Response of Multi-Scale Turbulence and Plasma Transport to Electron Cyclotron Heating on DIII-D

by

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with

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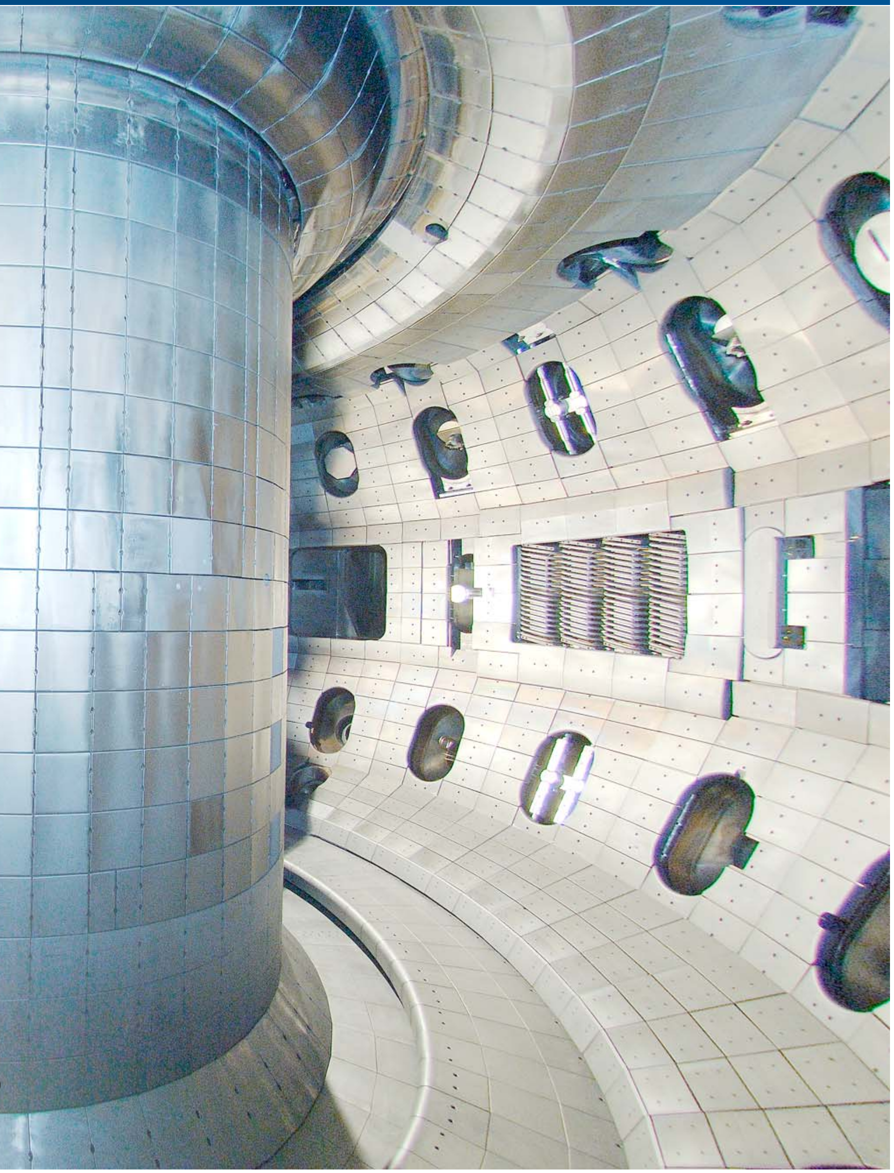

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Theoretical work indicates high k turbulence may contribute to anomalous electron heat transport

- **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**

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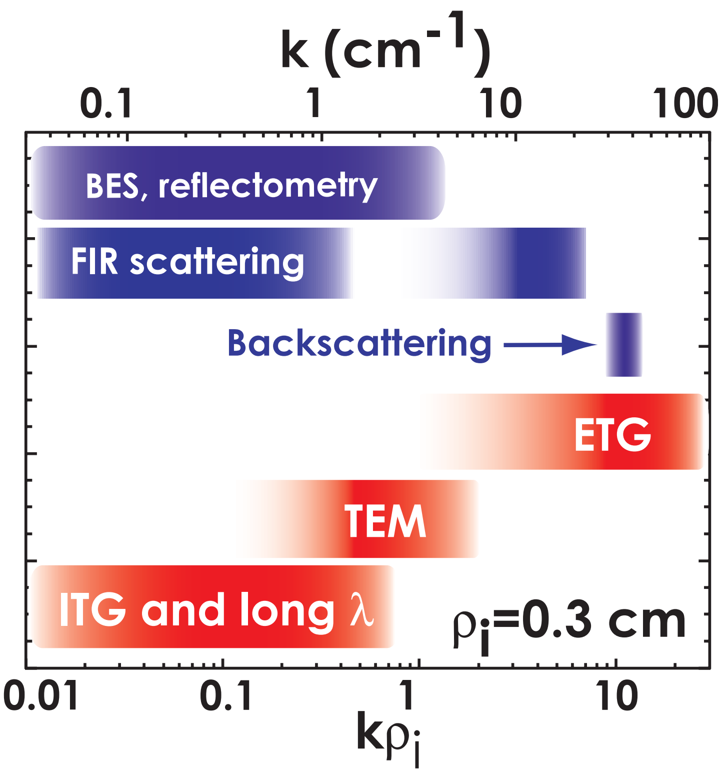
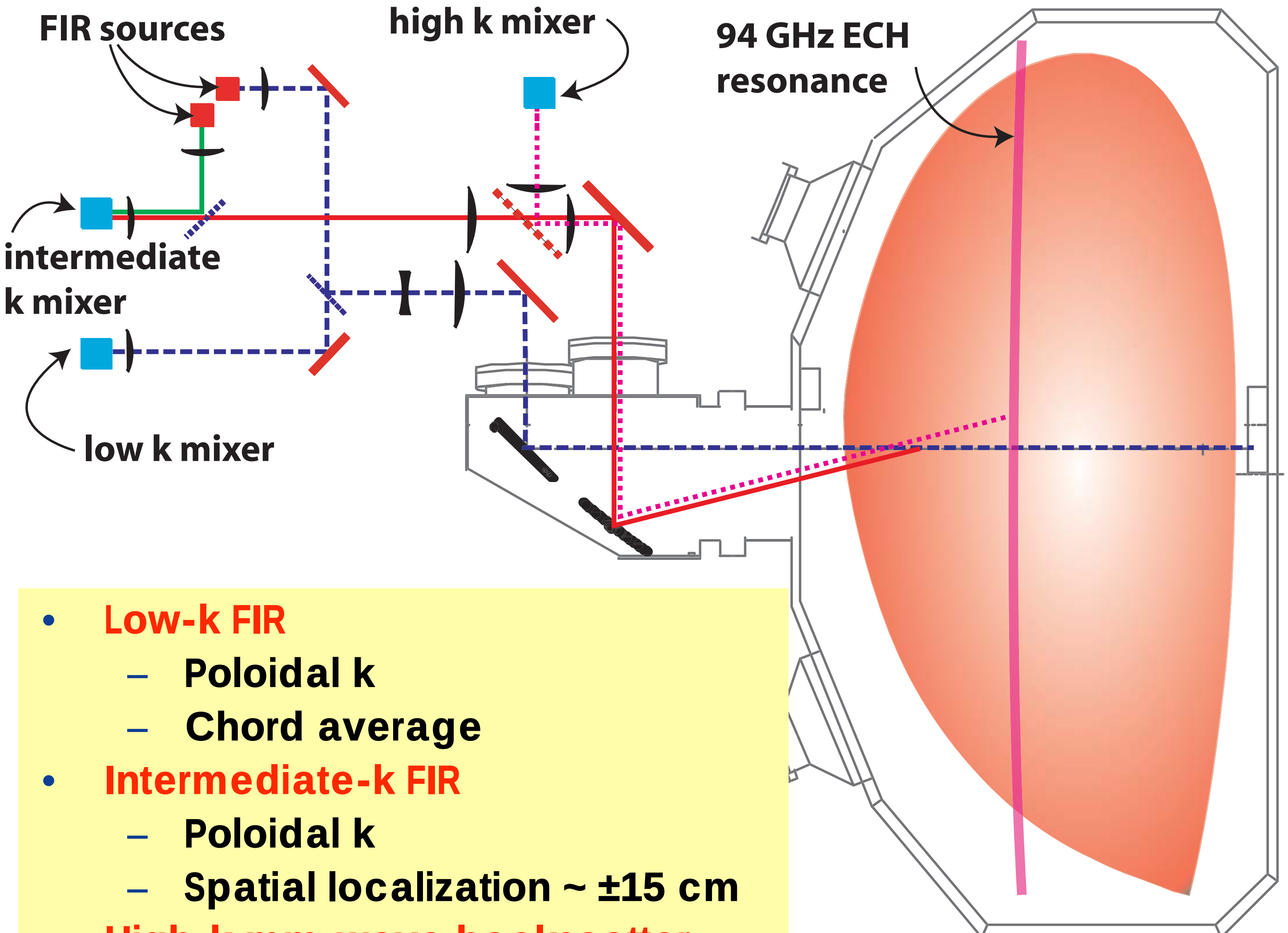
Broad Wavenumber Measurements Provide New, More Complete Picture of Turbulence Behavior on DIII-D



- **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 and new for this year core $\tilde{T}_e$ (from ECE).**
  - 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**

Low to High k Density Fluctuation Data From Scattering Diagnostics



- Low-k FIR
  - Poloidal k
  - Chord average
- Intermediate-k FIR
  - Poloidal k
  - Spatial localization ~ ±15 cm
- High-k mm-wave backscatter
  - Radial k
  - Chord from r/a=1 to 0.4

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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.

