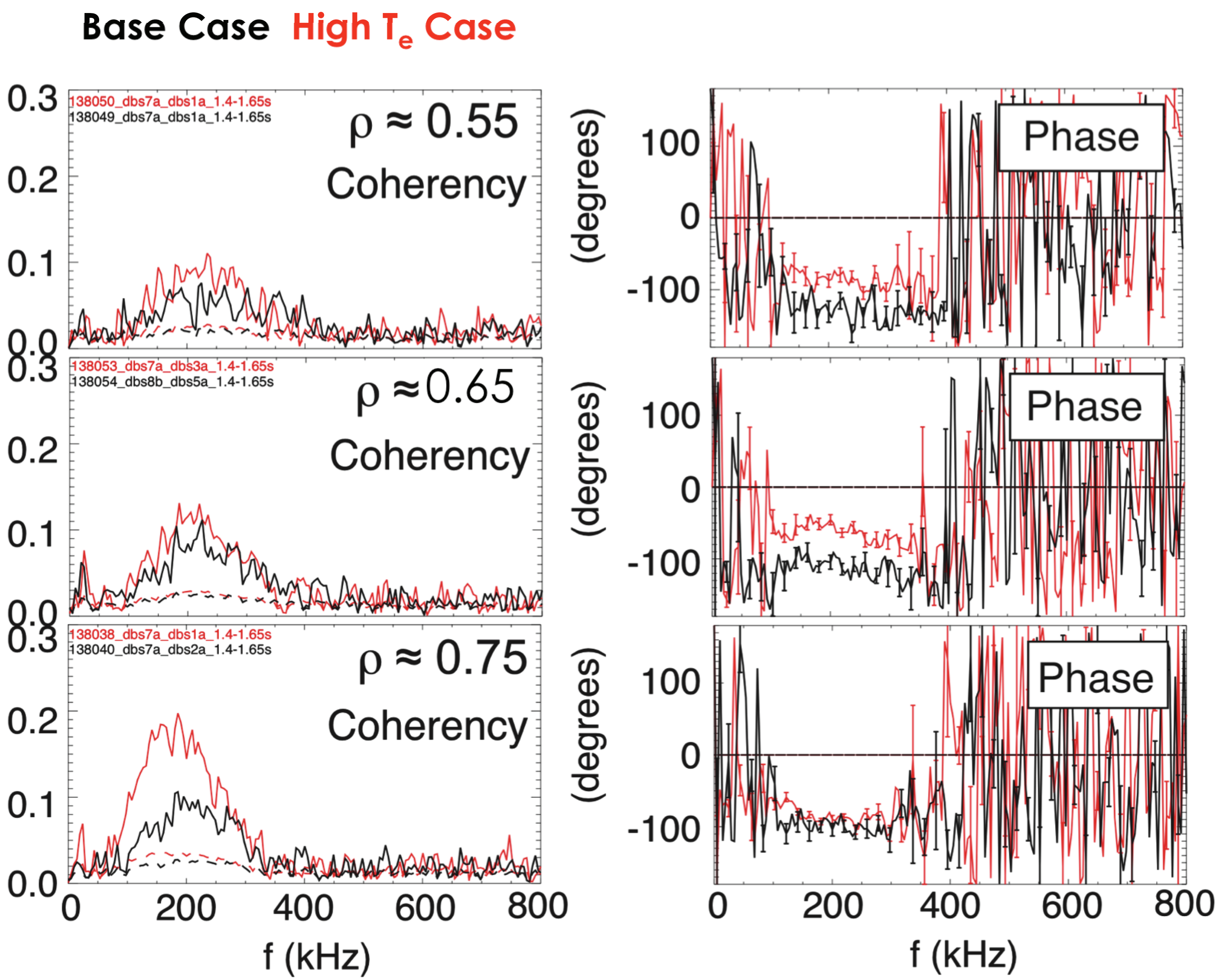
Many turbulence diagnostics deployed:

