ETG Scale Turbulence and Transport in the DIII–D Tokamak EX/P4-37

T.L. Rhodes*

Presented by E.J. Doyle*

for

W.A. Peebles,* M.A. Van Zeeland,† J.S. deGrassie,† R.V. Bravenec,‡ K.H. Burrell,† G.R. McKee,§ J. Lohr,† C.C. Petty,† X.V. Nguyen,* E.J. Doyle,* C.M. Greenfield,† L. Zeng,* and G. Wang*

*University of California-Los Angeles, Los Angeles, California.
†General Atomics, San Diego, California.
‡University of Texas, Austin, Texas.
§University of Wisconsin. Madison, Wisconsin.

Presented at the
21st IAEA Fusion Energy Conference
Chengdu, China

October 16–21, 2006

DIII–D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

New results since FEC 2004

- Observed correlation of increased high k (~35 cm^{-1}, $k_{\perp}\rho_i$=4-10) turbulence with increased electron heat transport.
  - Consistent with high k turbulence driving at least part of electron heat transport.
- Determined that high k (~35 cm^{-1}) is not a short λ remnant or tail of low k (~1 cm^{-1}) ITG/TEM type modes
- Differing effect of electric field shear on low and high k observed:
  - Low k fluctuation behavior consistent with reduction due to E_r shear
  - High k apparently not affected by E_r shear
- Relative levels of high and low k fluctuation levels comparable to non-linear turbulence simulation (GYRO) results

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

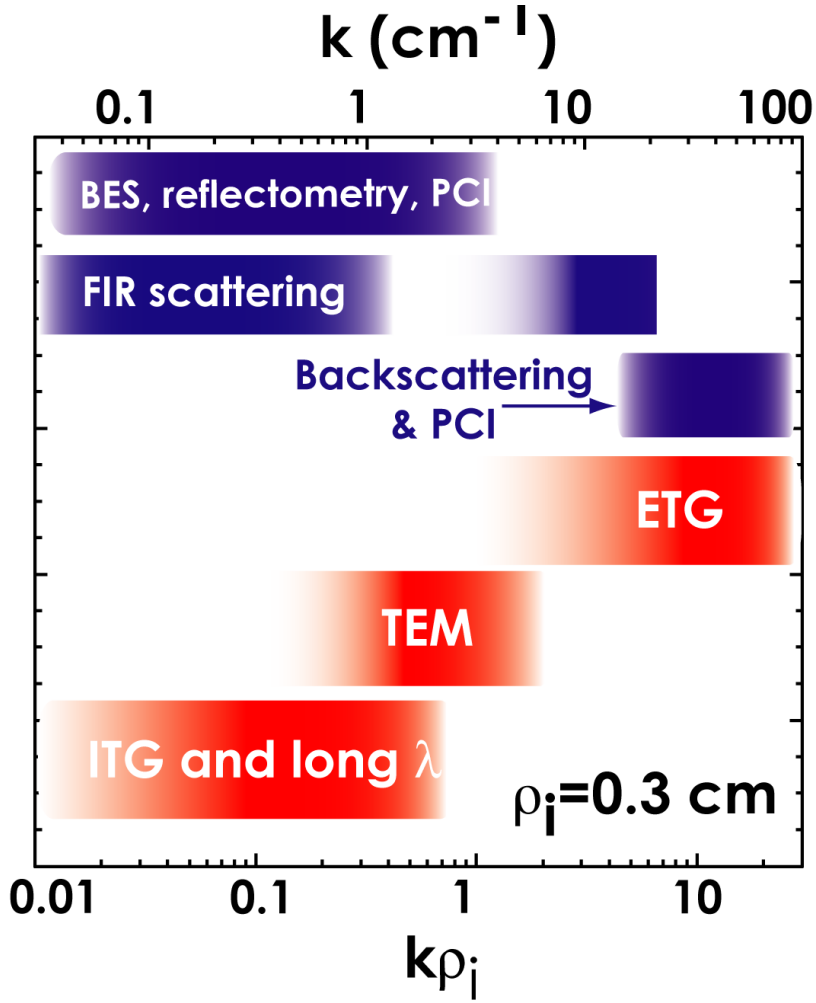
Recent theoretical work indicates high k turbulence may contribute to anomalous electron heat transport

- Source of electron thermal transport often not well understood.
  - Ion temperature gradient (ITG) ($k_\perp \rho_i$~0-1),
  - Trapped electron drive (TEM) ($k_\perp \rho_i$~0-2)
  - Electron temperature gradient (ETG) ($k_\perp \rho_i$ >2)
- High frequency, high *k* modes predicted to drive varying levels of electron heat transport.
  - Dorland, et al., PRL (2000), Jenko and Dorland, PRL (2002), Labit and Ottaviani, PoP (2003), Li and Kishimoto, PoP (2004), Horton, et al., PoP (2004), Lin, et al., PoP(2005), Gürcan and Diamond, PoP (2004),
  - Predictions range from small to significant depending upon model and plasma.
  - Motivates experimental measurements
    - DIII-D, NSTX, FT-2, Tore-Supra

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Broad Wavenumber (~0-35 cm^{-1}) ñ Measurements Provide New, More Complete Picture of Turbulence Behavior on DIII-D



- **Ultimate goal: test and validate turbulence simulations via experimental comparison.**
  - Compare turbulence behavior over large k range.
- **BES, FIR, PCI, reflectometry, magnetics, high k backscatter.**
  - Broad k range:
    - ~ 0-40 cm^{-1}, $k_\perp \rho_i$~0-10
- **Important to measure broad k range due to potential interaction of various k ranges + allows closer comparison to theory.**

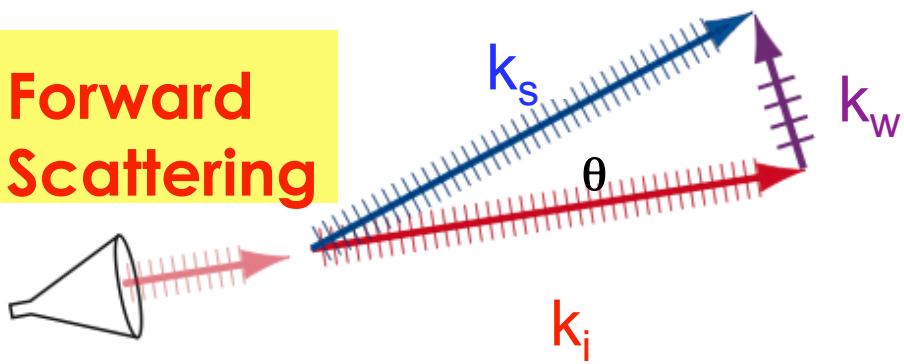
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

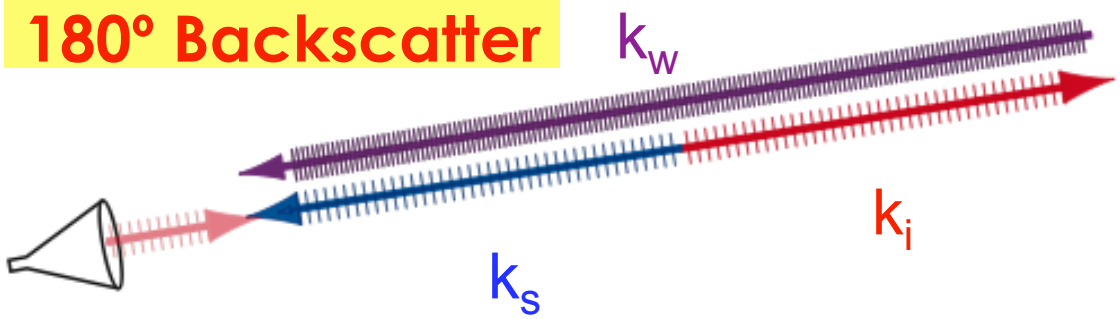
Approach: Collective Thomson scattering is well-suited to study long-to-short wavelength turbulence

Can cover large range of k's depending upon geometry and probe frequency used.

Forward Scattering



180° Backscatter



Momentum matching gives

$\vec{k}_i + \vec{k}_w = \vec{k}_s$

Energy conservation gives

$\omega_i + \omega_w = \omega_s$ i.e scattered radiation Doppler shifted.