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.

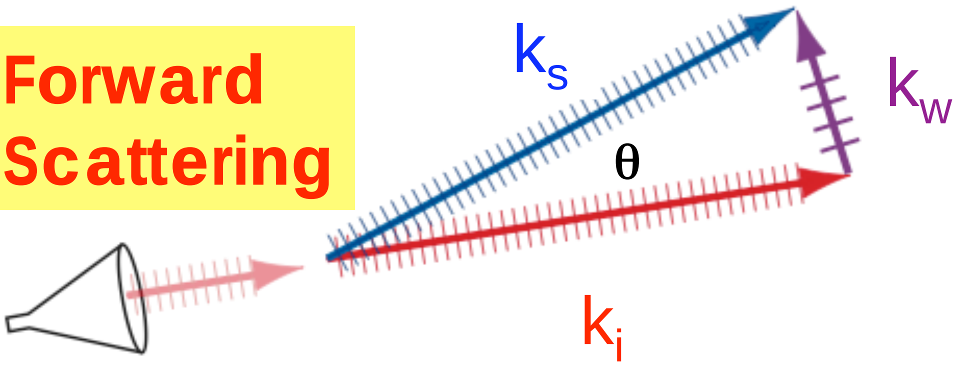
Bragg Law:

For $k_i \sim k_s$, can show that

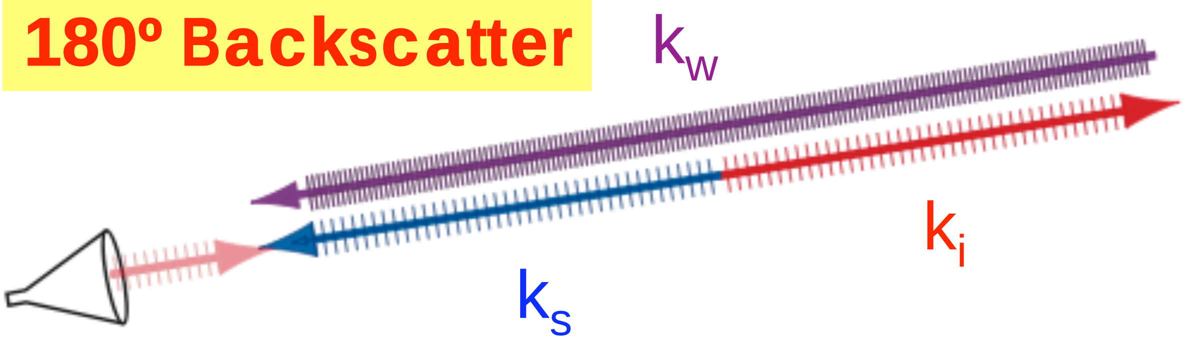
$$\mathbf{k_w = 2k_i \sin(\theta/2)}$$

Where θ is scattering angle

Forward Scattering



180º Backscatter



FIR scattering is dominantly k_θ

High k backscattering is dominantly k_r

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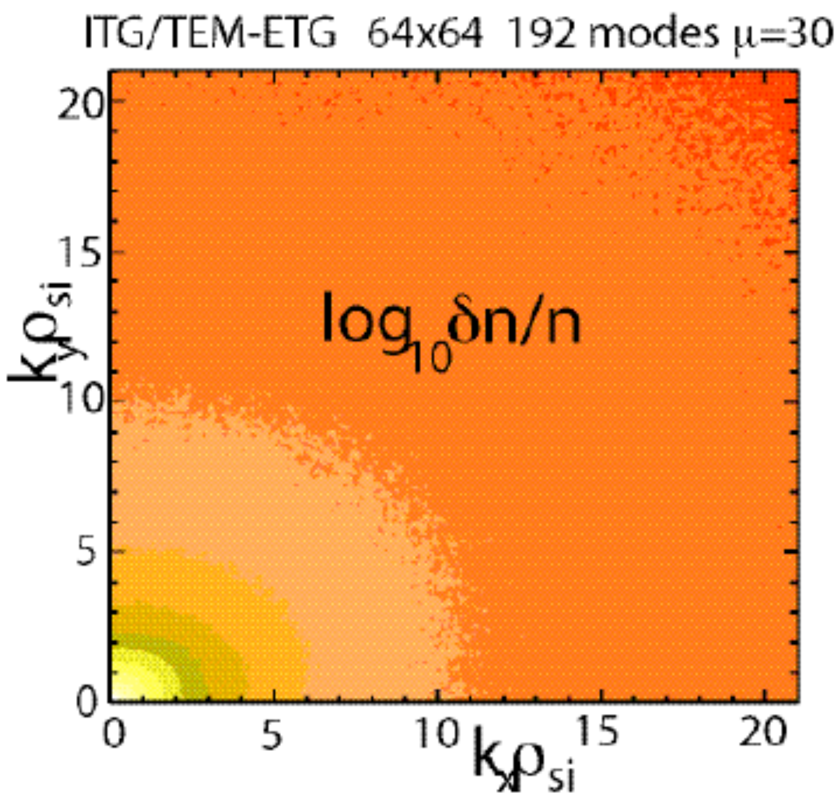
Recent GYRO Simulations Find ETG Scale Turbulence Isotropic in k_r-k_θ



- **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.**

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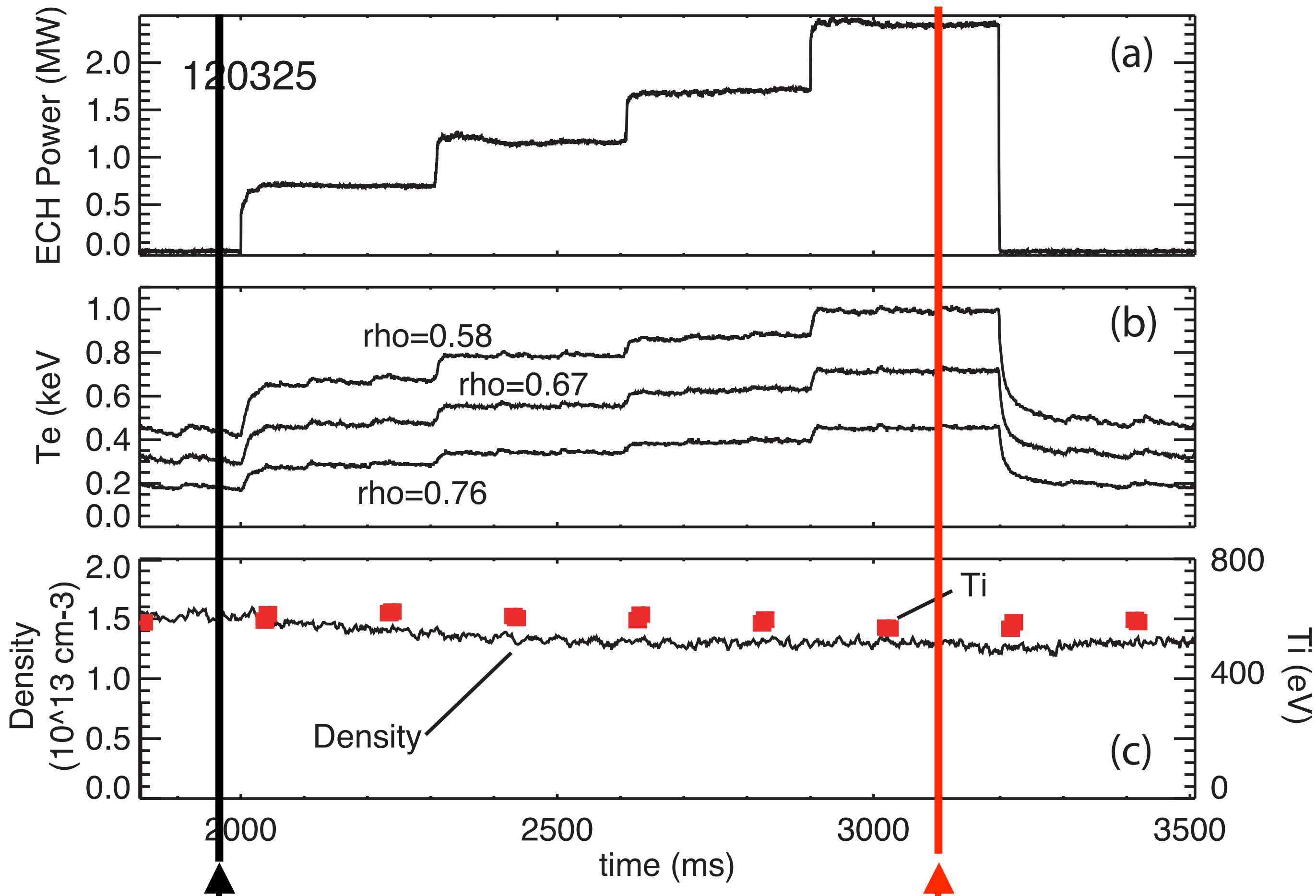
Electron Cyclotron Heating (ECH) Used to Modify Plasma and Turbulence Behavior