$\tilde{n}_e$-$\tilde{T}_e$ Phase Angle
Low-k $\tilde{n}/n$ (BES)
Low-k $\tilde{T}_e/T_e$ (CECE)
Intermediate-k $\tilde{n}$ (Doppler Backscattering)
High-k $\tilde{n}$ (Backscattering)

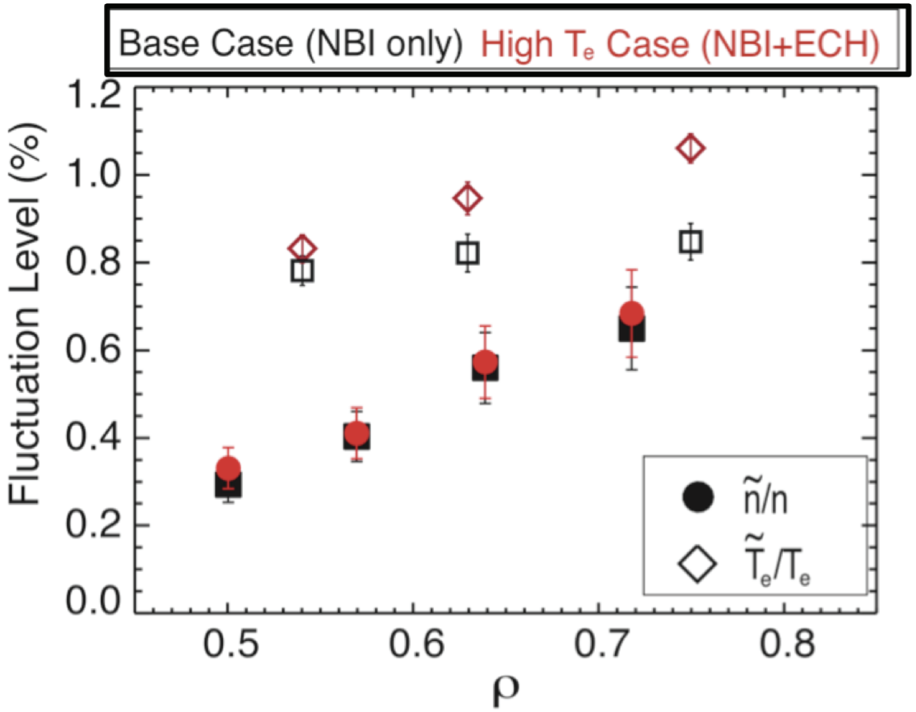


Turbulence measured $0.5 < \rho < 0.8$

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



Turbulence Across Wide Range of ITG/TEM/ETG Scales – Largest Changes seen in low-k $\tilde{T}_e/T_e$ and Phase Angle