Bragg Law:

For $k_i \sim k_s$, can show that

$$\mathbf{k_w = 2k_i \sin(\theta/2)}$$

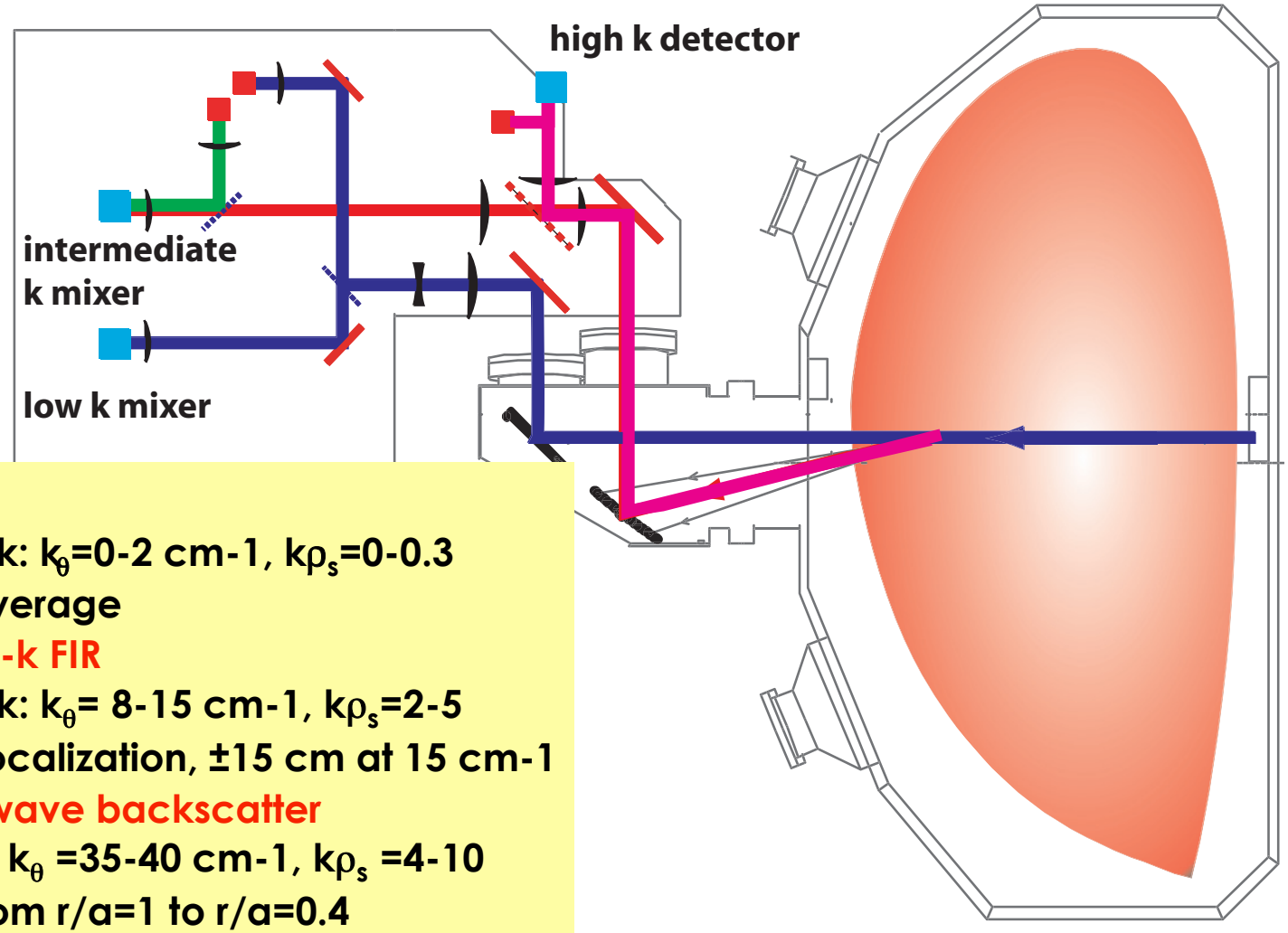
Where θ is scattering angle

FIR scattering is dominantly k_θ
High k backscattering is dominantly k_r

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Simultaneous data from low to high k using FIR and mm wave scattering diagnostics

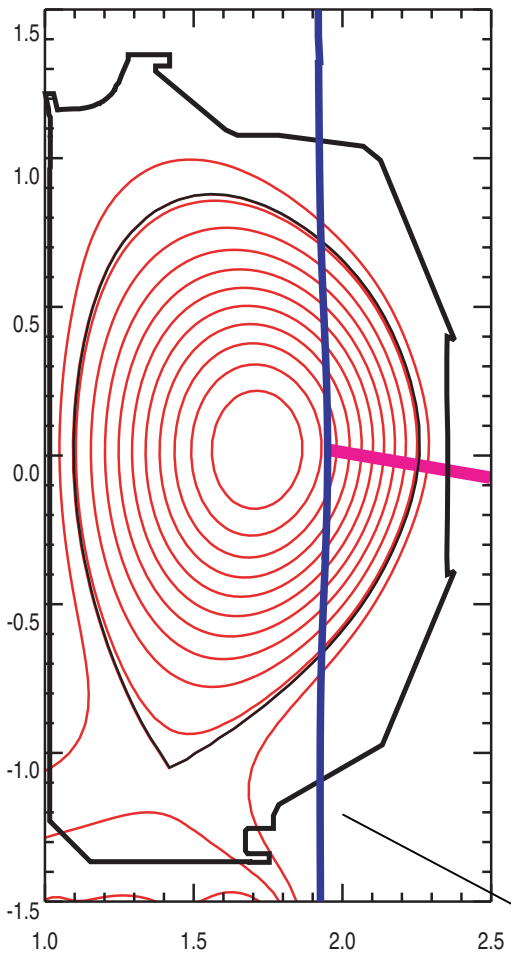


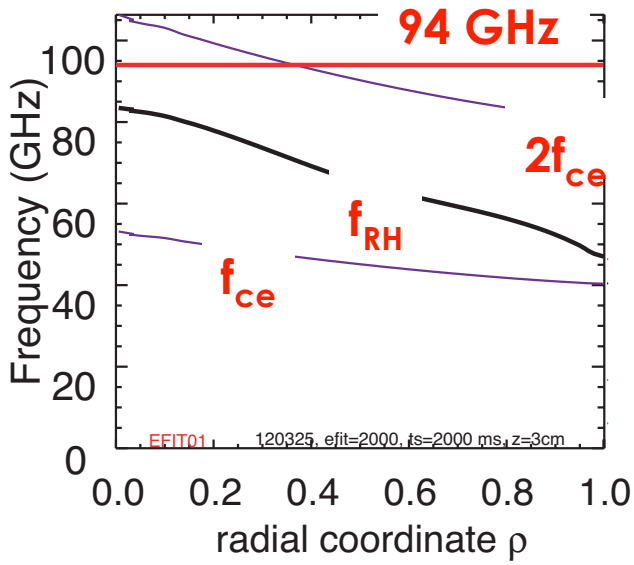
- Low-k FIR
  - Poloidal k: k_θ=0-2 cm-1, $k\rho_s$=0-0.3
  - Chord average
- Intermediate-k FIR
  - Poloidal k: k_θ= 8-15 cm-1, $k\rho_s$=2-5
  - Spatial localization, ±15 cm at 15 cm-1
- High-k mm-wave backscatter
  - Radial k: k_θ =35-40 cm-1, $k\rho_s$ =4-10
  - Chord from r/a=1 to r/a=0.4

