First observation of low, intermediate & high k turbulence in DIII-D & initial comparisons with gyrokinetic predictions

W.A. Peebles, T.L. Rhodes, M. Van Zeeland, D.R. Mikkelsen,
M. Gilmore, L. Zeng, D. Baker, K.Burrell, J.C. DeBoo, W. Dorland,
E.J. Doyle, J.S. deGrassie, C.M. Greenfield, T. Jernigan,
G. McKee, X.V. Nguyen, C. Petty, G. Staebler, & G. Wang.

The DIII-D Team

DIII-D
NATIONAL FUSION FACILITY
SAN DIEGO

UCLA

Overview

- **Anomalous electron thermal transport - motivation**
  - improved understanding important from both basic science & fusion perspectives
  - essential to study broad turbulent wavenumber spectrum ($0.1 < k\rho_s < 10$) – especially high k (ETG modes) **– connect to gyrokinetic simulations**

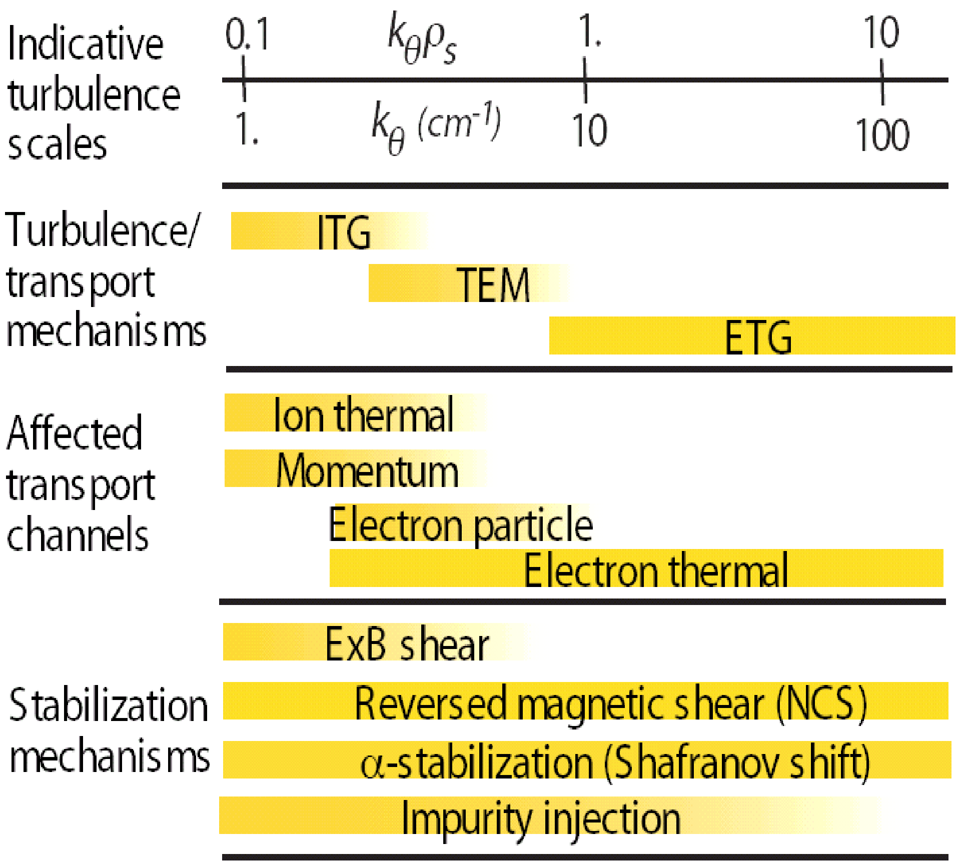
First high k turbulence measurements on DIII-D

novel microwave backscattering approach on DIII-D

- **Initial results in Ohmic plasma confirm a broad turbulent spectrum**
  - consistent with linear stability calculations
- **Electron cyclotron heating (ECH) and neutral beams (NB) used to modify profiles – particularly Te- & study effect on turbulence**
  - **low, intermediate** & **high k** respond differently and vary with spatial location.
  - initial comparison with linear calculations indicate clear differences, **motivates comparison with more detailed nonlinear gyrokinetic calculations**

High k measurement tools now available

Dominant turbulent modes in fusion plasmas



ETG (electron temperature gradient)

highest growth rate; very large wavenumbers - cascade to lower k, formation of radial streamers

The intermediate/low wavenumber region occupied by ITG (ion temperature gradient), **TEM** (trapped electron mode) **or even ETG modes**

ExB suppression effective at longer wavelengths – reduction of ion transport

Magnetic turbulence may also be important in core of AT plasmas

Important to investigate complete spectrum

Measurement approach on DIII-D

Turbulence	Approach
Low k $k_\perp\rho_s$ ~0.1, $0cm^{-1} < k_\theta < 5cm^{-1}$	**Collective scattering, BES & reflectometry** Spatial localization from ~1cm to chord averaged. **Probes k_θ , $\tilde{n}$**
Intermediate k $k_\perp\rho_s$~ 1, $5cm^{-1} < k_\theta < 15cm^{-1}$	**Collective scattering** Spatial localization ~ 40cm **Probes $k_{\theta,}$ $\tilde{n}$**
High k $k_\perp\rho_s$ ~ 5 - 10, k_r ~ $35cm^{-1}$	**Microwave backscattering** (now) - **phase contrast imaging** (future) Spatial localization Now ~ 50cm and ~20cm **Currently probes k_r,** $\tilde{n}$
Magnetic turbulence Tearing modes, etc	**Future plans (2005)** include sensitive Faraday rotation $\tilde{B}$ measurement.