Measured Changes in Low-k (ITG/TEM scale) Turbulence

- **CECE:**

Increase in low-k $\tilde{T}_e/T_e$ of 10-30%

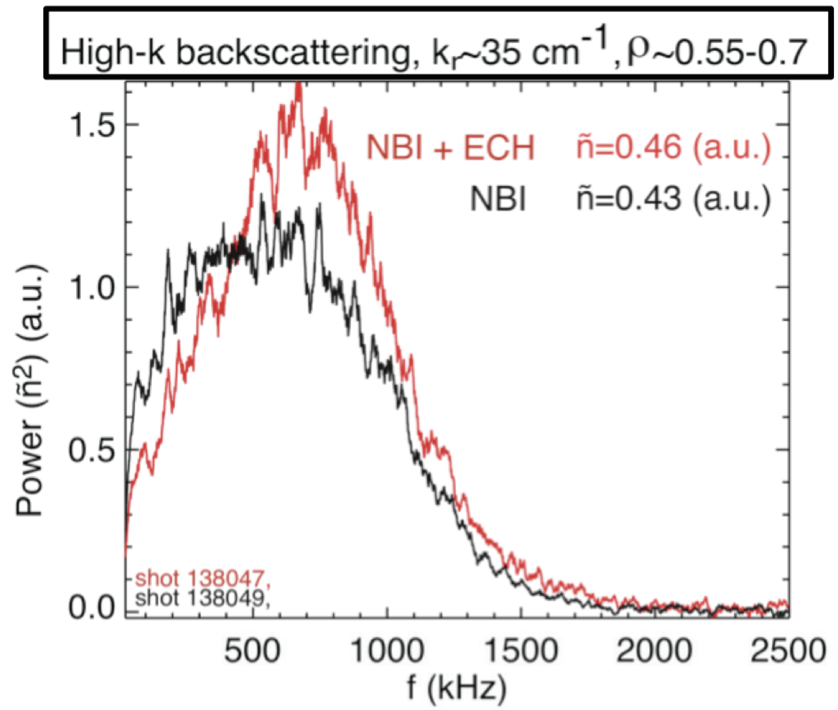
- **BES:**

Increase in low-k $\tilde{n}/n$ of 5-10%

Measured Changes in High-k (ETG scale) Turbulence

- **Backscattering:**

Increase in high-k $\tilde{n}$ of 6%



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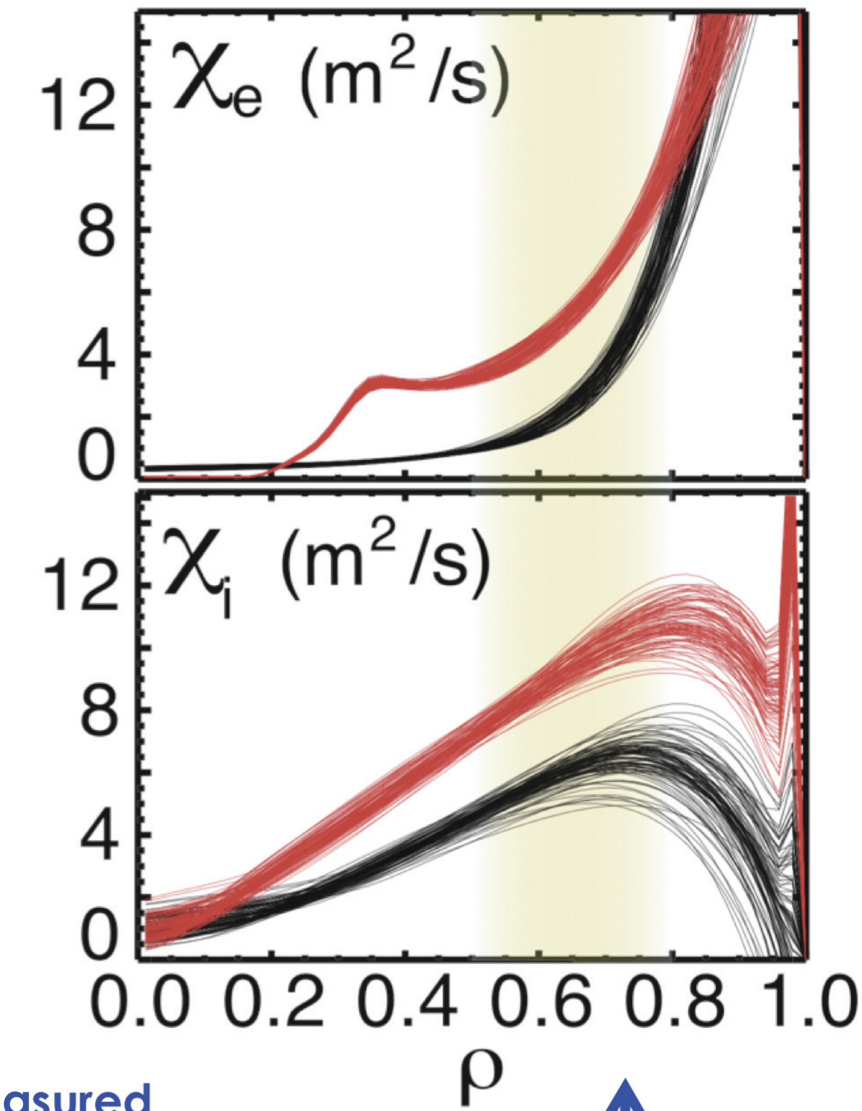
Increase in Transport and Linear Growth Rate Observed in High T_e case