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

High k system measures k_r along a chord





High k signal from chord, typically ρ>0.4

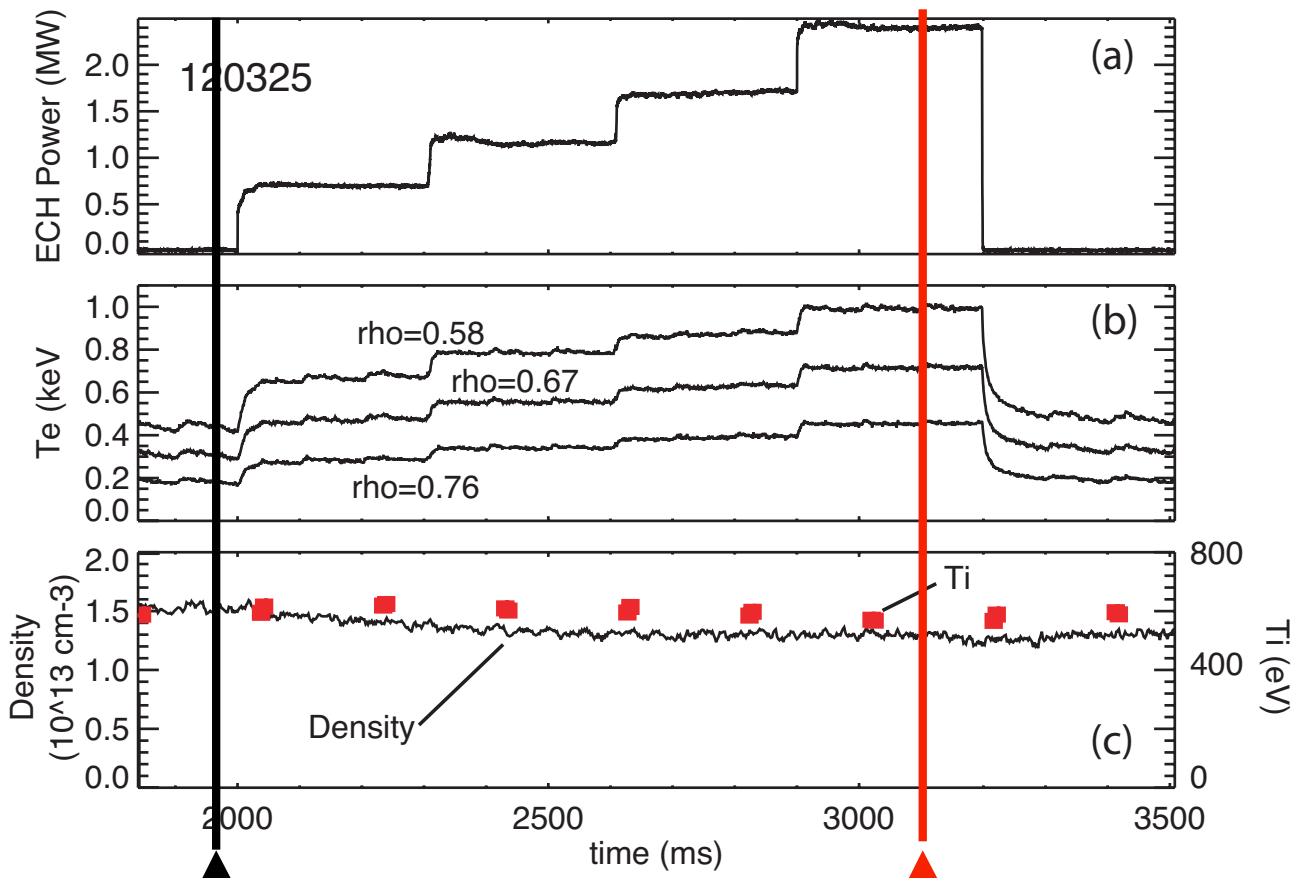
94 GHz, ECE resonance

- **k is dominated by radial k_r with small poloidal k_θ component**
  - e.g., $k_r \approx 34.95$ cm^{-1} and $k_\theta \approx 1.2$ cm^{-1} for k=35 cm^{-1}.
- **Wavenumber resolution $\Delta k \approx \pm 0.2$ cm^{-1}.**
- **Frequency is well above cutoff**
  - Refraction small, <1°
- **Refractive index reduces probed k 35-40 cm^{-1} for plasmas discussed here.**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Electron Cyclotron Heating (ECH) of plasma primarily modified Te and turbulence behavior



- **Used ECH (~2.5 MW) to locally heat plasma**
  - I_p=800kA, B_T=2 T, n_e=1.7x10^{13} cm^{-3}
- **T_e increased, small decrease in n_e, no effect on T_i**
- **Monitor fluctuation levels, gradients, etc. and compare to theory.**

Times used in analysis:

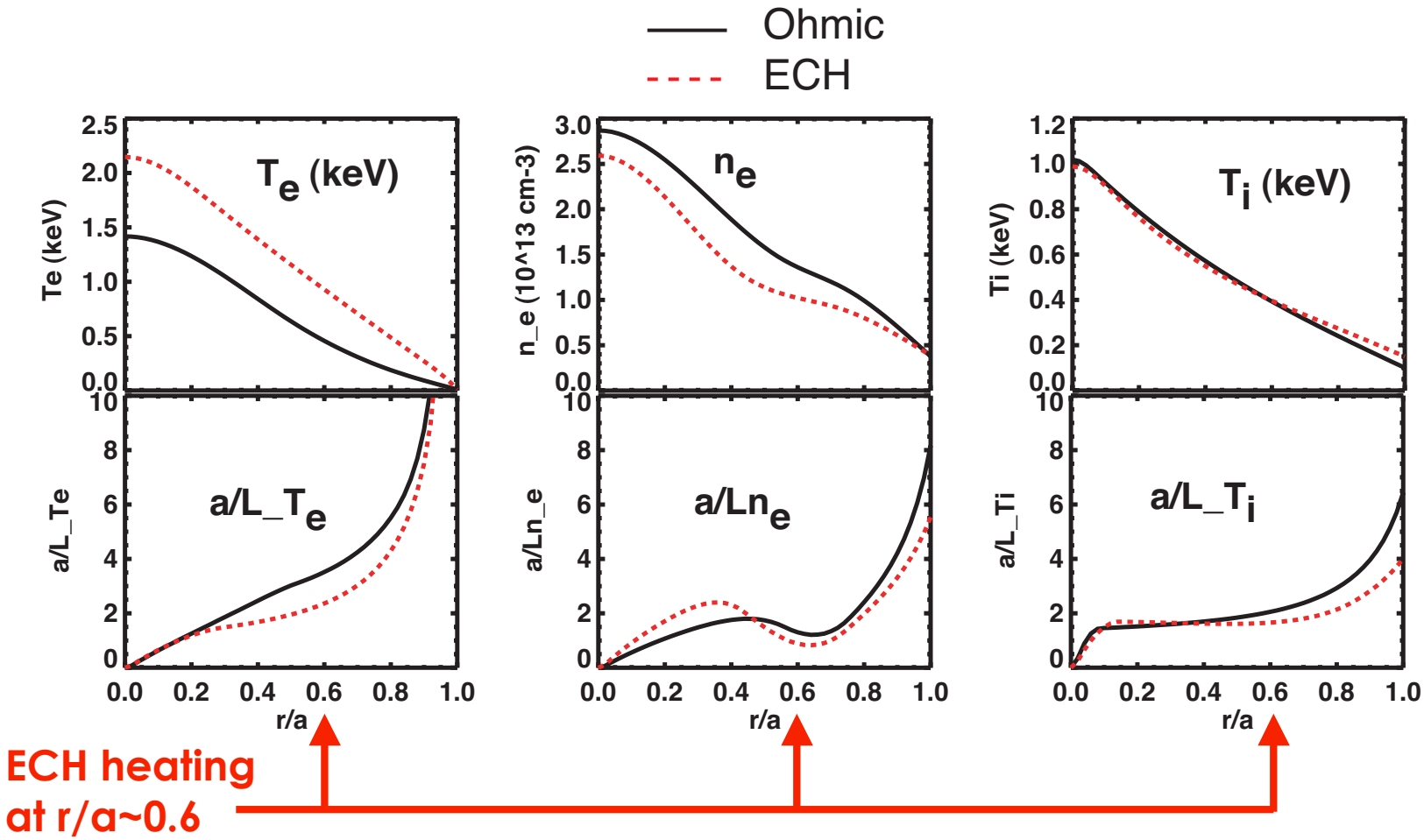
ECH, 3100 ms

Ohmic, 1975 ms

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

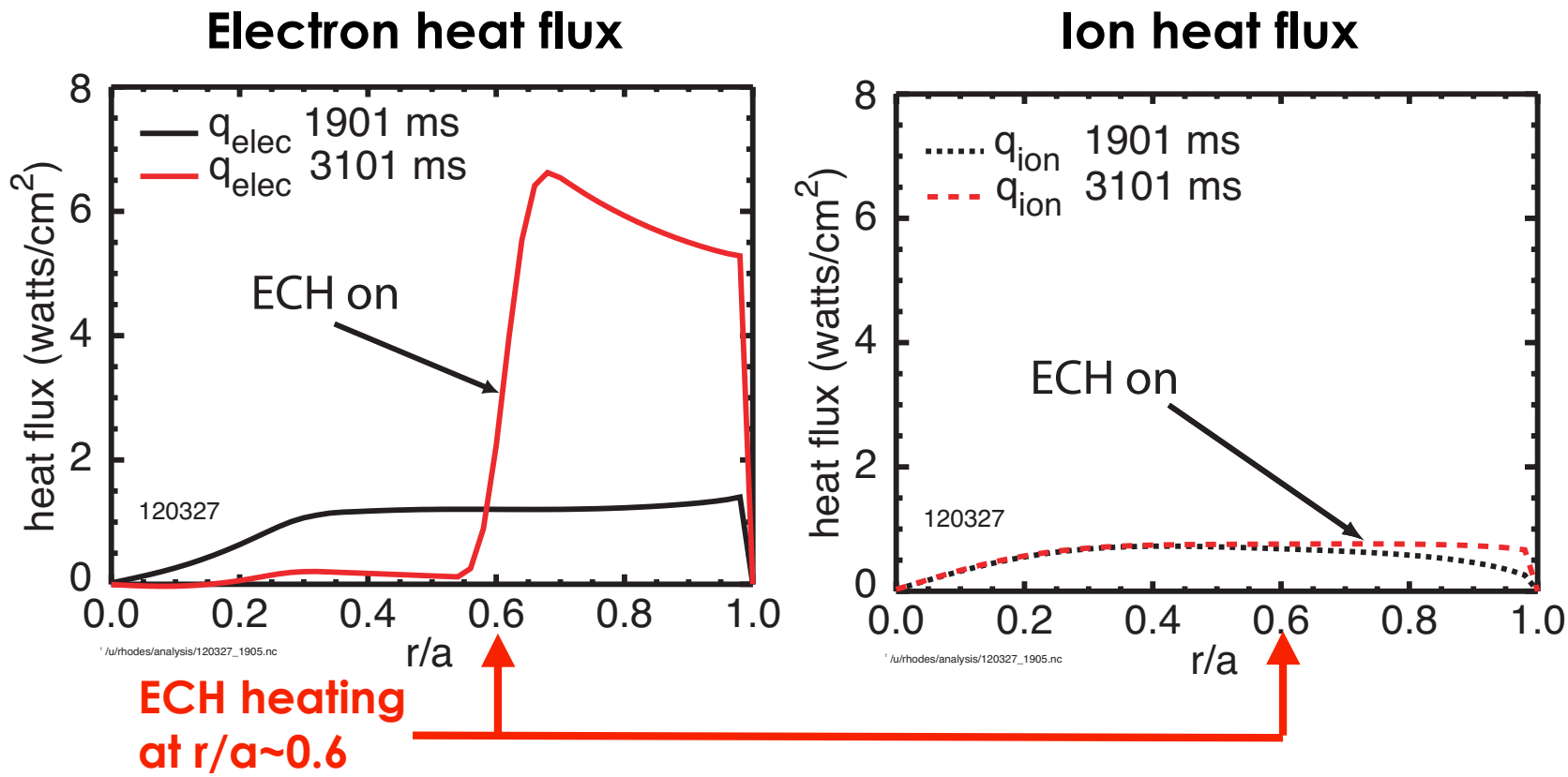
UCLA

T_e increased with ECH, n_e decreased, modifying potential instability drives



- **Effect of ECH is observed most strongly on T_e.**

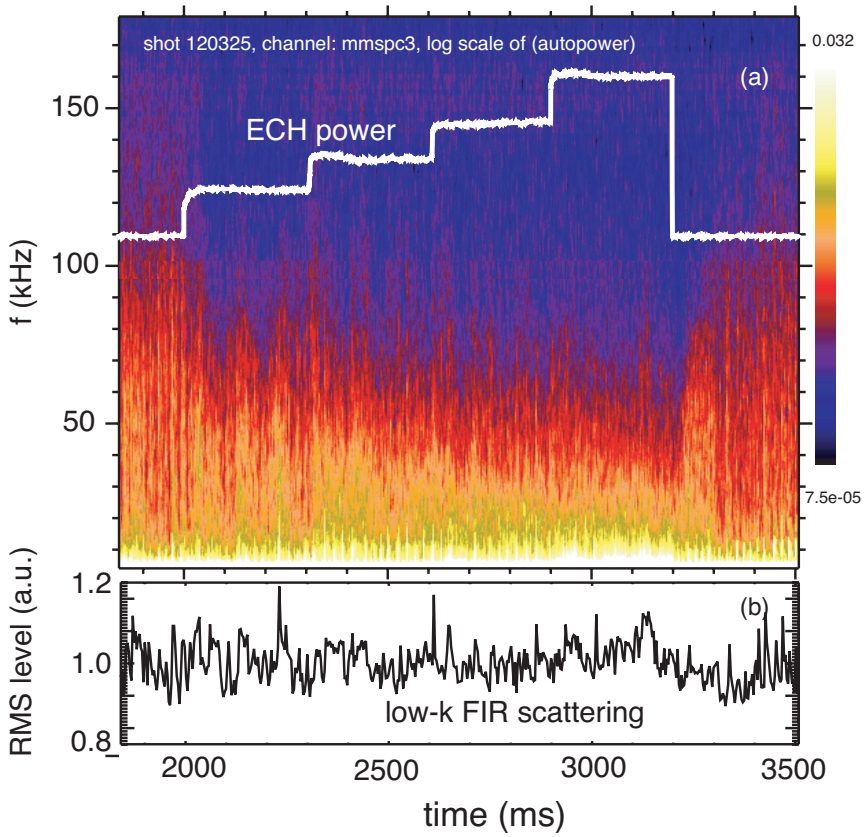
Electron heat flux increased substantially with ECH



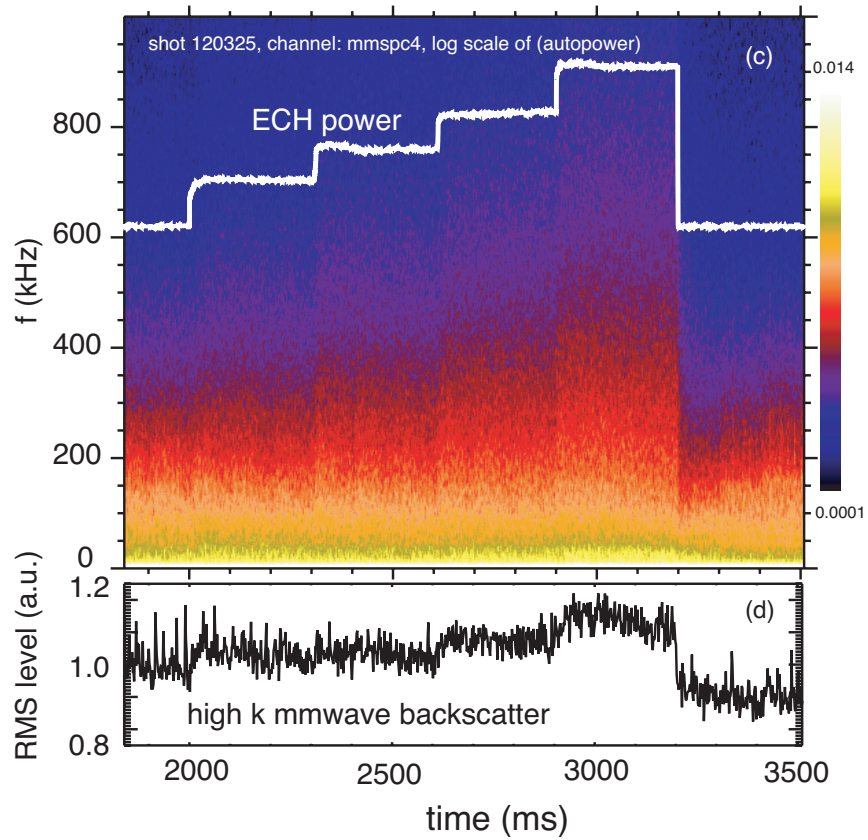
- **Fluxes determined using power balance and ONETWO transport code.**
- **Ion heat flux not strongly modified.**

Differing response to ECH indicates that high k (35 cm^{-1}, $k_\perp \rho_i$=4-10) is not a remnant or tail of low k (~1 cm^{-1})

Low k FIR scattering, mainly k_θ



High k mm wave scattering , mainly k_{radial}



- **High k fluctuation level increases while low k ~constant.**
  - Low k reflectometry also shows no increase with ECH
  - Important as this relates to origin of high k
- **Note narrowing of low k frequency spectrum**
  - consistent with a change in the Doppler shift.