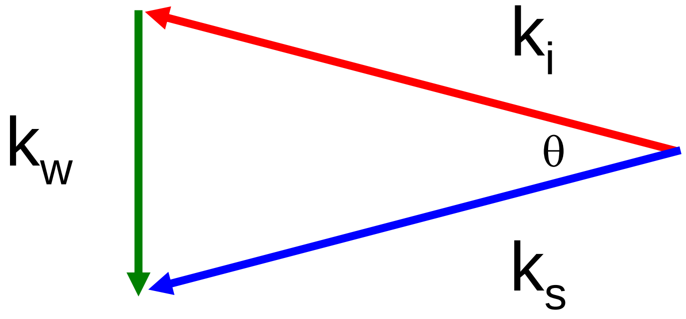
Collective Thomson scattering

Momentum matching gives

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

Energy conservation gives

$\omega_i+\omega_w=\omega_s$ i.e lab reference frame



Bragg Law:

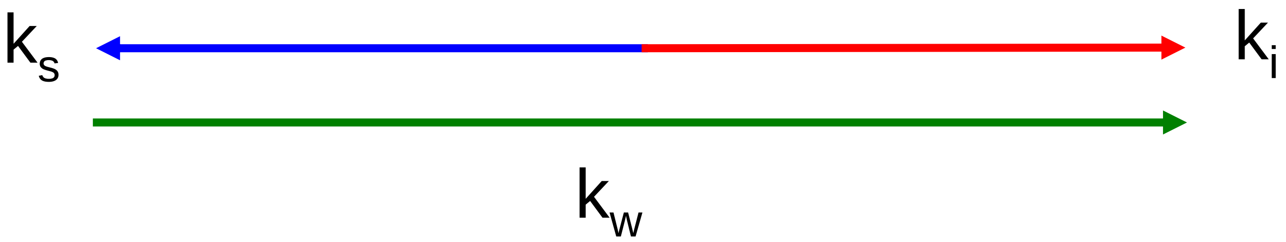
For $k_i \sim k_s$, can show that

$\mathbf{k_w = 2k_iSin}\theta/_2$

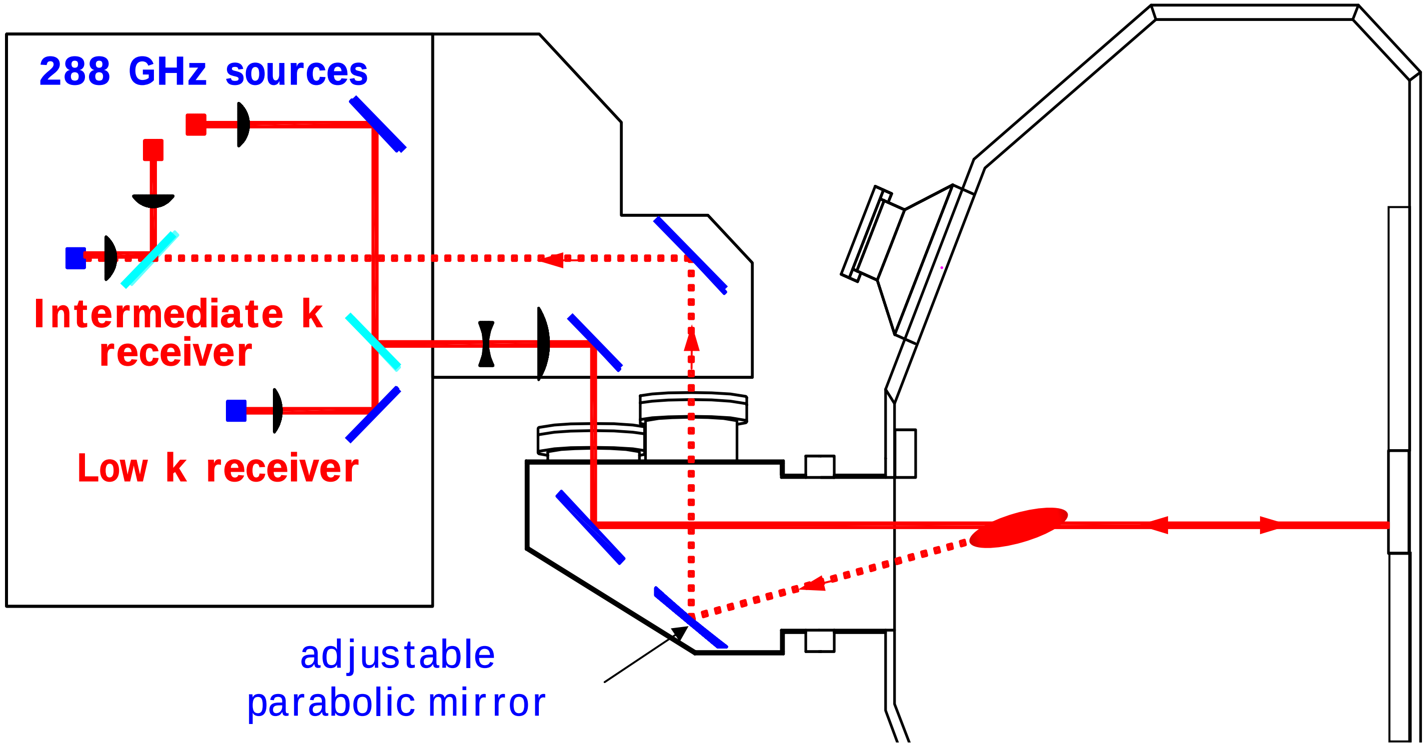
where θ is the scattering angle.

When scattering is <u>backward</u> (~180°) probed wavenumber ~2k_i

Probes wavenumbers along incident beam



Low ($k<1\text{cm}^{-1}$), and intermediate k ($7-12\text{cm}^{-1}$) turbulence measured via far-infrared (FIR -288GHz) O-mode scattering



Low and **intermediate** wavenumbers (**k_θ**) probed via forward scattering at **288GHz**. The incident **O-mode** radiation propagates across the plasma midplane and retro-reflects from tile on the inner wall. Forward scattered radiation detected.