- With ECH:
  - ONTEWO: Transport increases
  - Uncertainty is estimated using a Monte-Carlo Analysis
  - Electron mode linear growth rate Increases

    ITG mode growth rate decreases

    Growth rate of most unstable mode increases



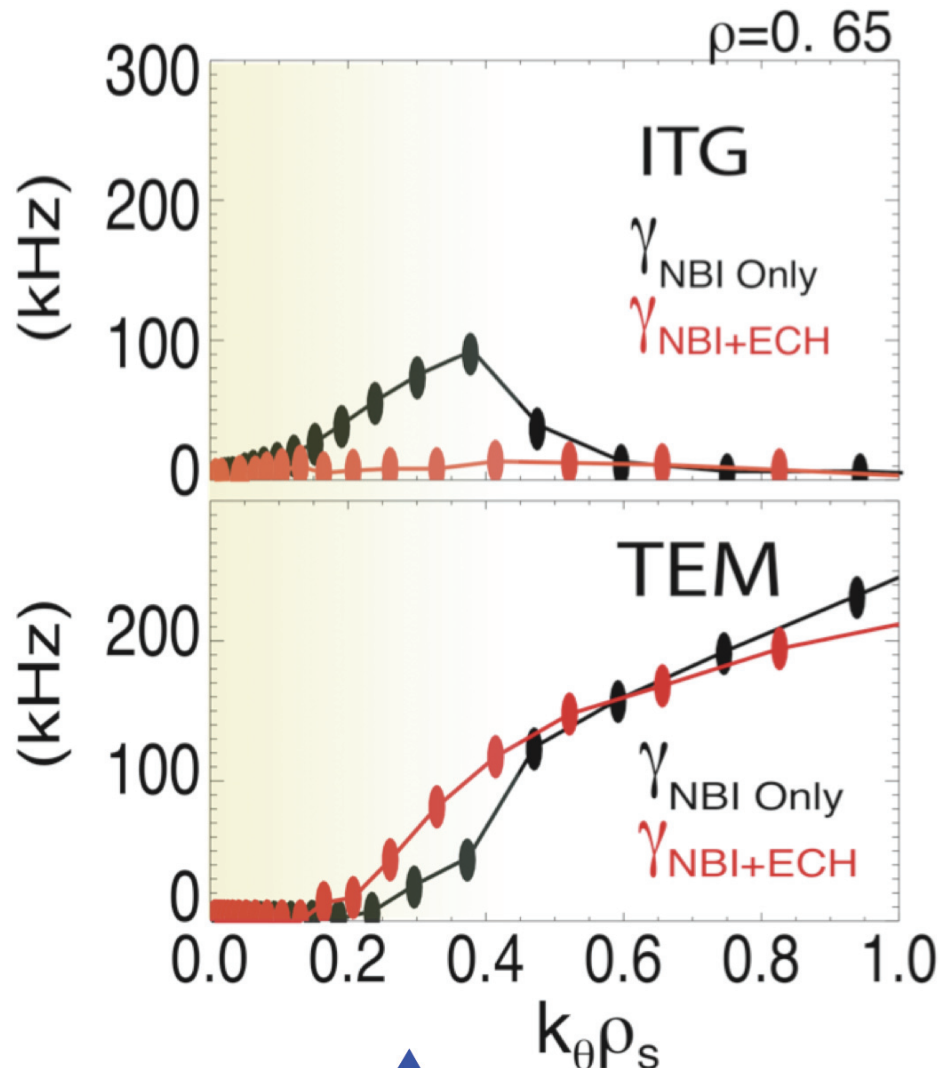
Turbulence measured
$0.5 < \rho < 0.8$

Increase in Transport and Linear Growth Rate Observed in High T_e case

- **With ECH:**
  - Transport increases
  - Uncertainty is estimated using a Monte-Carlo Analysis
  - **TGLF:**
    Electron mode linear growth rate Increases