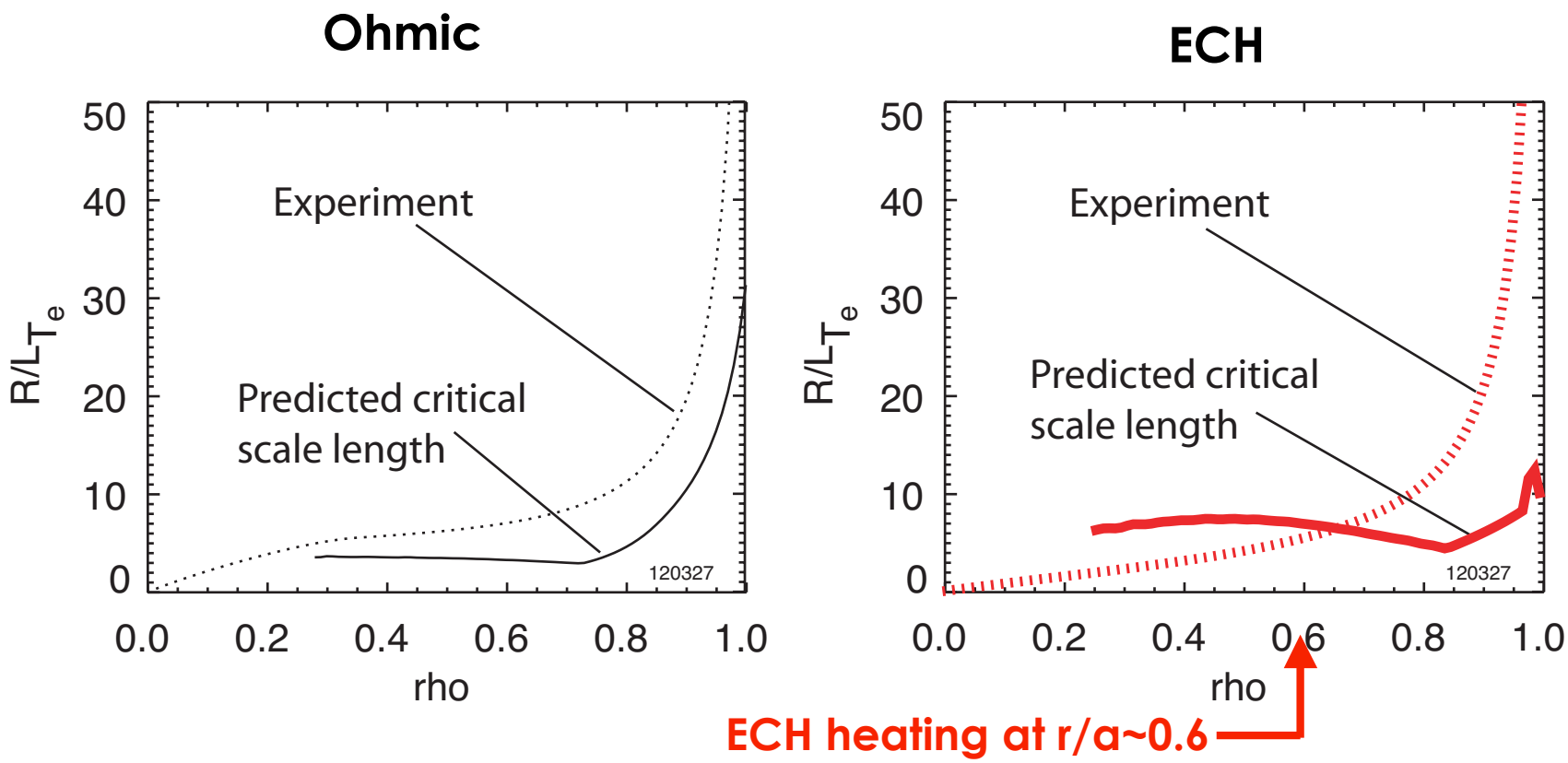
Increase in high k turbulence correlates with increased electron heat flux

- Lack of change in ion heat flux consistent with lack of change in low k turbulence
- Increased electron heat flux due solely to increased high k fluctuations not measured, can be estimated to be as much as 30% over base flux using $\tilde{q}_e = n\langle \tilde{T}_e \tilde{E}_\theta \rangle / B \propto n k_\theta T_e^2 (\tilde{n}/n)^2 / B$
  - Flux due to high k higher if include measured increase in T_e
  - Need more direct experimental tests plus non-linear simulations.

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

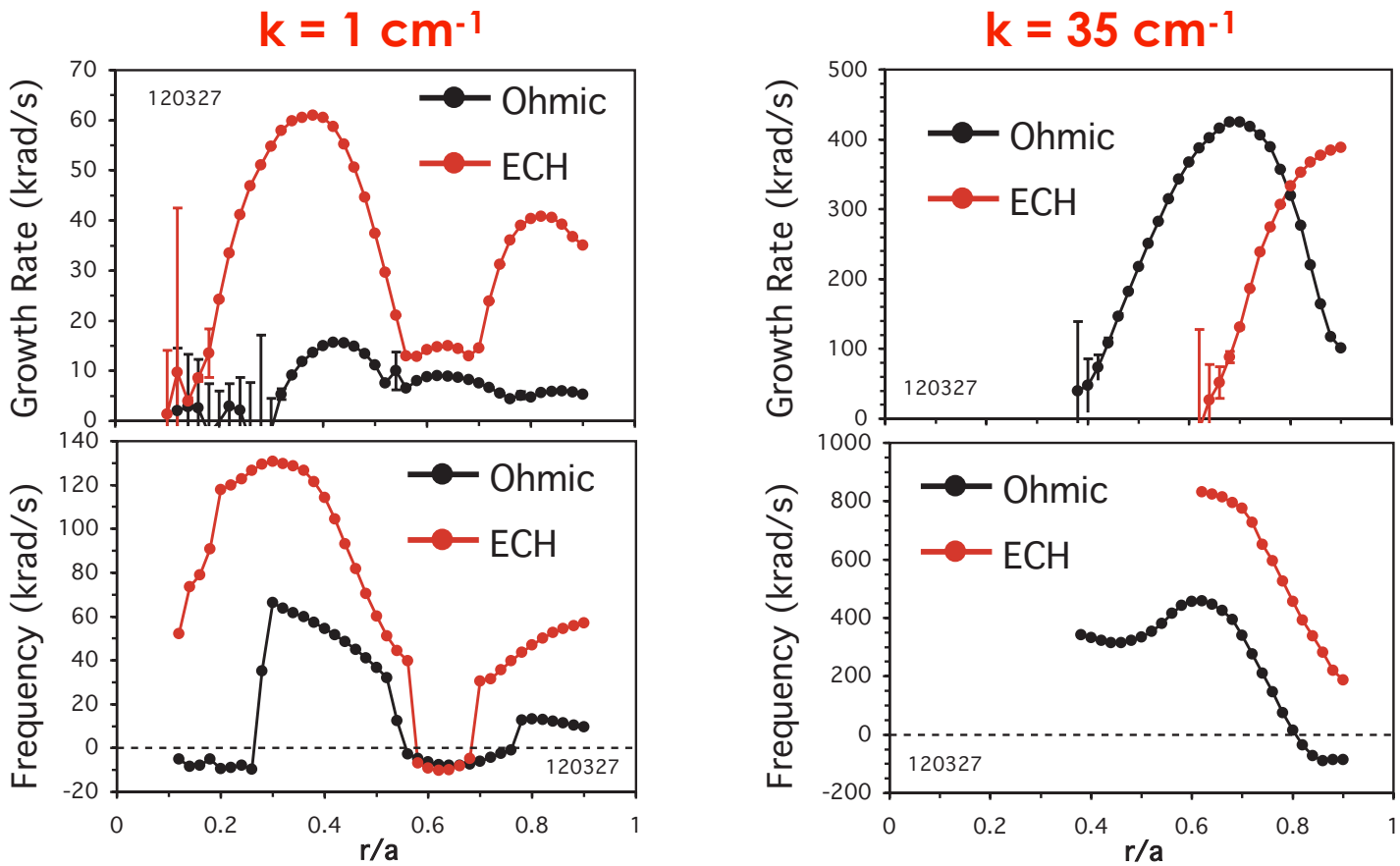
UCLA

Critical gradient analysis indicates plasma is unstable to electron temperature gradient driven modes (ETG)



- **Experimental T_e scale length exceeds predicted critical scale length for electron temperature gradient driven modes (ETG) over large region**
  - Critical scale length from Jenko, et al. PoP2001

Linear gyrokinetic calculations (GKS code) show increases in both low and high k growth rates with ECH



- GKS: linear gyrokinetic code calculates growth rates and frequencies for toroidal drift waves
- Calculations are for k_θ, high k is principally k_r.