High k (k~35cm^{-1}) turbulence measured via X-mode microwave (94GHz) backscattering

High radial k (35cm^{-1}) probed via backscattering at **94GHz** (**green**)

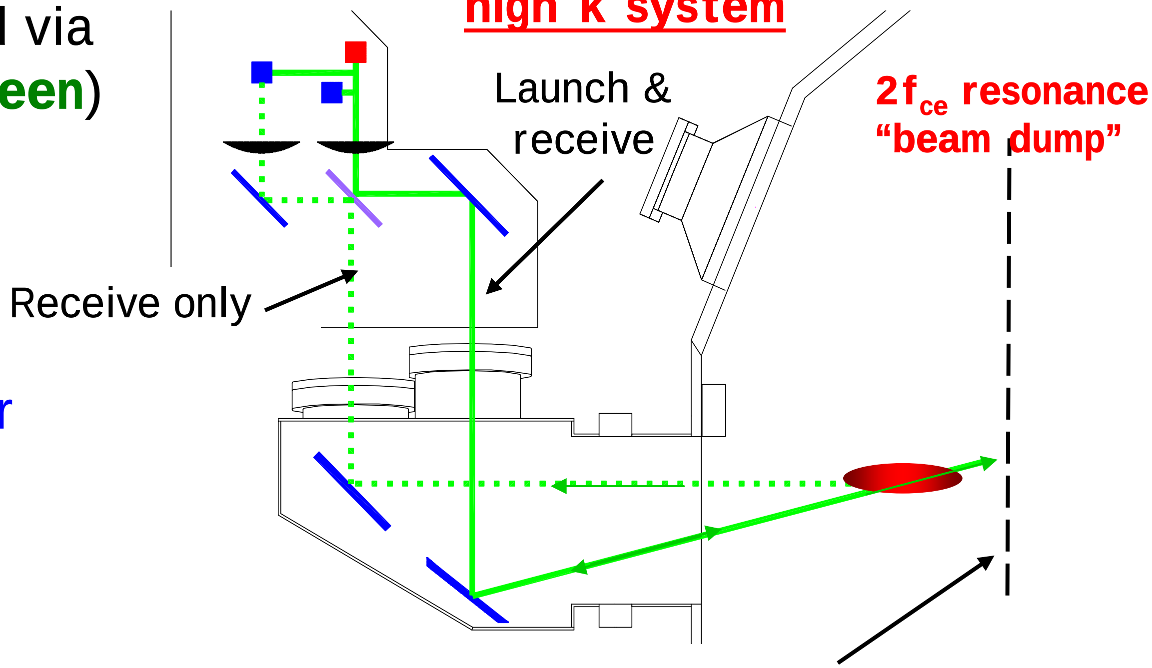
Two distinct measurements:

(1) 180°pure backscatter
Edge to 2fce resonance layer

(2) 165° core localized
measurement (Δr~20cm)

The two views probe effectively identical k's ~35cm^{-1}

94 GHz backscattering
high k system



$2f_{ce}$ X-mode resonance layer acts as an **internal beam dump** for the incident and forward scattered 94 GHz radiation.

94 GHz backscattering integrated into overall scattering system

Validity tests of scattering data

- **FIR data low & intermediate k**

  Laboratory tests prior to installation: cross-talk, spatial localization, etc.

  No crosstalk observed between turbulence data

  Observed proportionally higher Doppler shifts as k is increased (ExB Doppler shift)

- **94GHz backscatter data – high k**

  Laboratory tests prior to installation: cross-talk, spatial localization.

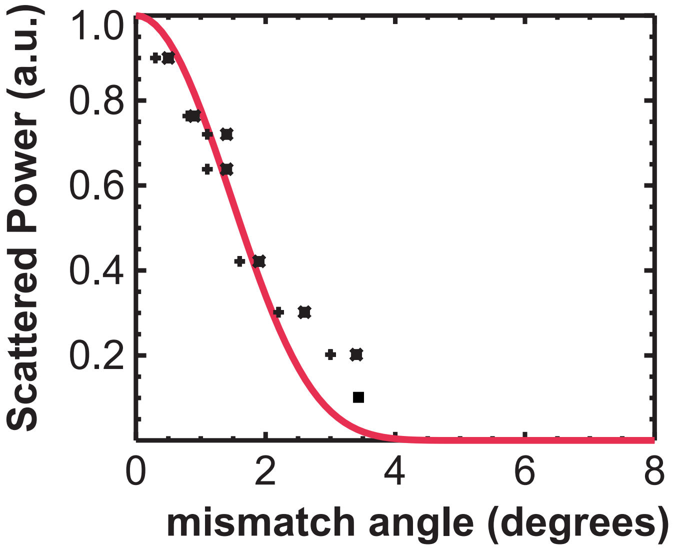
  Sees no MHD modes unlike low k

  No coherency found between low-k FIR data and backscatter microwave signal

Backscatter nature of signal confirmed

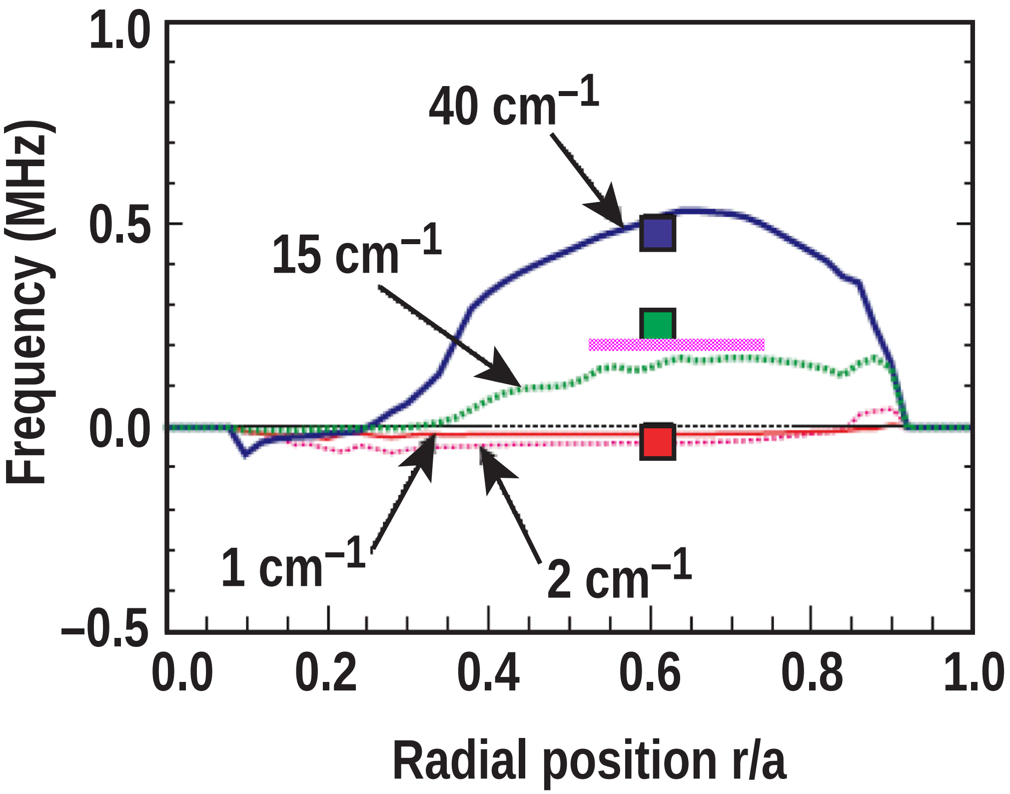
Probed wavevector is mismatched or misaligned with plasma turbulence wavevector