    ITG mode growth rate decreases

    Growth rate of most unstable mode increases



Phase Angle measured at Low-k

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- $\tilde{n}$-$\tilde{T}$ cross-phase angle in theory and simulations
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Compare Measured $\tilde{n}_e$-$\tilde{T}_e$ cross-phase angle With Results From Local, Nonlinear GYRO Simulations

– GYRO is an initial value, Eulerian (Continuum) 5-D gyrokinetic transport code [Candy and Waltz PRL 91, 045001 (2003)]

– **Local simulations include real geometry, drift-kinetic electrons, e-i pitch-angle collisions, $(M_i/m_e)^{1/2} = 40$, electromagnetic effects, dynamic Carbon ions and equilibrium ExB flow**

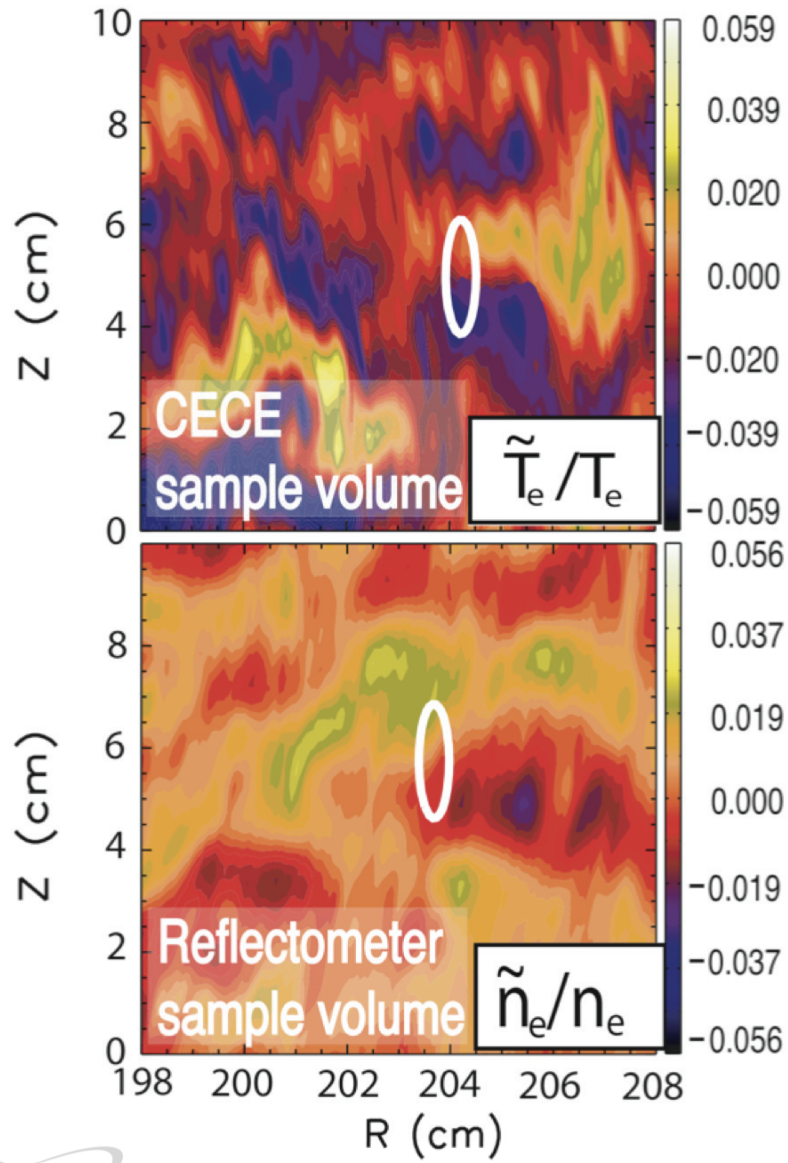
– Take experimental profiles (T_e, T_i, n_e, E_r) as input