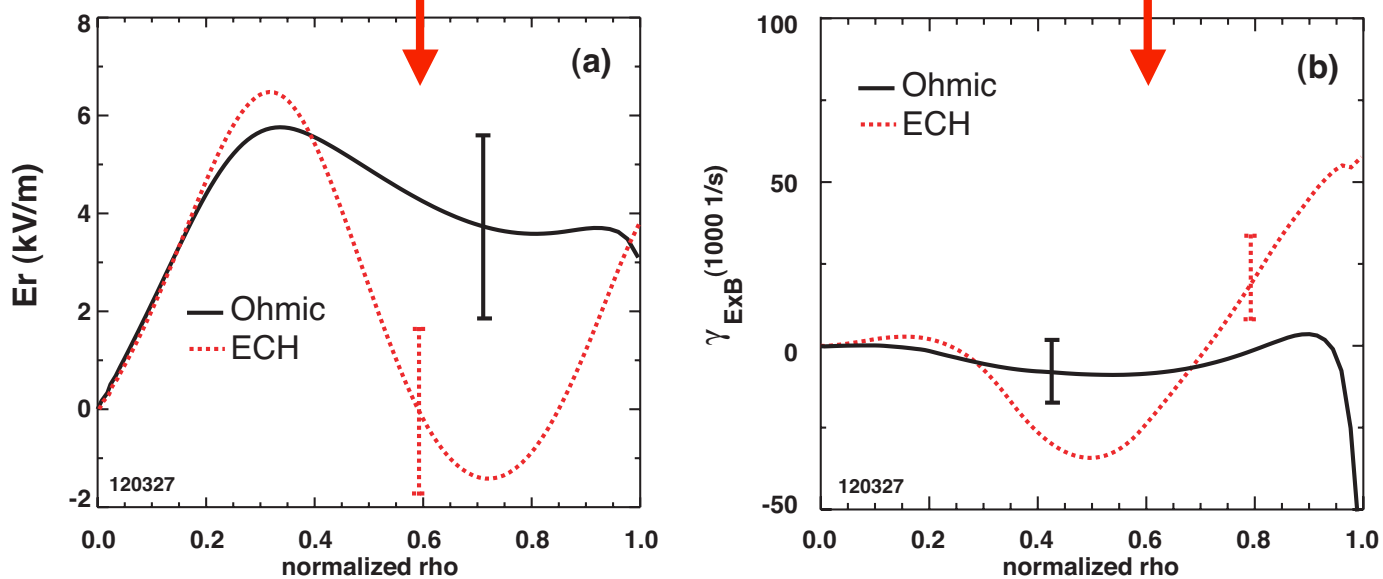
- Expect increases in both low and high k in outer plasma regions - however, experimentally low k ñ is constant.

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Radial E_r decreases with ECH however resulting E_r shear is increased

ECH heating at r/a~0.6

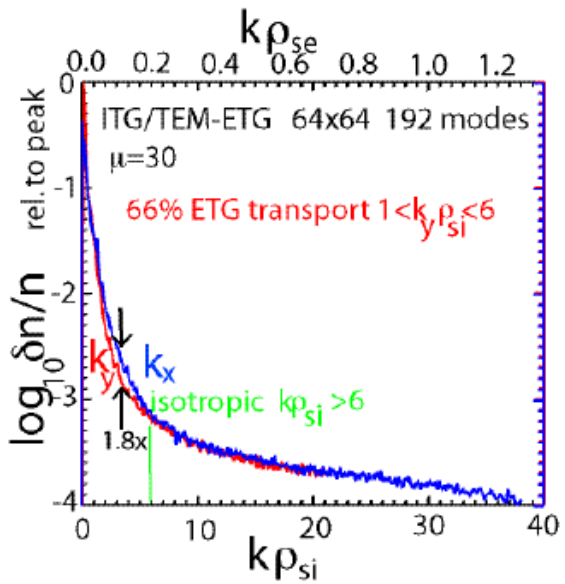


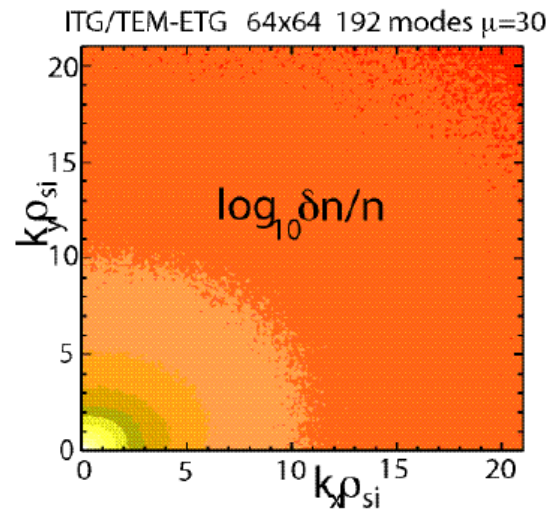
- **Resulting decrease in V_{ExB} is consistent with observed decrease in frequency width of low k fluctuations.**
- **ExB shearing rate is found to be a significant fraction of calculated low k growth rates.**
  - Potential explanation for GKS prediction of increased low k during ECH while experiment shows constant level
  - Note that high k apparently unaffected by shear

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Recent GYRO simulations find ETG scale turbulence isotropic in k_r-k_θ





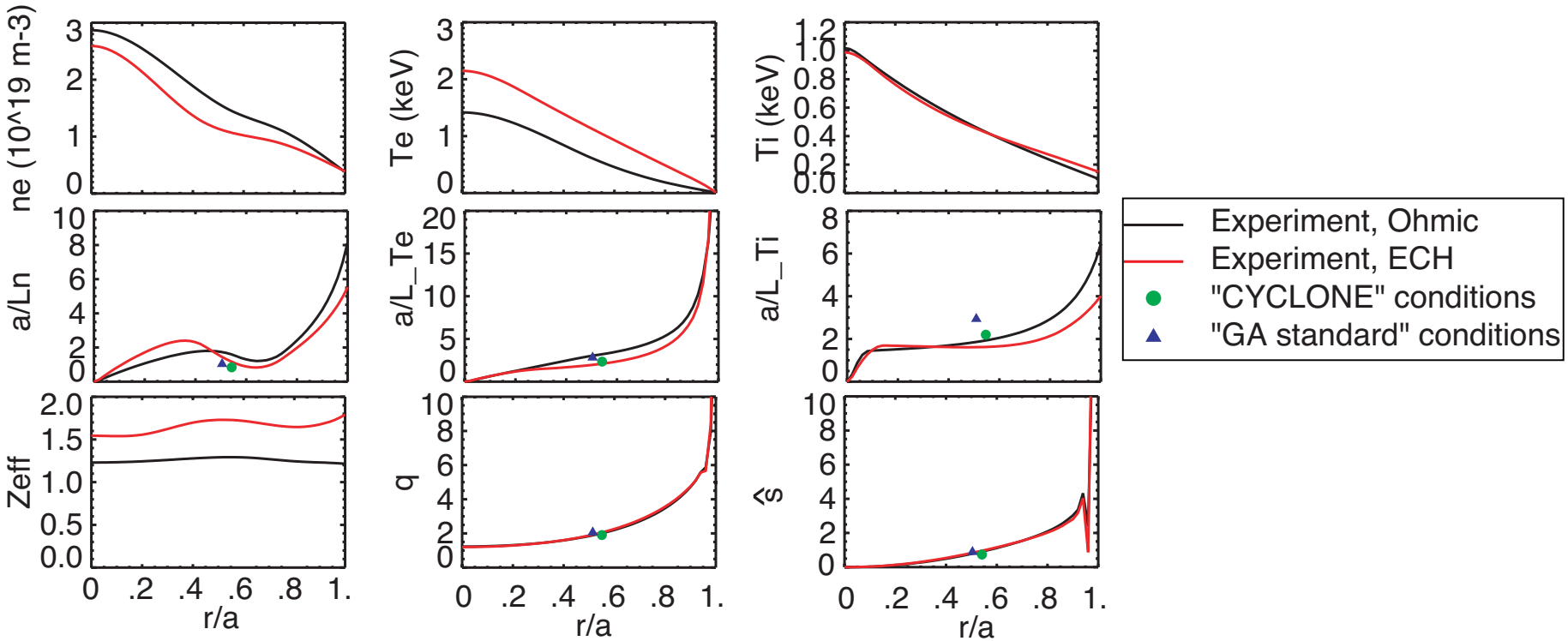
GYRO simulations: $\mu=(m_i/m_e)^{1/2}=30$