- **2.5 MW ECH to locally heat plasma near r/a=0.6**
  - I_p=800kA, B_T=2 T, $n_e=1.7\times10^{13}$ cm^{-3}
- **T_e increased, 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

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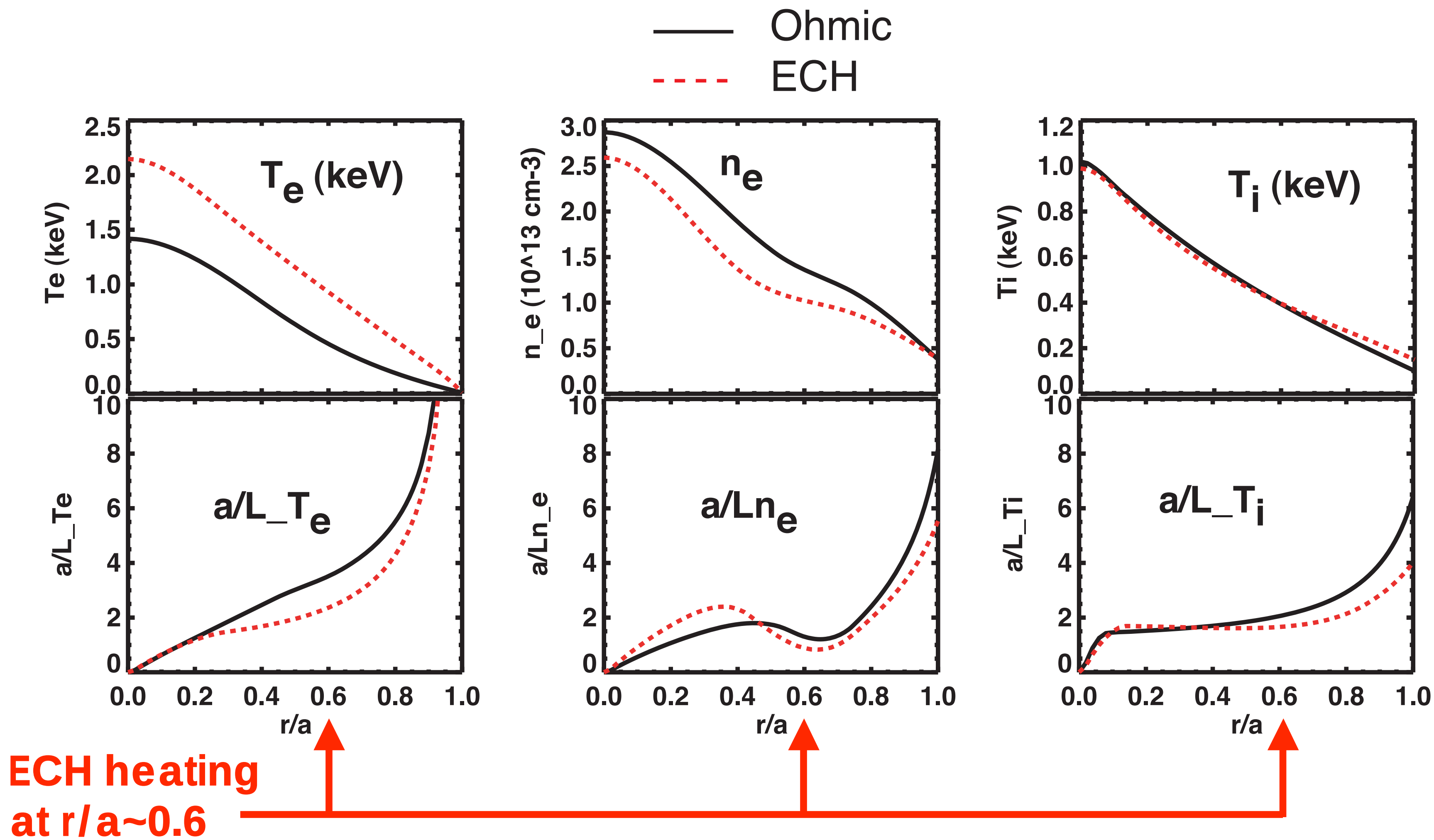
T_e Increased and n_e Decreased With ECH, Modifying Instability Drives



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

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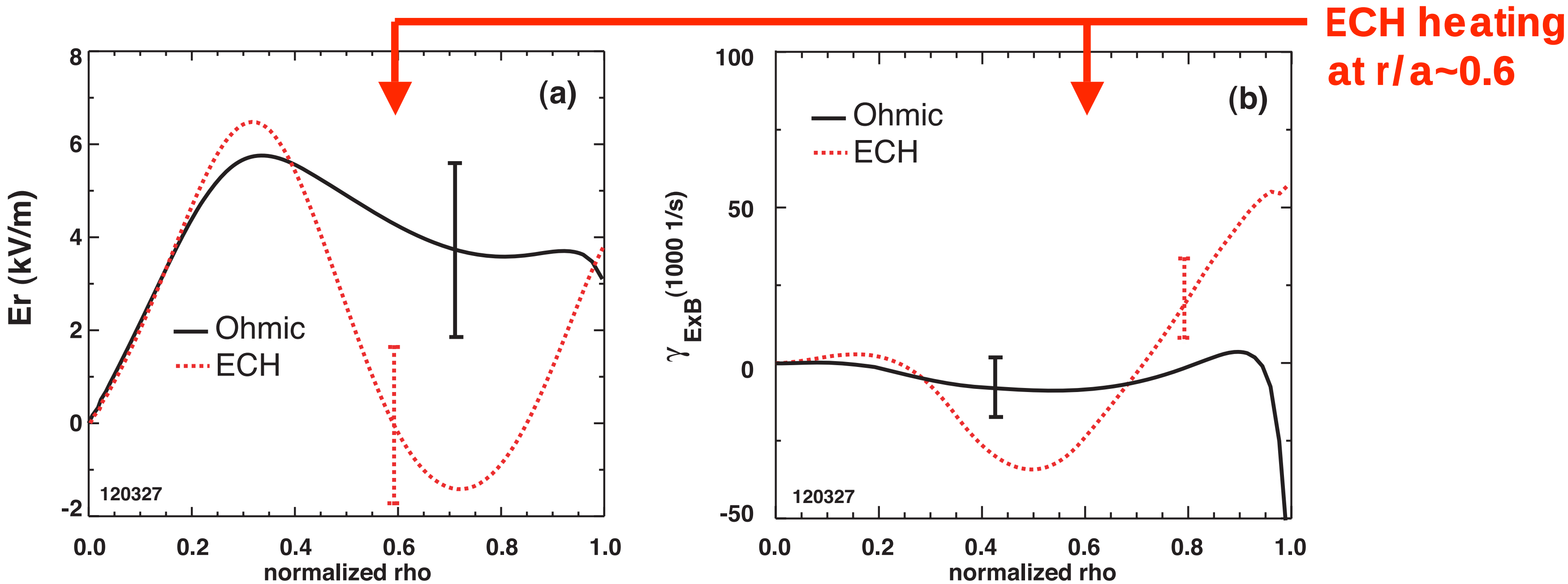
Radial Electric Field E_r Decreases With ECH and Resulting E_r Shear Is Increased