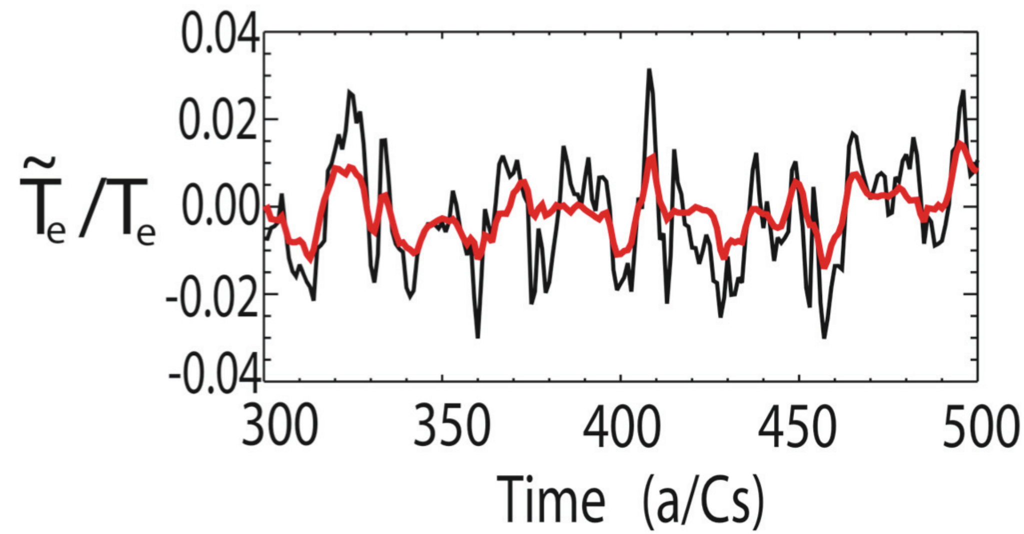
  – Need quantitative comparisons (post-experiment) in addition to qualitative trend comparisons (pre-experiment)

  – Difficult to obtain convergence for Base Case (138040)

  – **High T_e Case Simulation has been completed (138038)**

Synthetic Diagnostics Used to Compare with Cross-Phase Angle and Two-Field Fluctuation Level Measurements