- **Non-linear turbulence GYRO simulations addressing realistic coupling ITG/TEM/ETG simulations (**From R. Waltz, et al., General Atomics)
- **GYRO simulation conditions are close to but not same as experimental plasma studied here and only one radial position.**
  - **Experiment covers range in both r/a and in plasma parameters**
  - **Need more simulation results to compare with !**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

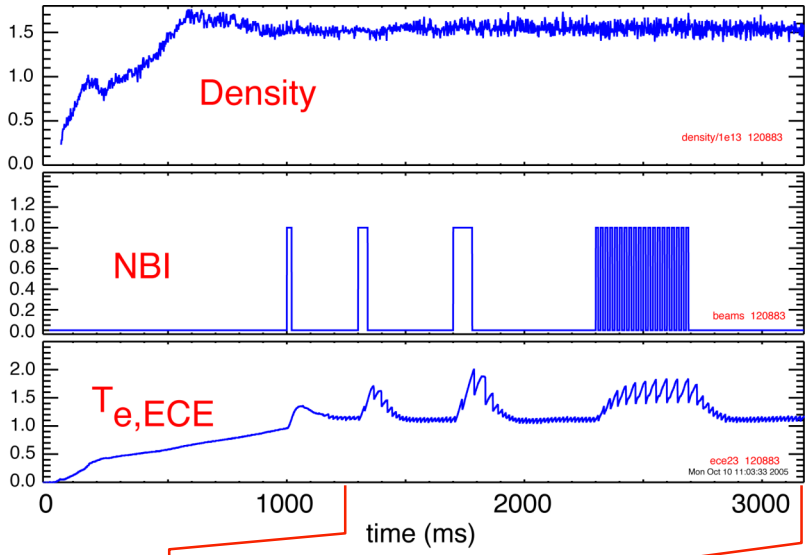
UCLA

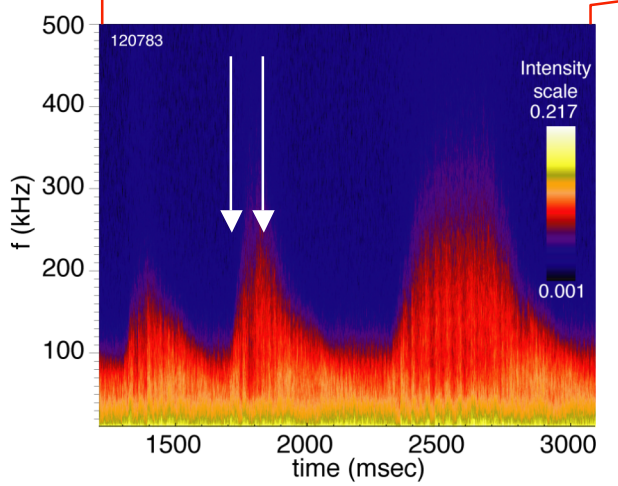
GYRO simulation parameters are close to experiment



- **GYRO simulation parameters (so-called "GA standard conditions")**
  - **$\hat{s}$ =1, q=2, r/a=0.5, R/a=3, a/L_T=3, a/L_n=1, T_e/T_i=1**
- **"Cyclone conditions" are similar:**
  - **$\hat{s}$ =0.8, q=1.4, r/a=0.54, R/a=3, a/L_T=2.3, a/L_n=0.73, T_e/T_i=1**
- **In simulation only one radial position documented, r/a~0.5**

Broadband turbulence response to short NBI blips somewhat different from ECH response



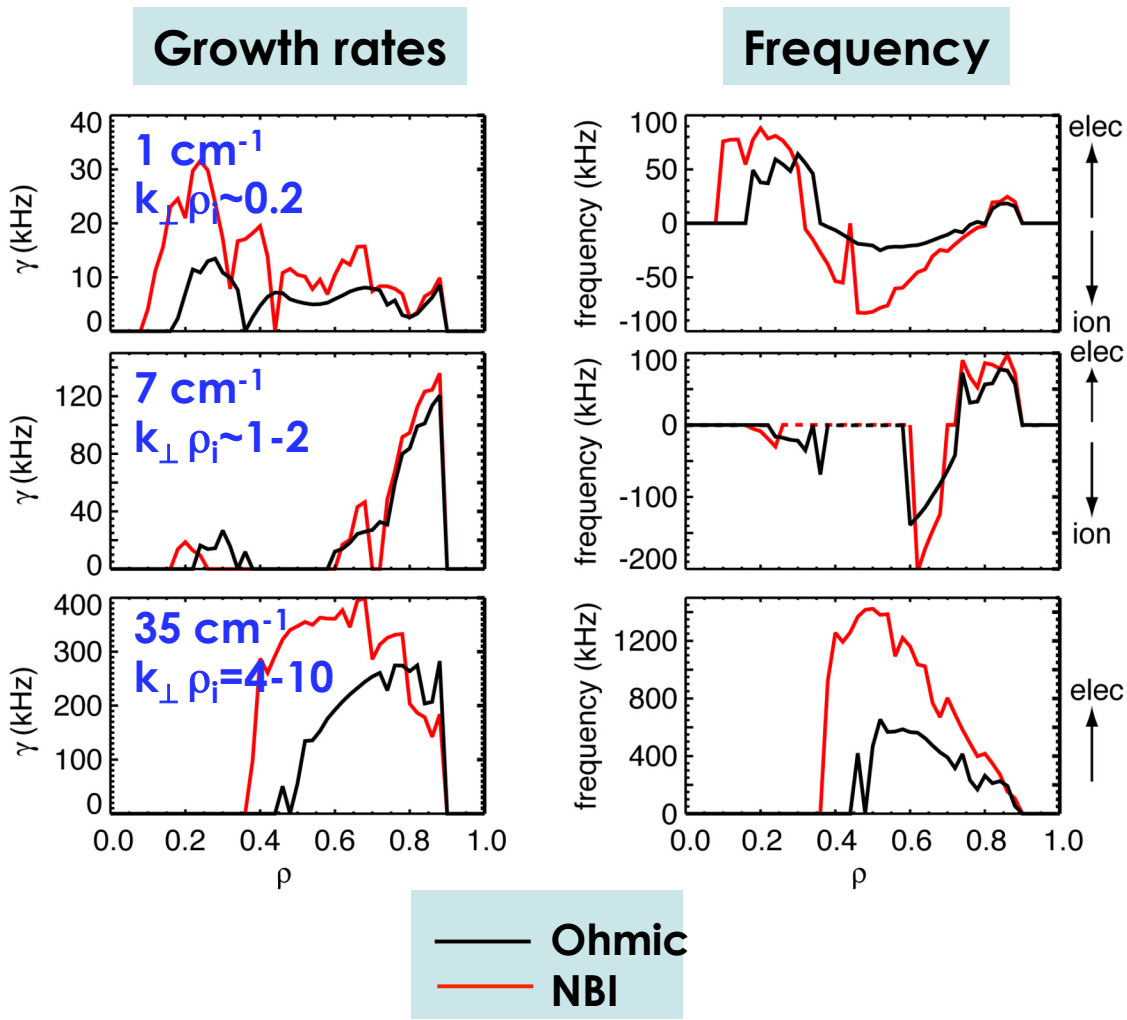


- Perturbed Ohmic plasma with short NBI blips (Pinj~2.5 MW)
  - I_p=800kA, B_T=2 T, n_e=1.7x10^{13} cm^{-3}
- T_e, T_i increased but no significant change in n_e
- Fluctuation levels increase with NBI over broad range in k
  - As opposed to only the high k increasing with ECH
  - Example shown is high k, 35 cm^{-1}.
  - Next compare theoretical and experimental response of different wavenumbers

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

GKS predicts plasma unstable over broad range in k: 1-35 cm^{-1}, $k_\perp \rho_i$~0-10