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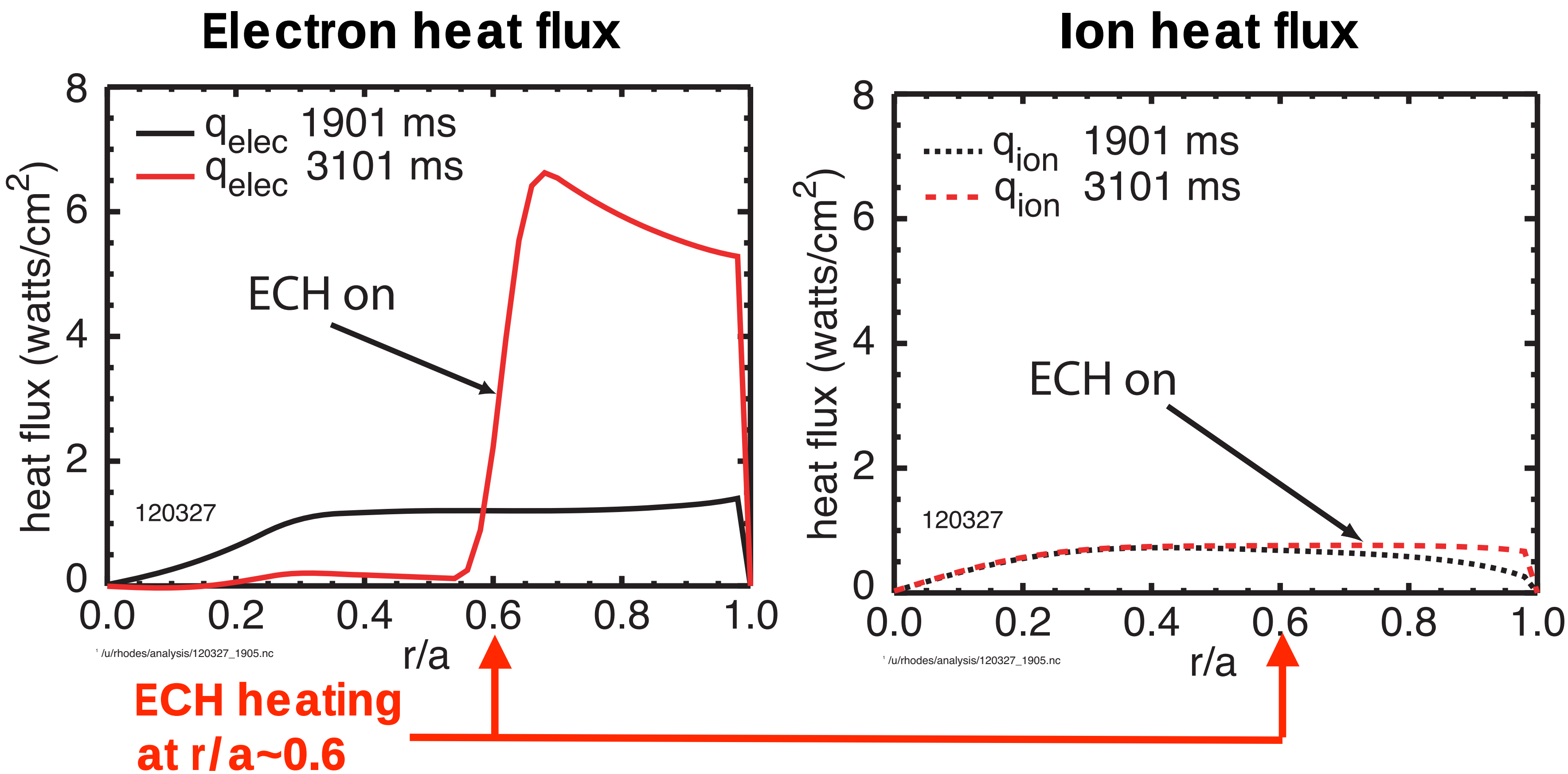
Electron Heat Flux Increased With ECH



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

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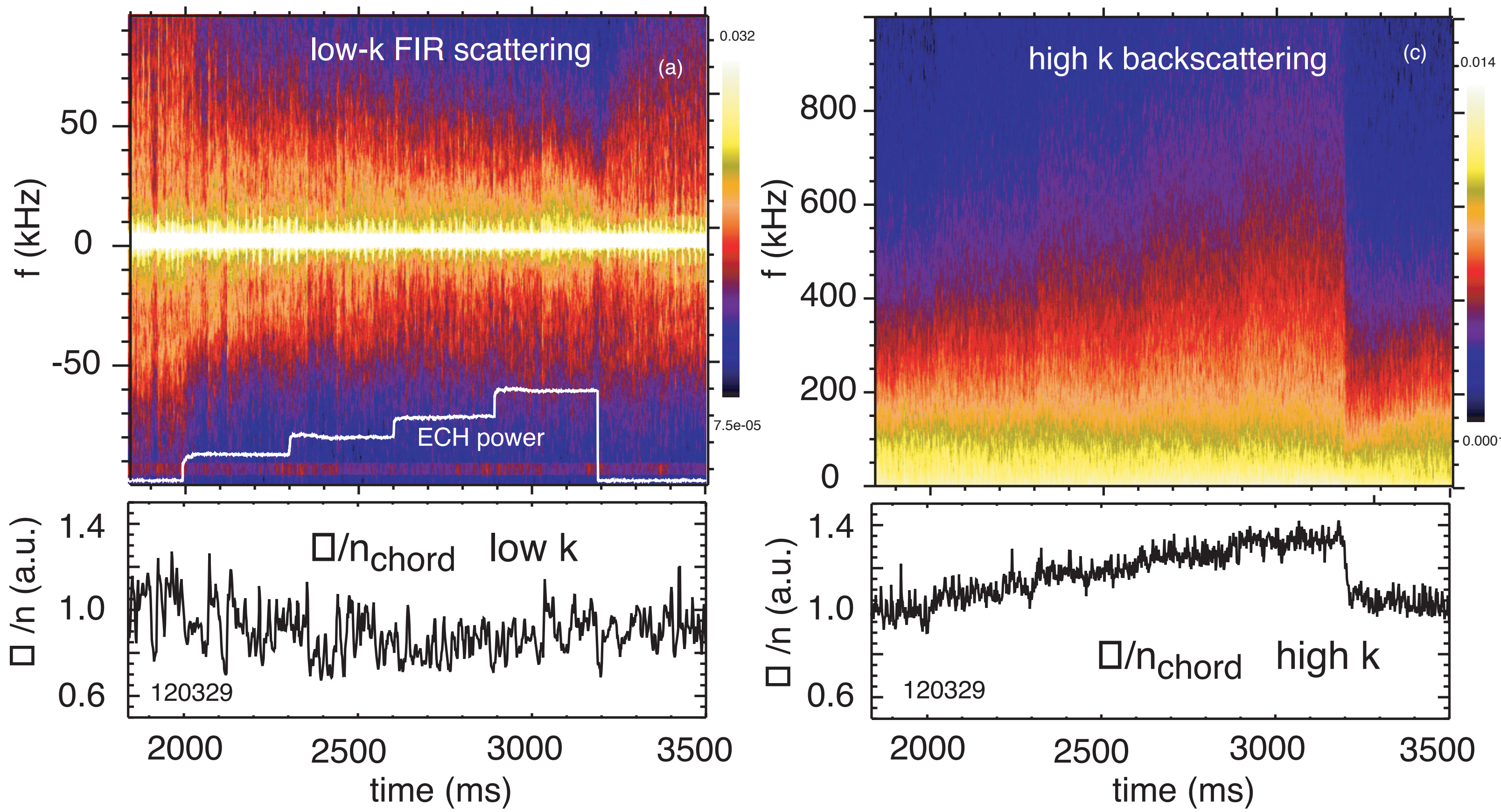
Differing Response to ECH Suggests that High k is Not a Remnant or Tail of Low k

Low k, mainly k_θ | **High k , mainly k_{radial}**



- **Relates to origin of high k**
- **Narrowing of low k frequency spectrum consistent with V_{ExB} due to modified E_r profile shown earlier**