Signal variation matches predicted response (Slusher & Surko, Phys Fluids 1980)



Initial observations in Ohmic plasma consistent with linear GKS calculations

GKS calculations



Non-linear calculations underway

Measurements indicate a broad turbulent wavenumber spectrum

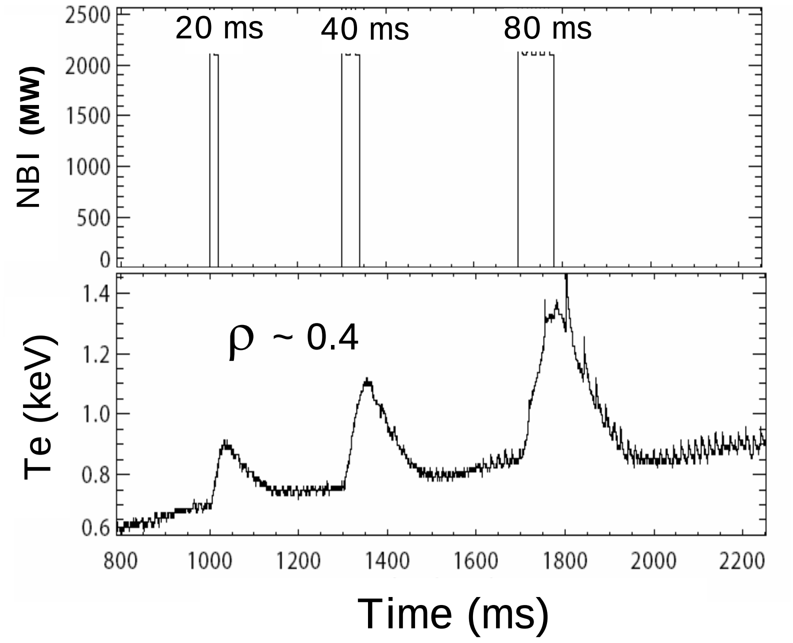
GKS linear growth rate calculations confirm modes unstable over broad wavenumber range (1 – 40cm^{-1})

Calculations of the real frequencies of the unstable turbulent modes also consistent with experimental measurement.

Colored squares indicate Gaussian widths of measured fluctuation spectra

Magenta line is electron bounce frequency, $\omega_b/2\pi \sim \varepsilon 1/2 Ve/Rq$

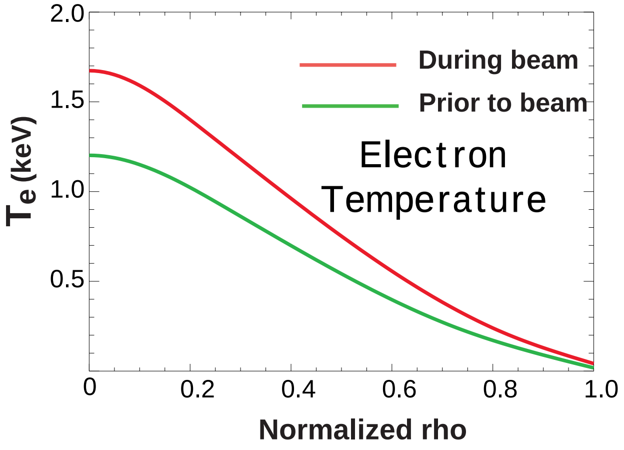
Utilize short duration NBI to modify Te profile

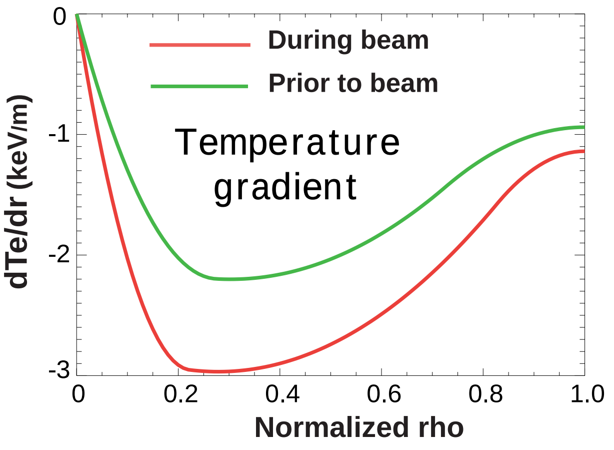


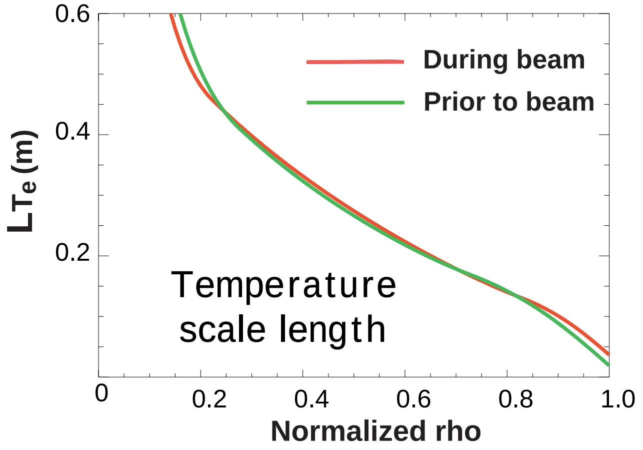
- Beam “blips” couple energy to electrons. Little change in electron temperature scale length (LT_e)
- Ion temperature and density remain effectively constant.