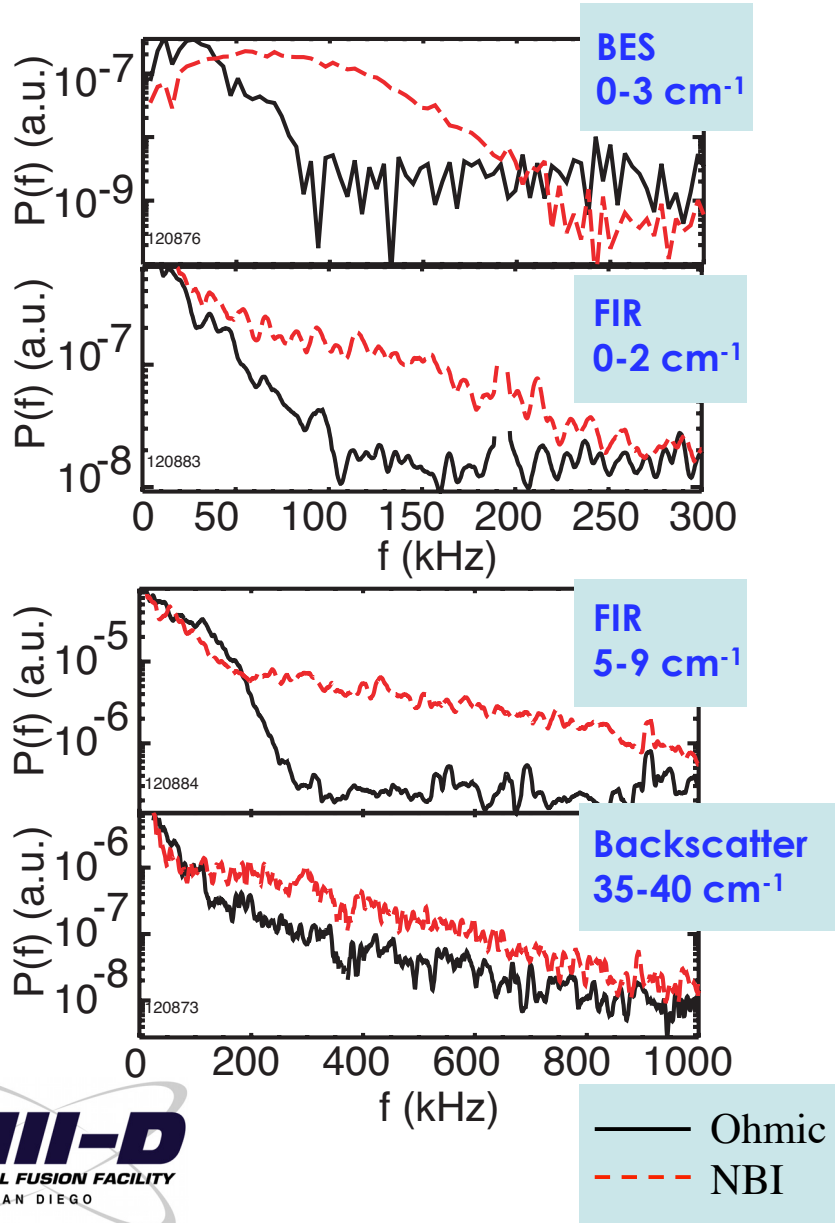


- Good counterpoint to ECH data.
- Range of instabilities corresponds to ITG, TEM, ETG type instabilities.
- Note that with exception of high k the growth rates do not change strongly with the NBI

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Quantitative comparison of high k and low k fluctuation levels reveals large difference in magnitude

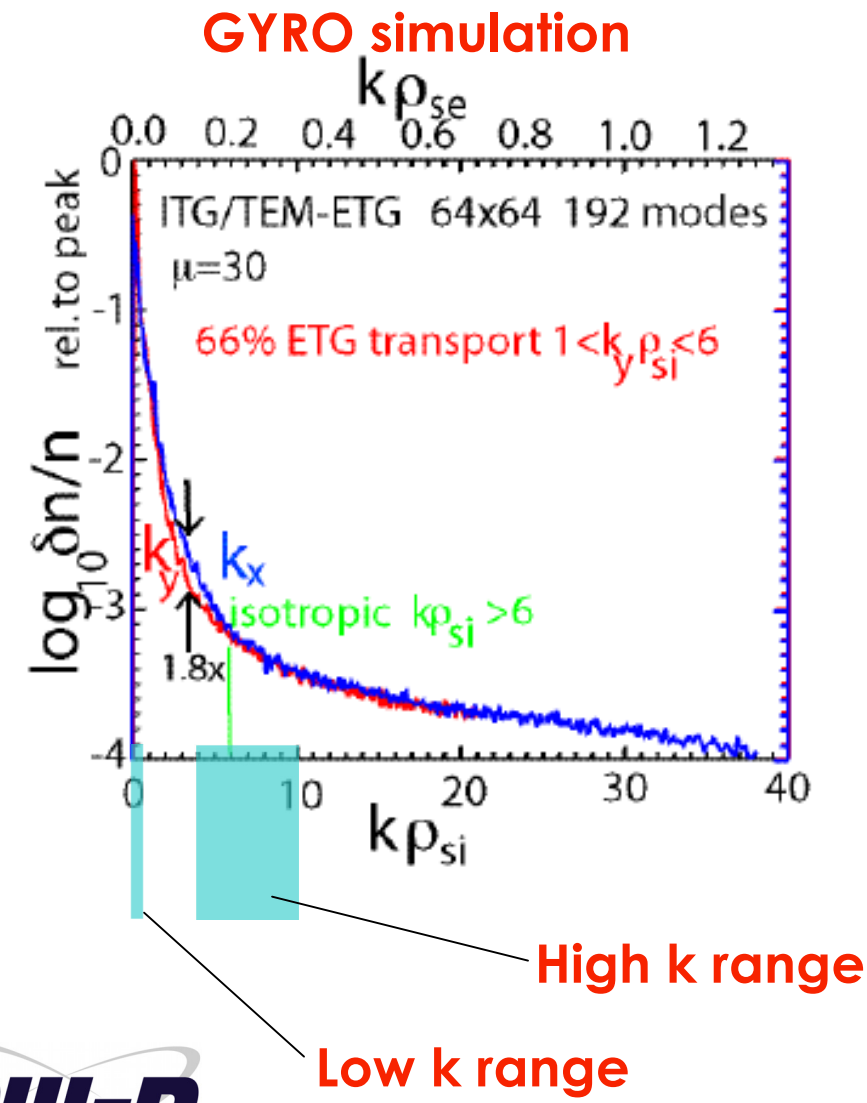


- **Fluctuation magnitude increases and broadens with NBI**
- **Ohmic fluctuation levels ñ/n:**
  - **Low k: ñ/n ~ 8x10^{-3}**
    - ρ=0.7, $k_\perp \rho_i$~0.2-0.4, BES
  - **High k: ñ/n ~ 3x10^{-6}**
    - ρ=0.4-1.0, $k_\perp \rho_i$=4-10 high k
  - ñ/n increases ~25% with NBI

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Ratio of high to low k fluctuation levels compare reasonably well with non-linear GYRO simulation



- **Simulation:**
  - $(\tilde{n}/n)_{high\ k}/(\tilde{n}/n)_{low\ k} \sim 10^{-3}$
- **Ratio compares reasonably well with experimental ratio**
  - $(\tilde{n}/n)_{high\ k}/(\tilde{n}/n)_{low\ k} \sim .4\times10^{-3}$
- **Simulation shown is at r/a=0.5 and for conditions which are close to but not same as experimental plasma**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA

Summary

- DIII-D has a comprehensive set of turbulence diagnostics spanning a wide range in k: ITG, TEM, ETG relevant
- Observed correlation of increased high k (~35 cm^{-1}, $k_{\perp}\rho_i$=4-10) turbulence with increased electron heat transport.
  - Consistent with high k turbulence driving at least part of electron heat transport.
- Determined that high k (~35 cm^{-1}) is not a short λ remnant or tail of low k (~1 cm^{-1}) ITG/TEM type modes
- Differing effect of electric field shear on low and high k observed:
  - Low k fluctuation behavior consistent with reduction due to E_r shear
  - High k apparently not affected by E_r shear
- Relative levels of high and low k fluctuation levels comparable to non-linear turbulence simulation (GYRO) results

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

UCLA