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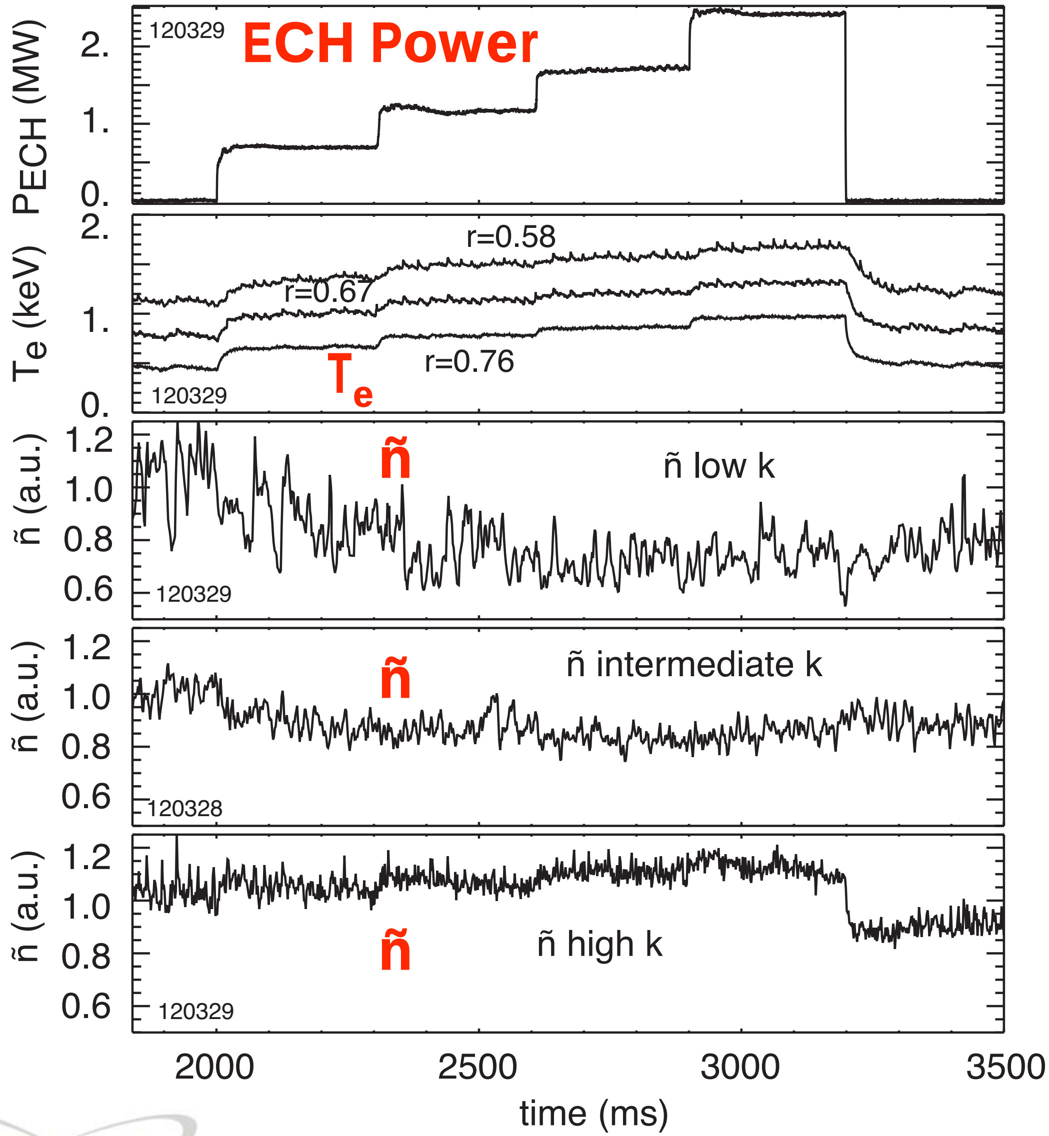
High k is Also Responds Differently than Intermediate k



low k, $k_\perp\rho_i$~0.1-0.3

Intermediate k, $k_\perp\rho_i$~1-4

High k, $k_\perp\rho_i$~4-10

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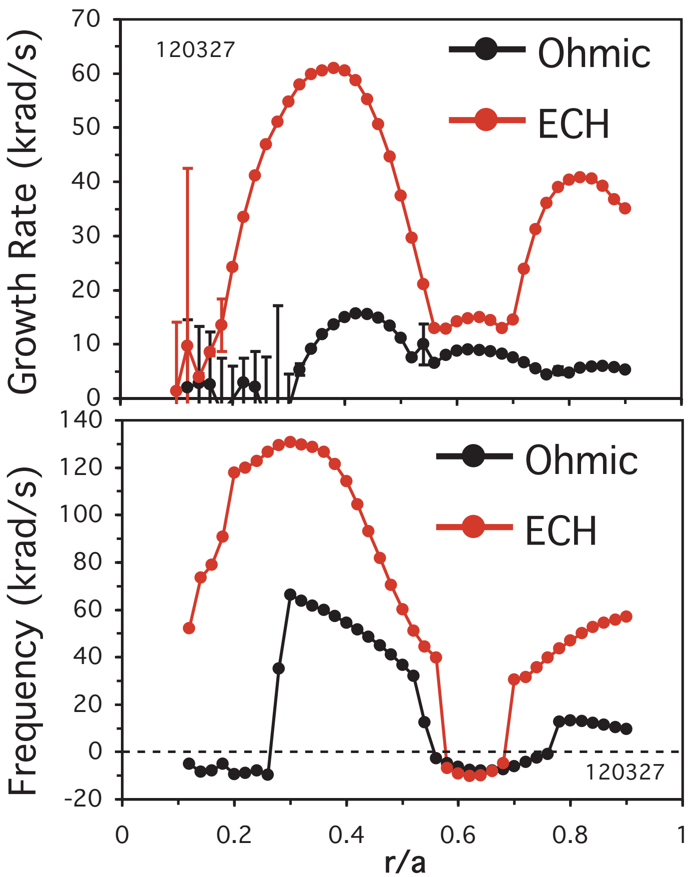
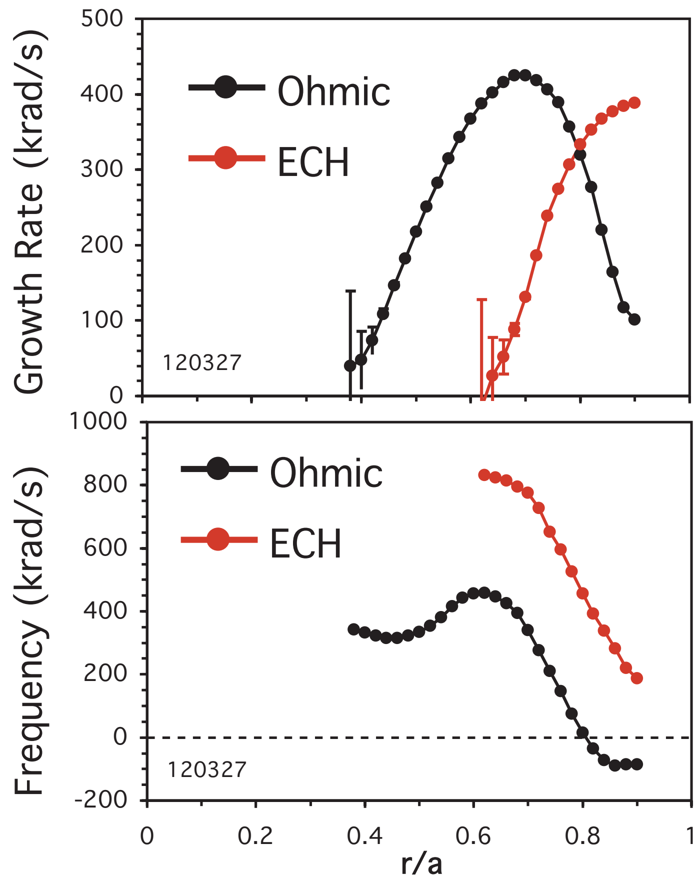
Calculated Low k Growth Rates Increase With ECH