Primary effect of NBI is to increase Te, dTe/dr and Te/Ti ratio

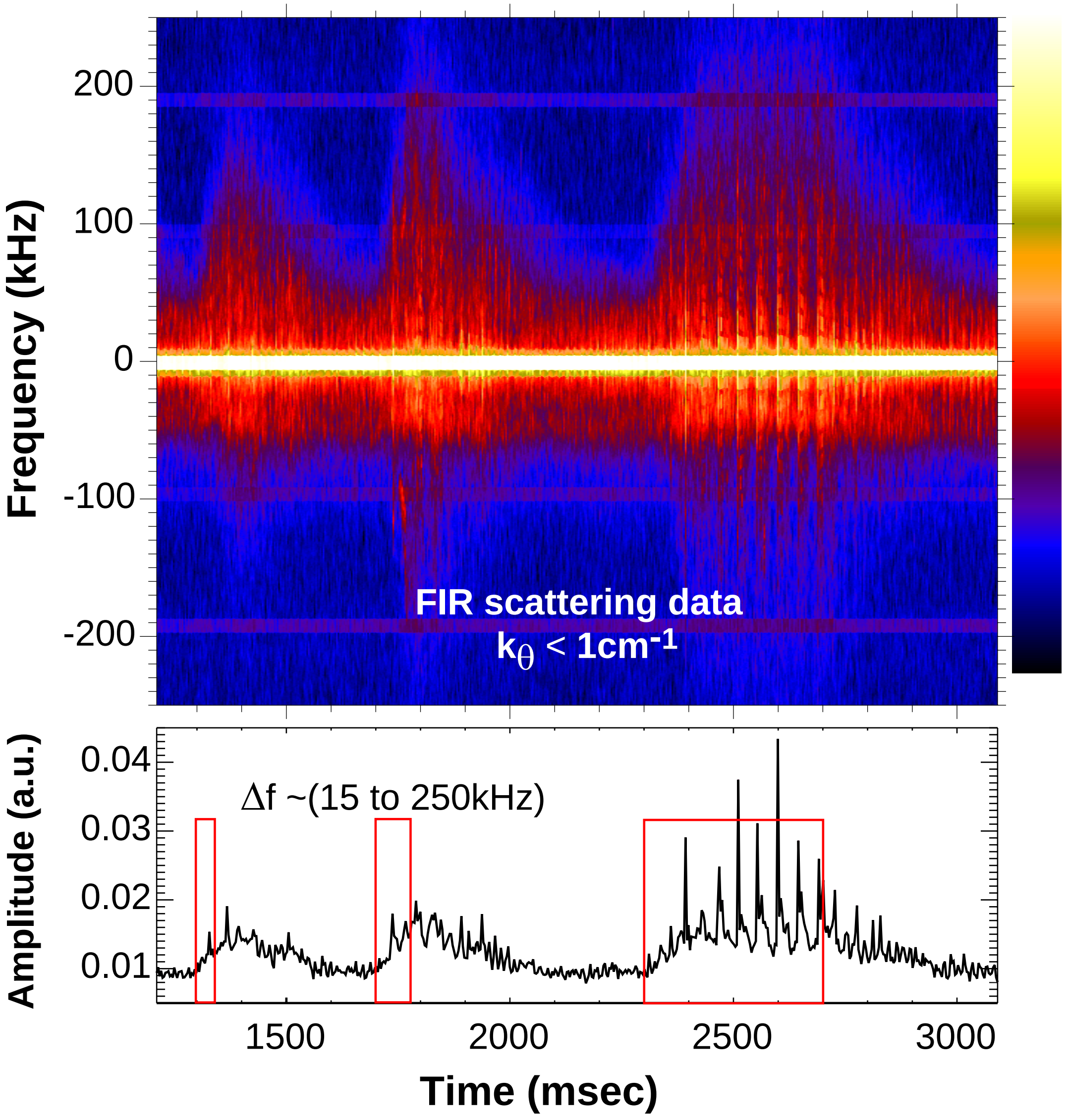
T_e/T_i increases by up to 50%
Rotation (E_r) also increases