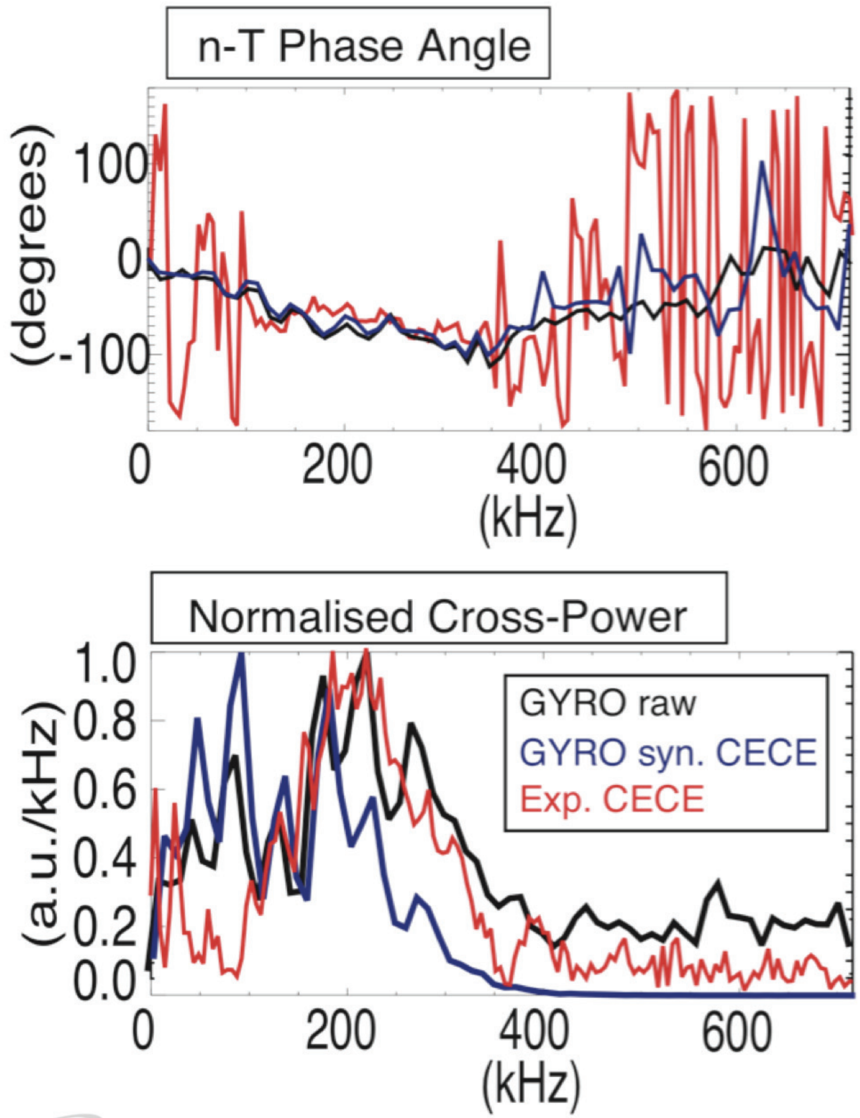


•Spatial Filter in synthetic diagnostics models sample volume size

•Fluctuation levels and spectral shape depend on details synthetic sample volume

[Holland, POP, 2009]

In Contrast to Fluctuation Levels and Spectra, the Cross-Phase Angle Is Found to Be Insensitive to Sample Volume Size



- **Nonlinear GYRO results**
  - Local Simulation at $\rho = 0.65$
  - Exp. High T_e Case, #138038

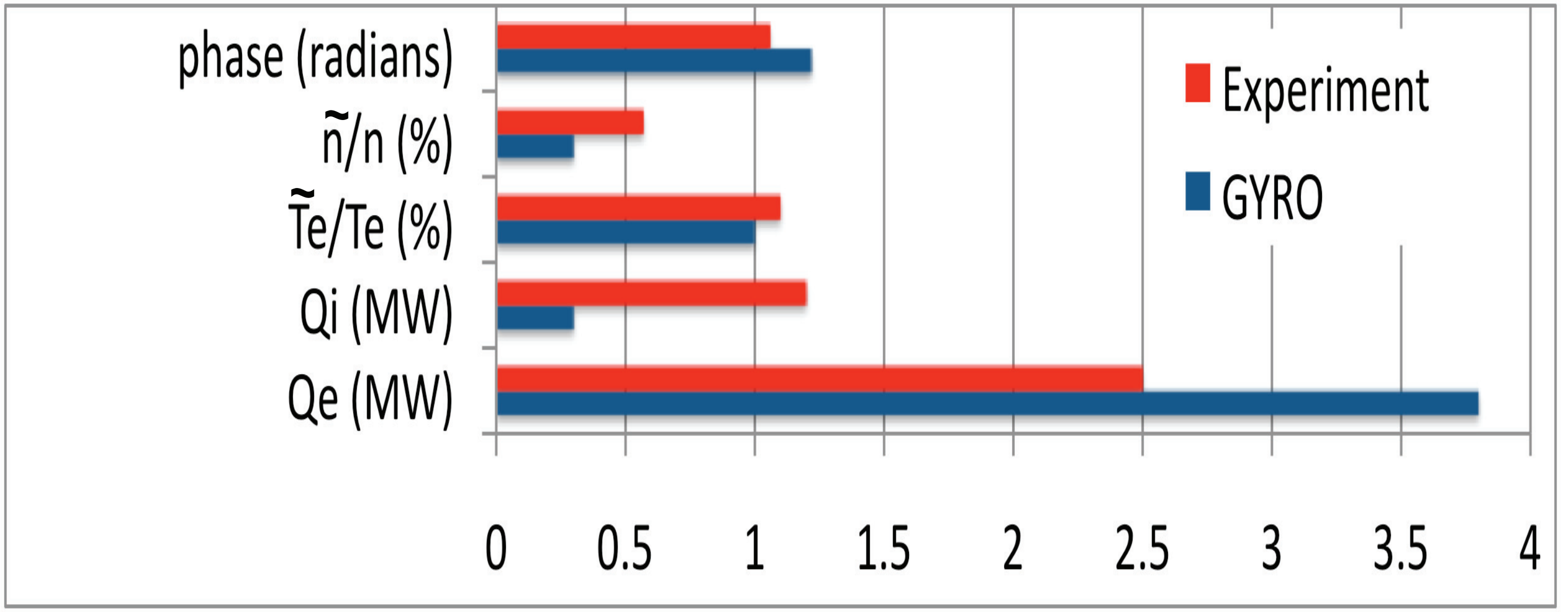
GYRO raw Phase	**= -70°+-2°**
GYRO syn. Phase	**= -71°+-1°**
Exp. n-T phase	**= -61°+-12°**