$k = 1\ cm^{-1}$



$k = 35\ cm^{-1}$



- **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 decreases**

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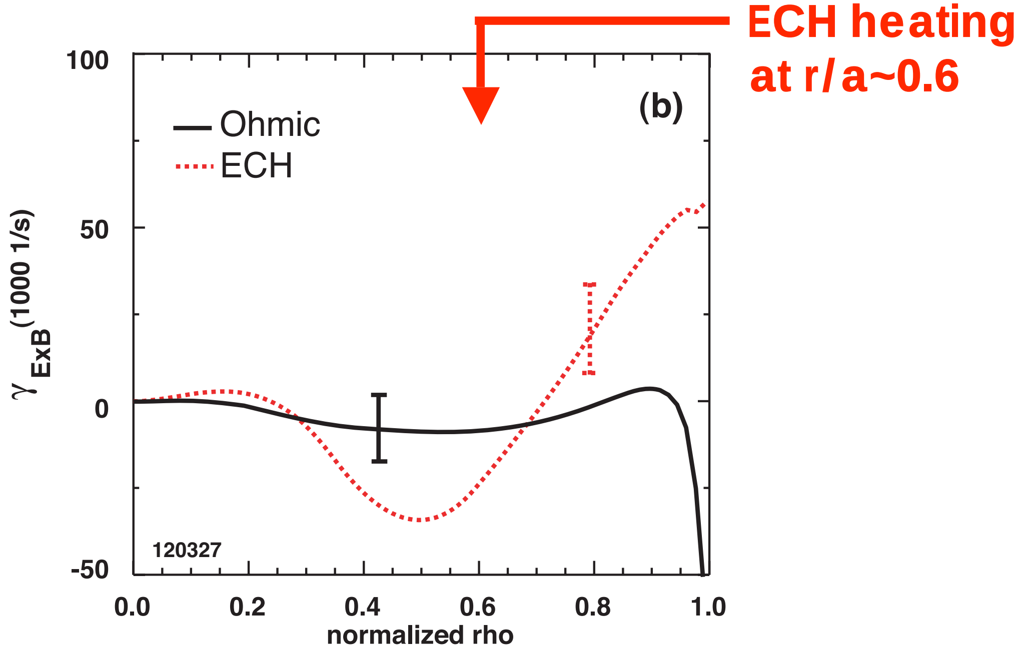
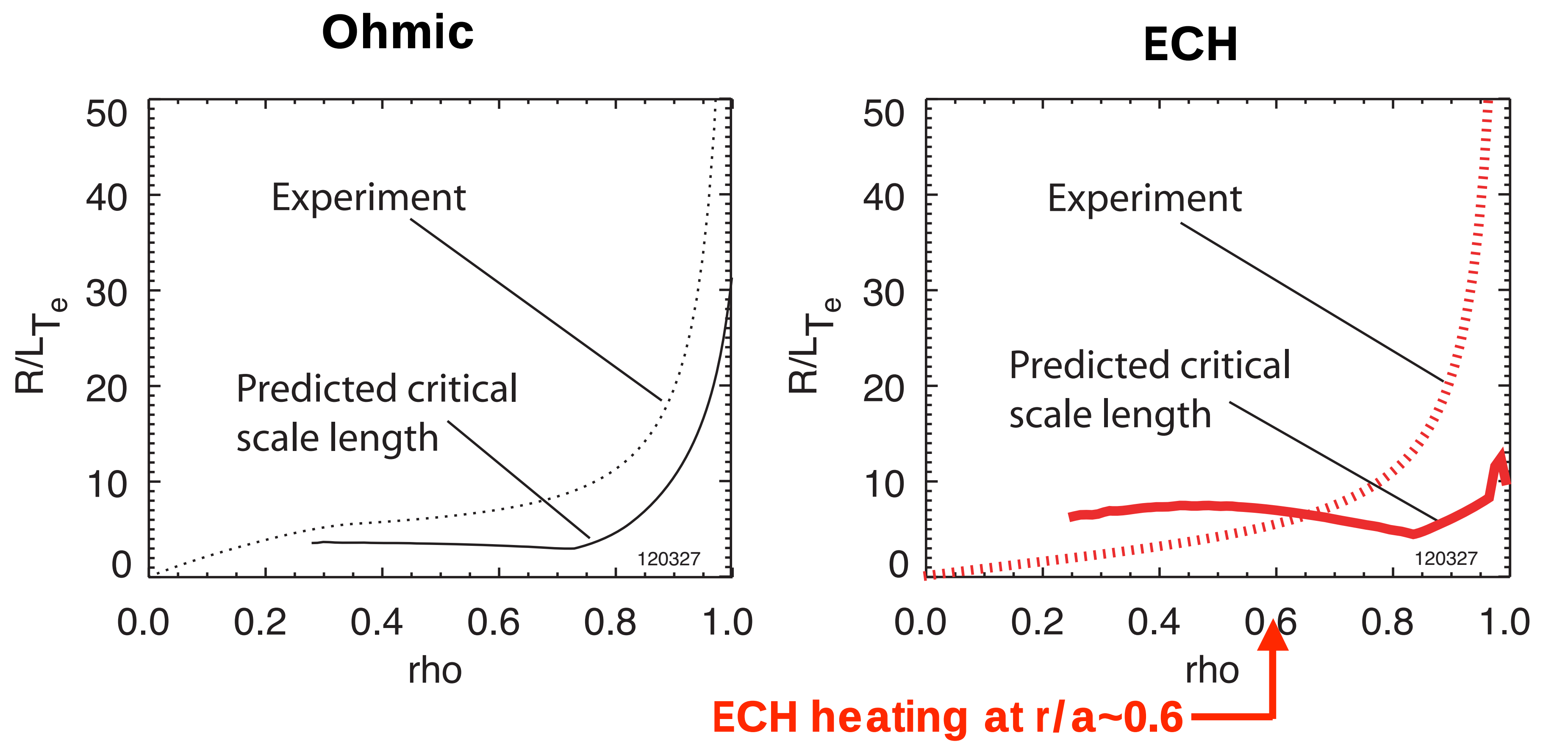
Increased E_r Shear During ECH Potentially Reducing Low K Fluctuations



- **ExB shearing rate is 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

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

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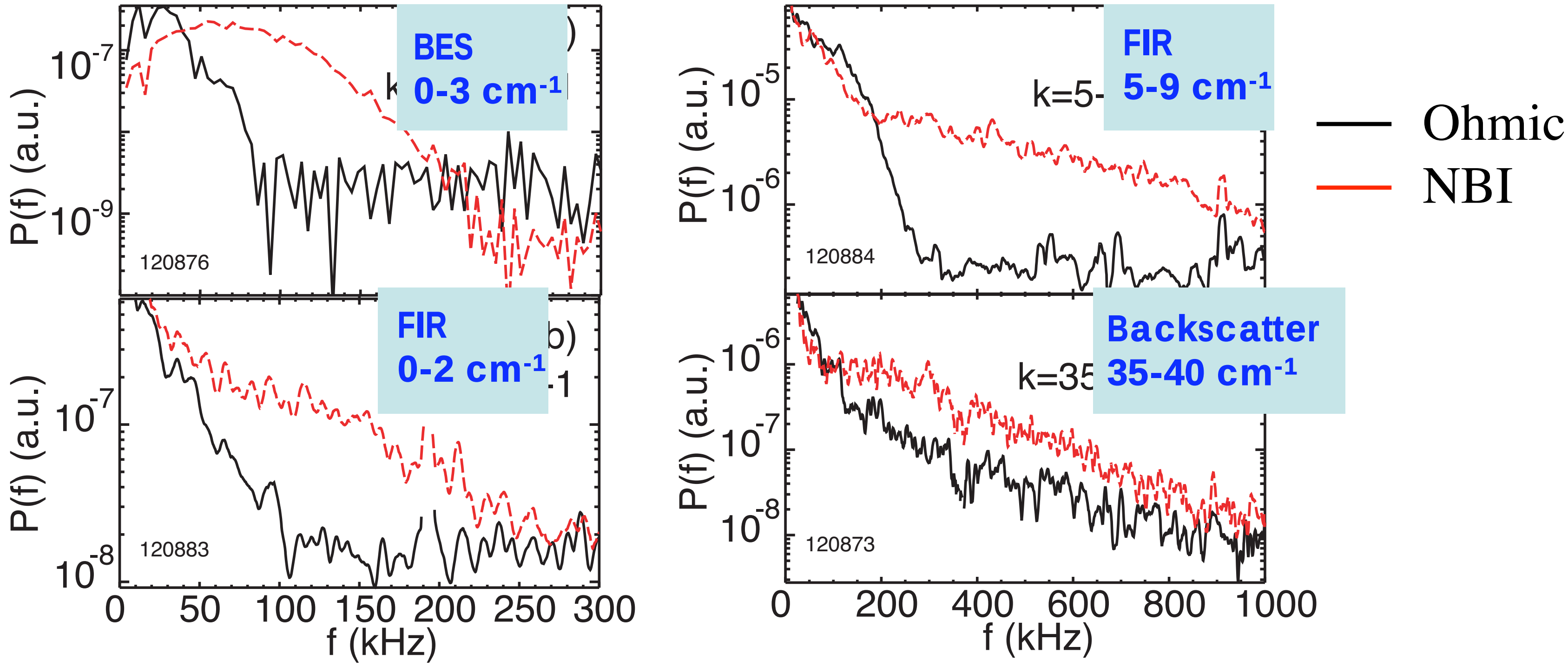
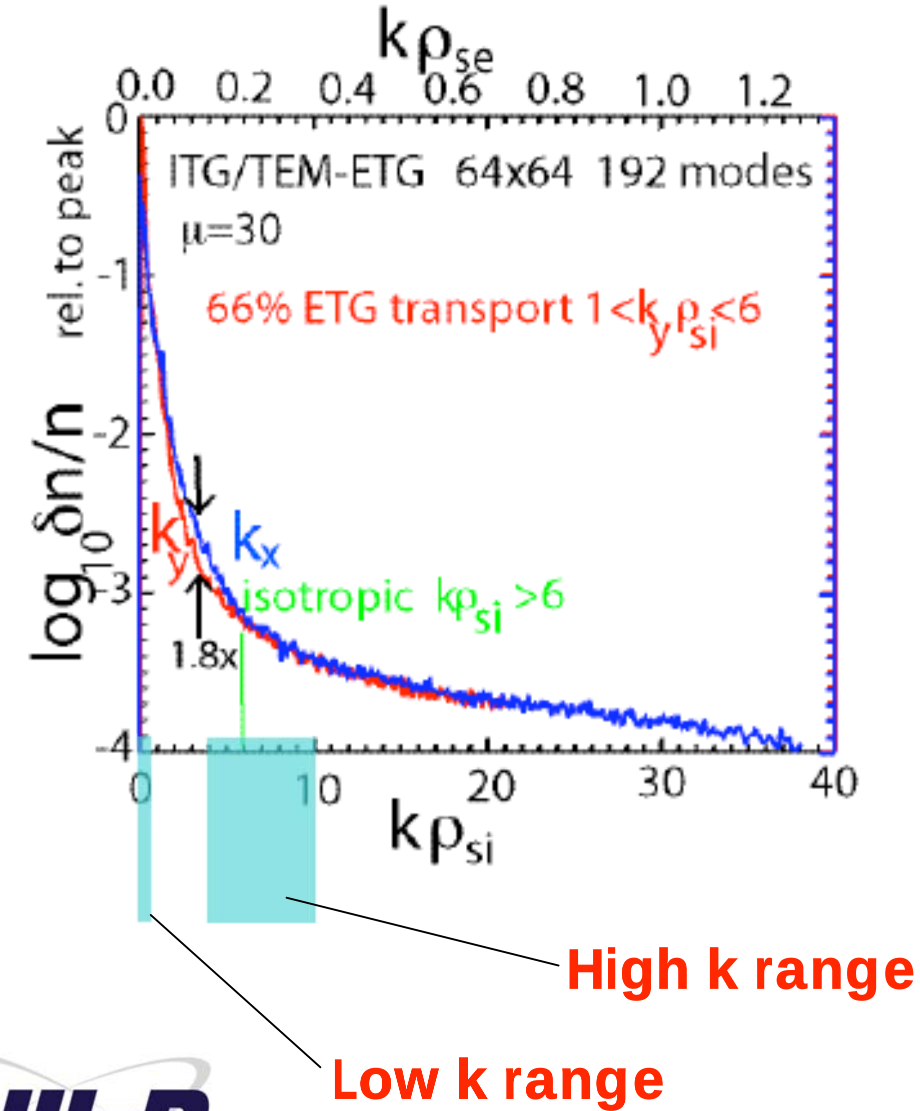
High and Low k ñ With Large Difference in Magnitude ~10^{-3}