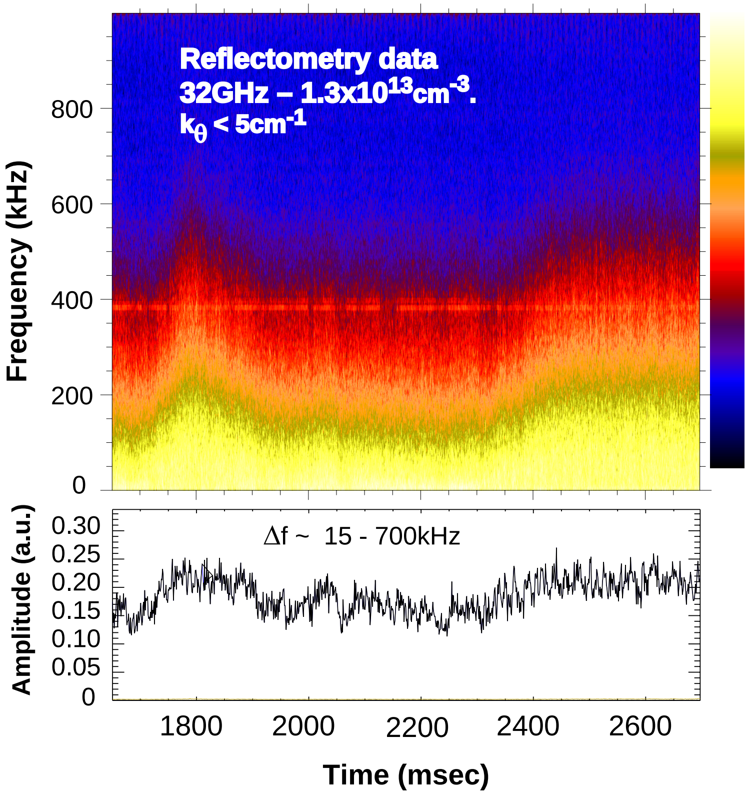


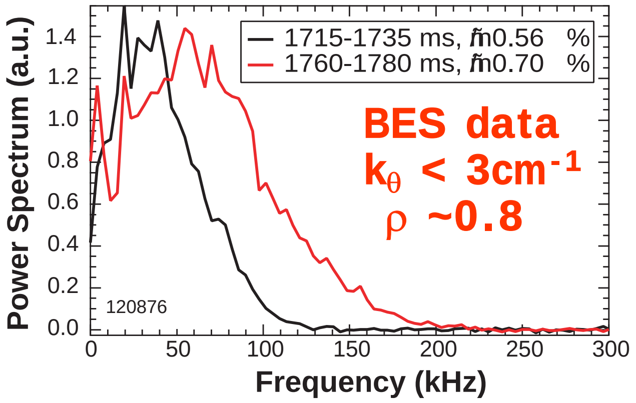




Scattering, BES & reflectometry all indicate low k turbulence increases

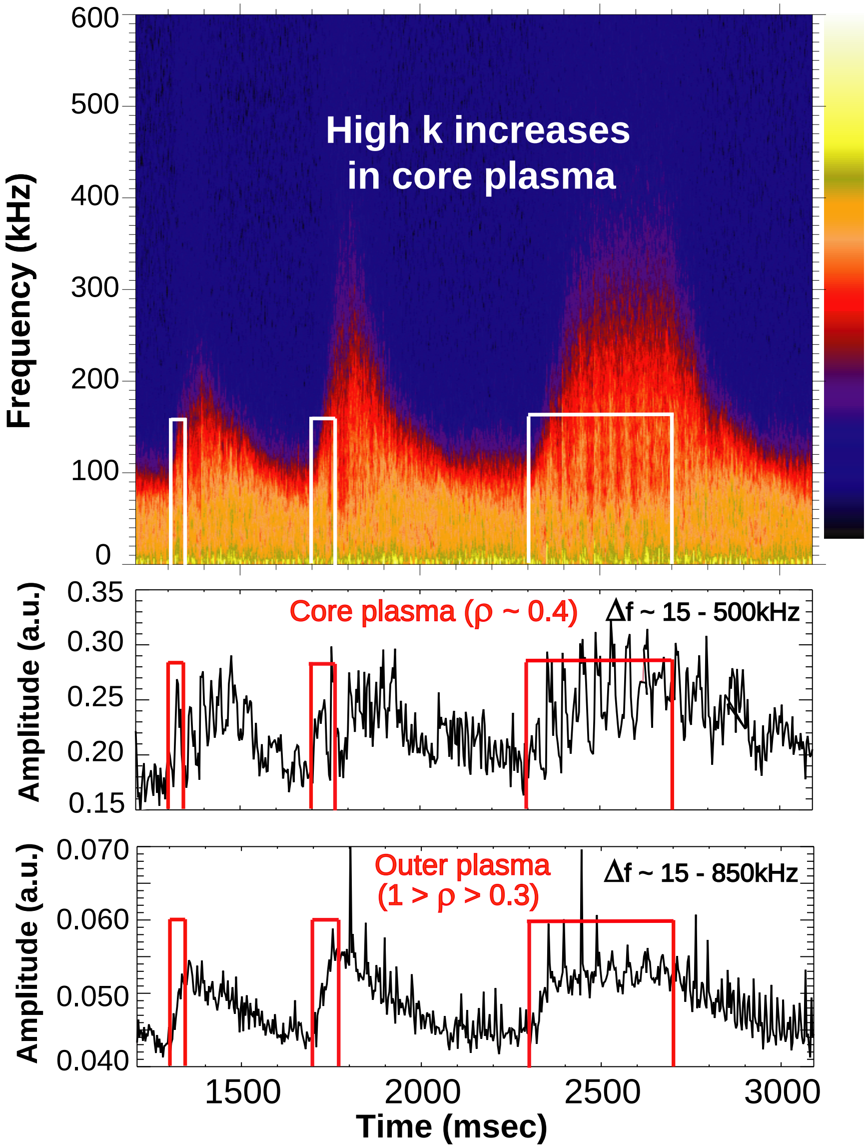




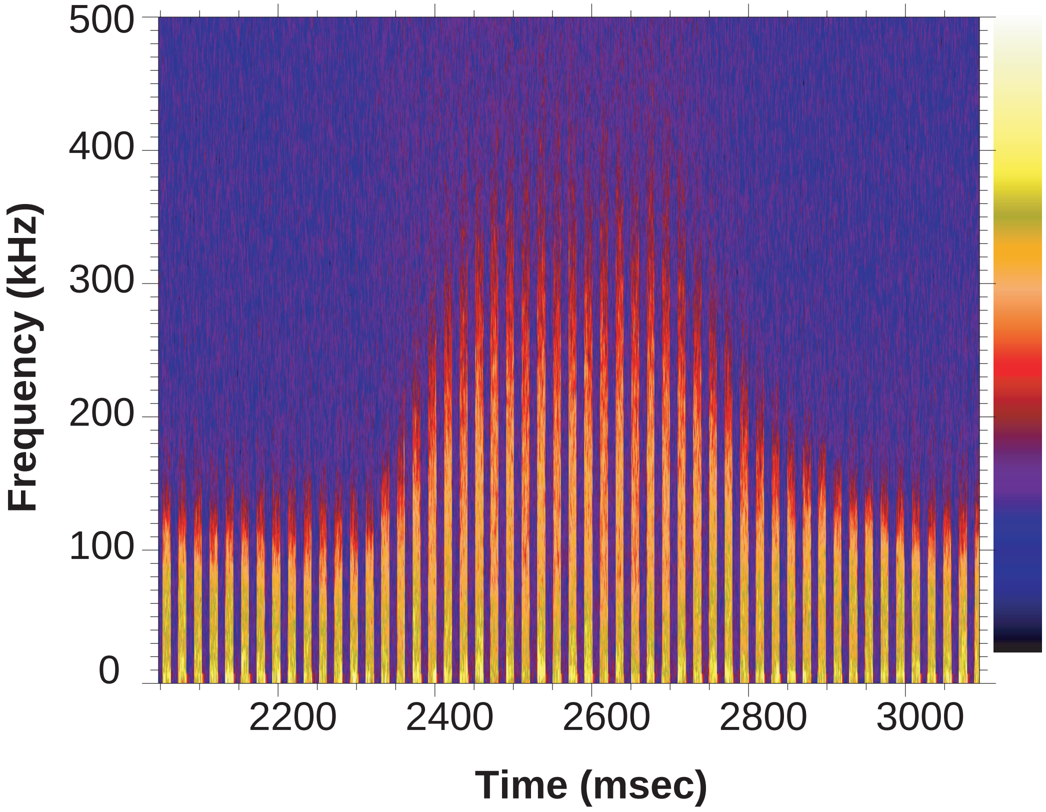