- **Synthetic spot-size has little effect on n-T cross-phase**

- **Higher frequencies in n-T cross-power spectrum are filtered by sample volume size**

New Experiment Quantitatively Tests GYRO at Multiple Levels

- **Nonlinear GYRO results (post-experiment)**
  - Local Simulation at $\rho = 0.65$
  - Exp. High T_e Case, #138038
- **Quantitative comparisons between phase angle, fluctuation levels and power flows are performed**
  - **Measured Phase Angle is in good agreement with GYRO results**



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•$\tilde{n}$-$\tilde{T}_e$ cross-phase angle has been measured successfully using combined Correlation Electron Cyclotron Emission (CECE) and Reflectometry Diagnostics

•Density and electron temperature fluctuations are out of phase: Predicted trend from GYRO is qualitatively consistent with measured change in α_{nT} at ρ = 0.55 and 0.65, but not at ρ = 0.75

•Preliminary quantitative agreement between measured α_{nT} and GYRO in the High T_e Case is very good, but Base Case simulation not yet completed

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Ongoing Work at DIII-D Focuses on Multi-Field Multi-Scale Fluctuation Measurements for Rigourous Code Comparisons

- **University of Wisconsin:** Measurements of $\tilde{T}_i$ will provide important new constraint on models of ITG transport **(I.U. UzunKaymak– Poster JP8.00116)**

- **UCLA:** Multi-channel Intermediate-k Doppler Backscattering for GAM/Zonal Flow studies **(J. C. Hillesheim – Contributed Oral CO4.00008)**

- **UCSD:** Kappa Dependence of Transport and Turbulence (**Holland –Poster TP8.00012)**

- **GA:** a/L_T Turbulence Drive Modification and Multi-field, Multi-Scale Turbulence Response (**DeBoo-Invited Talk KI3.00003)**

- **GA Theory :** Gyrokinetic transport solver TGYRO used to predict kinetic plasma profiles consistent with energy and particle fluxes in the DIII-D tokamak **(J. Candy - Invited Talk DI3.00002)**

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

Ongoing work with Quantitative GYRO comparisons: Complete Simulations for the Base Case and High T_e Case

- **Only High T_e Case has been simulated, Base Case is difficult**
  - Sensitivity scans/reduced models do not recover low-k turbulence
  - Do not achieve convergence, even including $k_\theta\rho_s < 3$
  - Impact of high-k on transport using ITG/TEM – ETG runs

- **Use TGYRO (TGLF+NEO) power matching profiles as input**

Self-consistently captures effects of sensitivity to input profiles when gradients are near threshold
[See Candy Invited Talk, this conference]