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

Measured ñ Compare Reasonably Well With Non-linear GYRO Simulation

GYRO simulation, R. Waltz, GA



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

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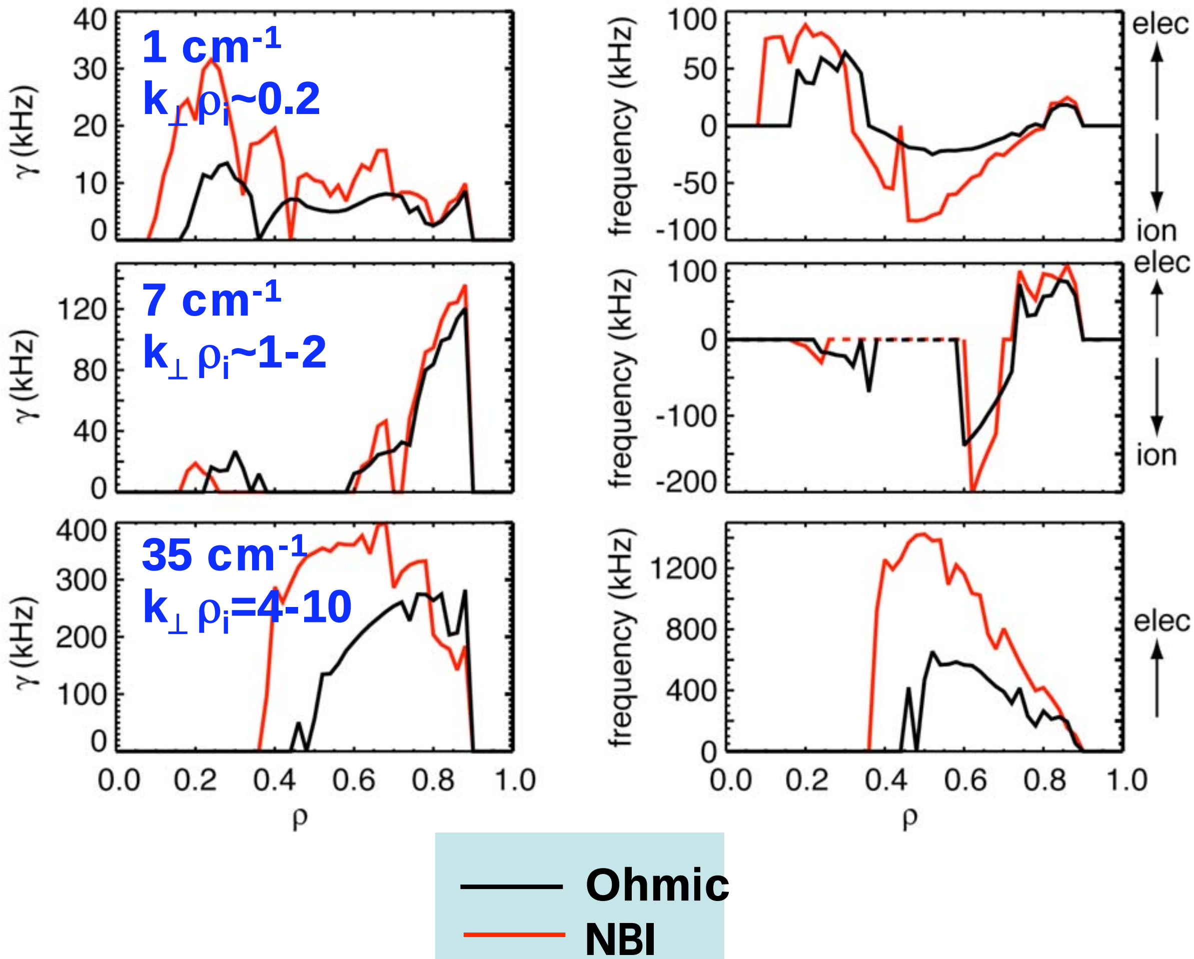
GKS Predicts Plasma Unstable Over Broad Range in k: 1-35 cm^{-1}, $k_\perp \rho_I$~0-10

Growth rates | **Frequency**



- **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**

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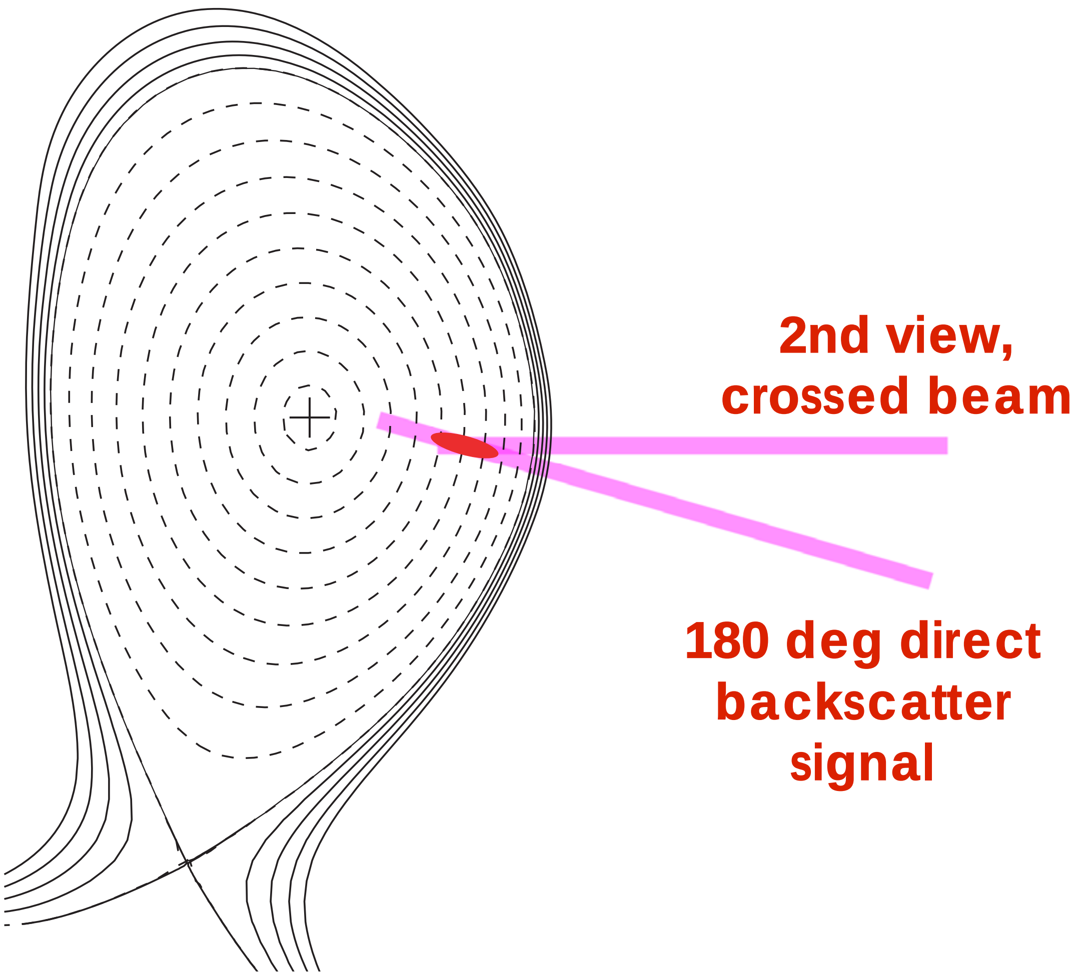
Second Channel of High k Backscatter Has Improved Spatial Resolution