NBI increases high k turbulence in both outer and core plasma

Large frequency upshift

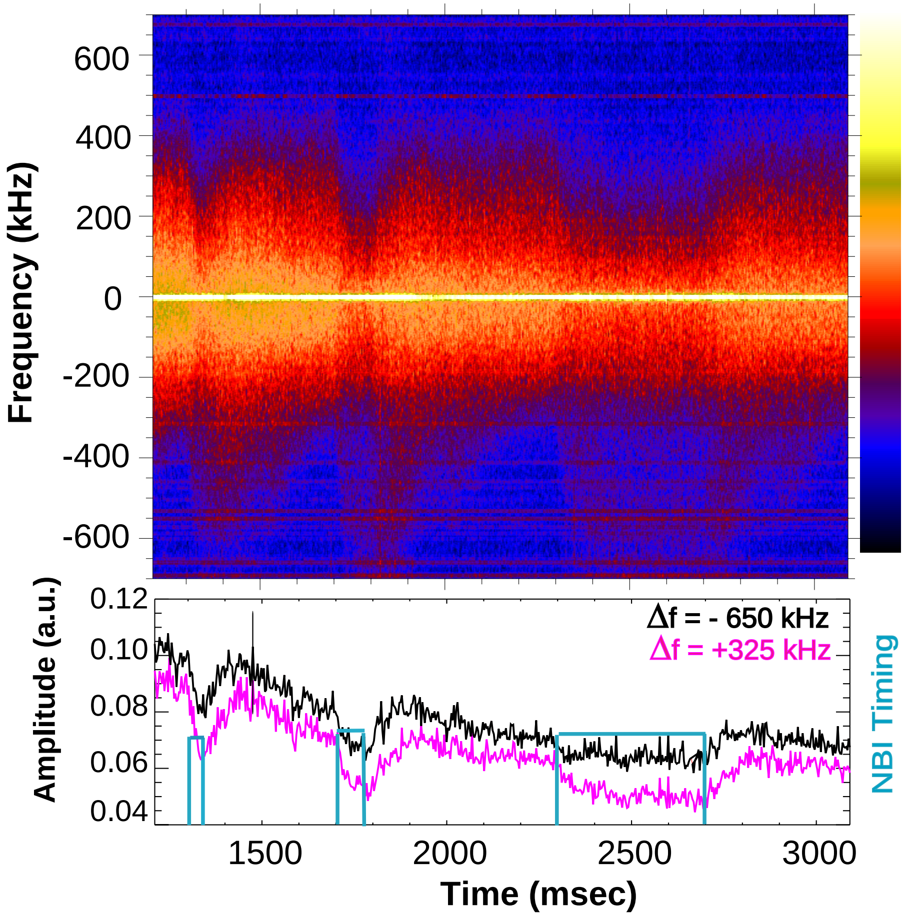


Modulation of incident power confirms that signal is scattering and NOT electron cyclotron emission