- **180 deg direct backscatter signal is chord average**
- **2nd view, crossed beam has improved spatial resolution**
  - Resolution depends upon crossing angle
  - Typical resolution is ±10 cm at $1/e^2$ in amplitude

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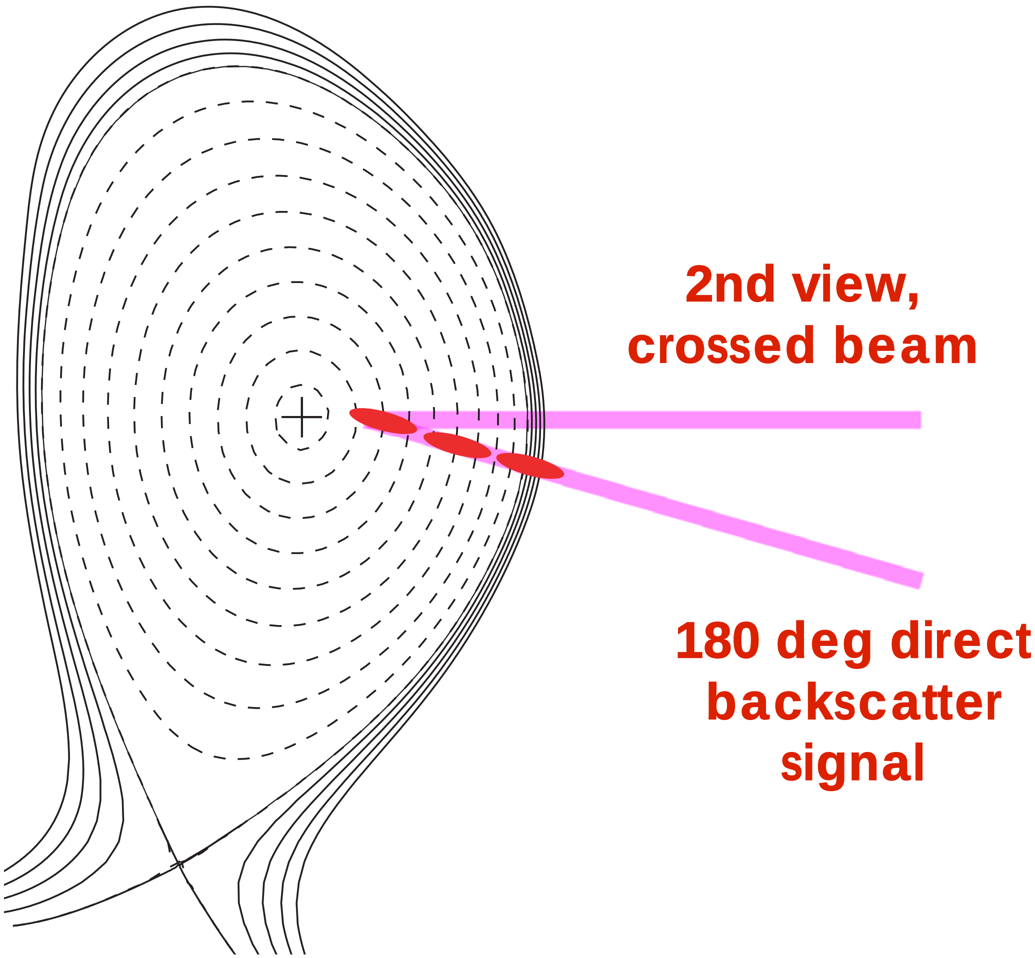
Second Channel of High k Backscatter Can Be Scanned Radially to Obtain Spatial Information on Fluctuations



- 180 deg direct backscatter signal is chord average
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  - Resolution depends upon crossing angle
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- **Radial location of 2nd view scanned by moving detector up or down.**

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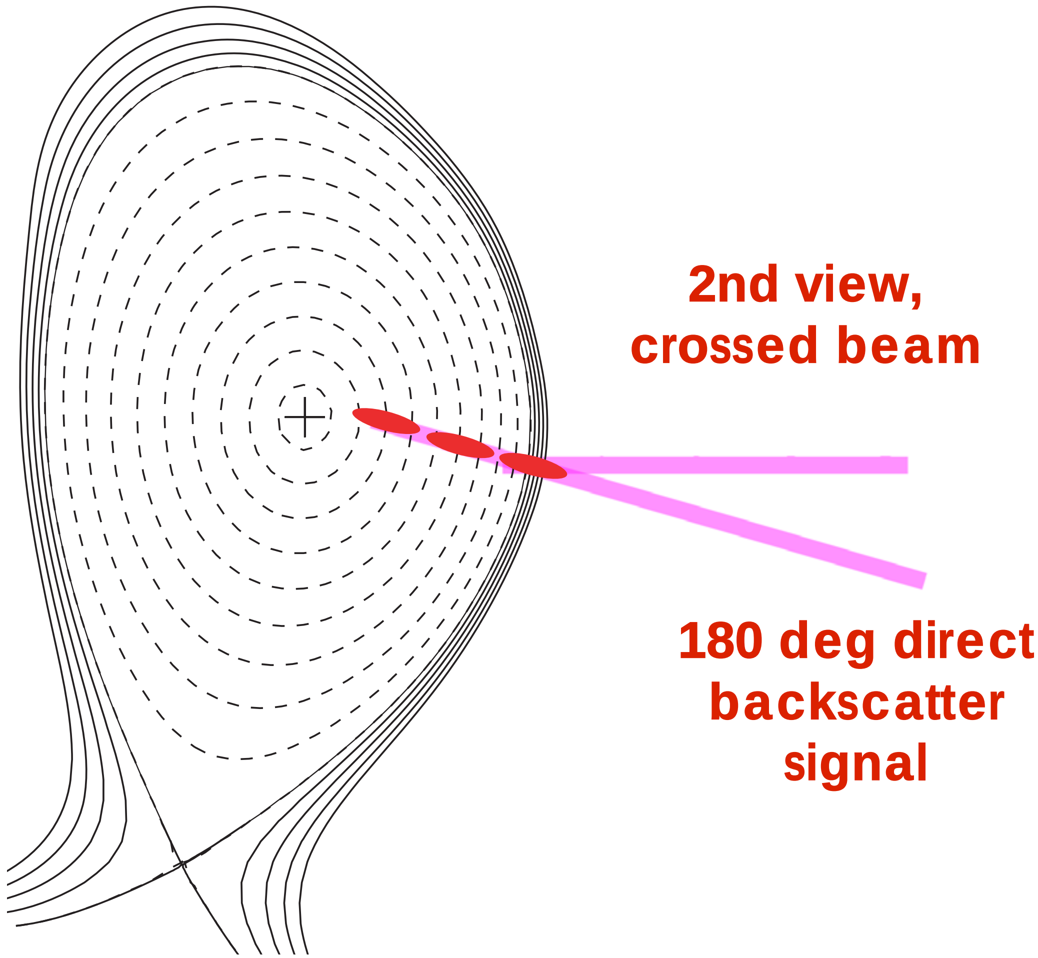
Second Channel of High k Backscatter Can Be Scanned Radially to Obtain Spatial Information on Fluctuations



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Summary

- Increased high k turbulence correlates with electron heat transport during ECH
- Measured high k is not a high k remnant or tail of ITG/TEM type modes
- Low k fluctuation behavior consistent with E_r shear, high k apparently not affected by E_r shear
- Spatial distribution of high k reveals distinct differences between edge to deep core