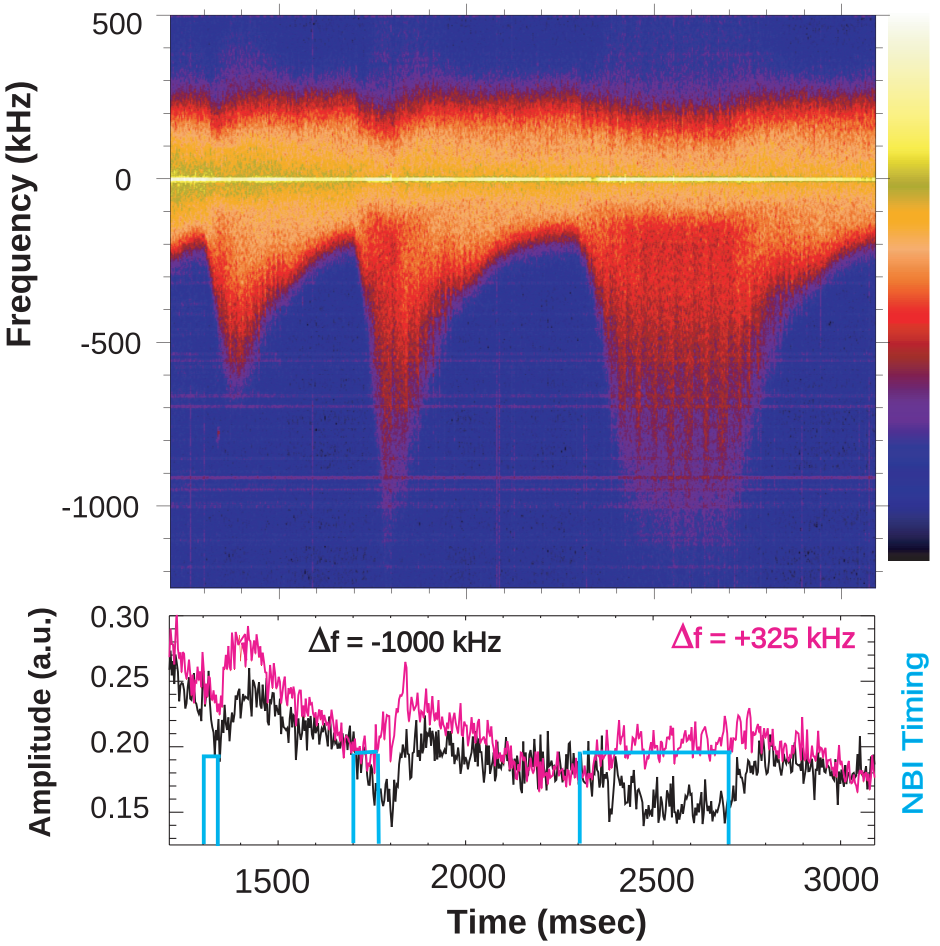


Intermediate k tends to decrease

9cm^{-1} decreases

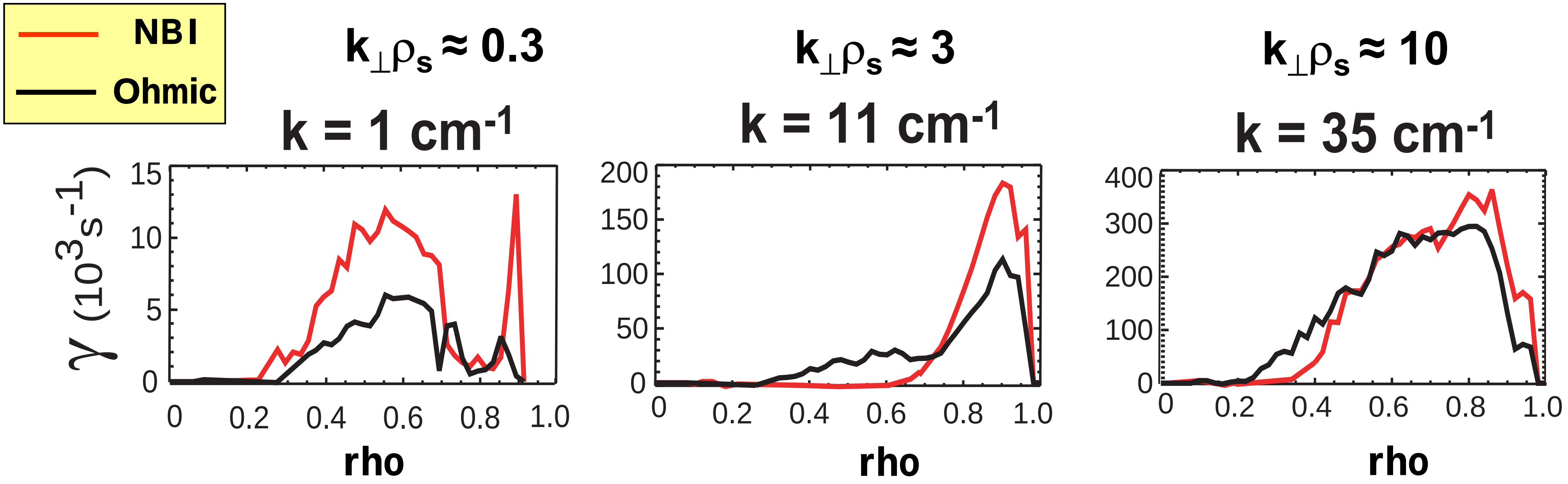


7cm^{-1} ~ constant



Intermediate k tends to decrease – more so at higher k, where the measurement is more localized to the core plasma

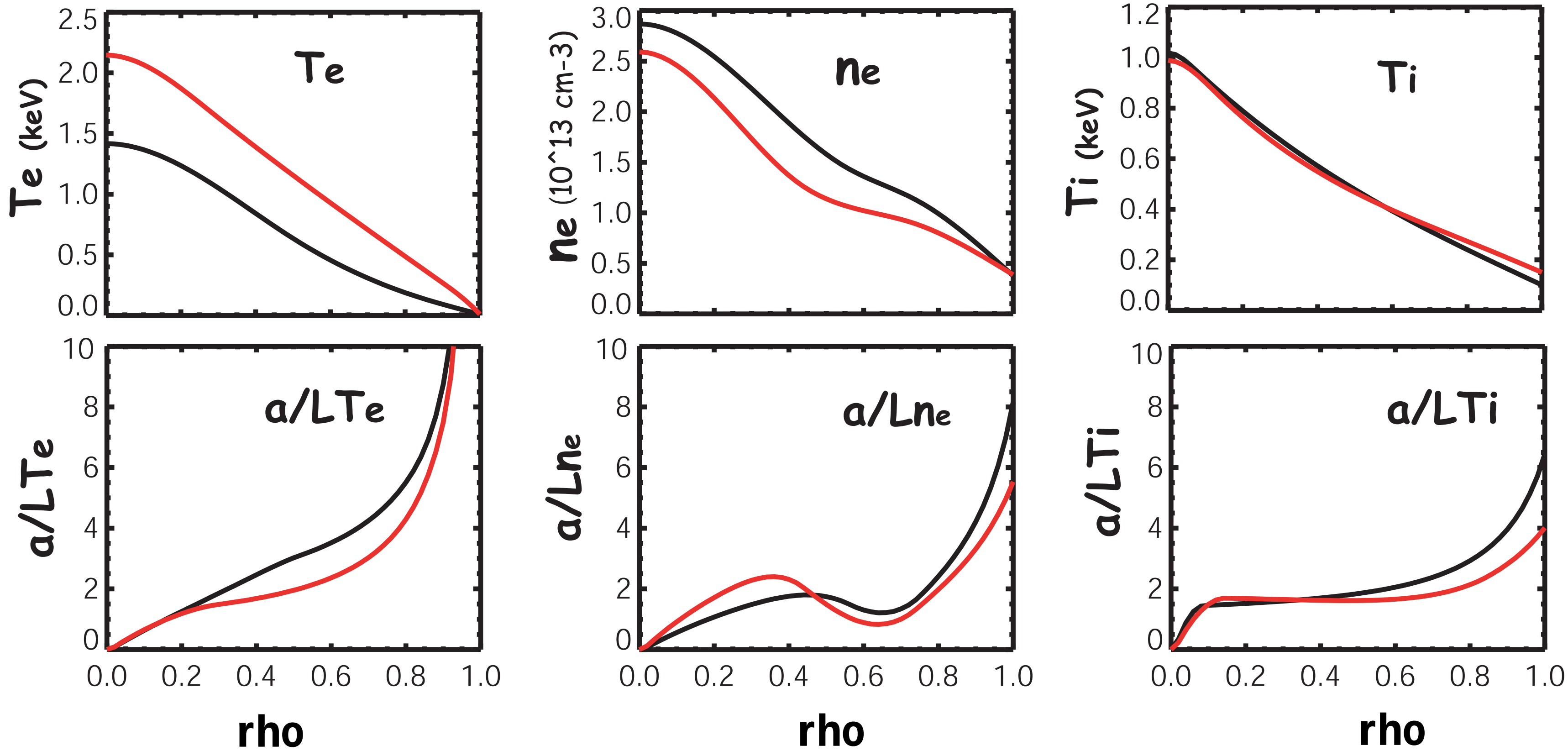
GKS linear growth rate calculations vary spatially and with wavenumber



Experiment	Low k	Intermediate k	High k
Outer plasma	↑ ✓		↑ ✓
Core plasma	↑ ✓	small ↓ ✗	↑ ✗

Detailed comparison requires nonlinear calculations: work underway

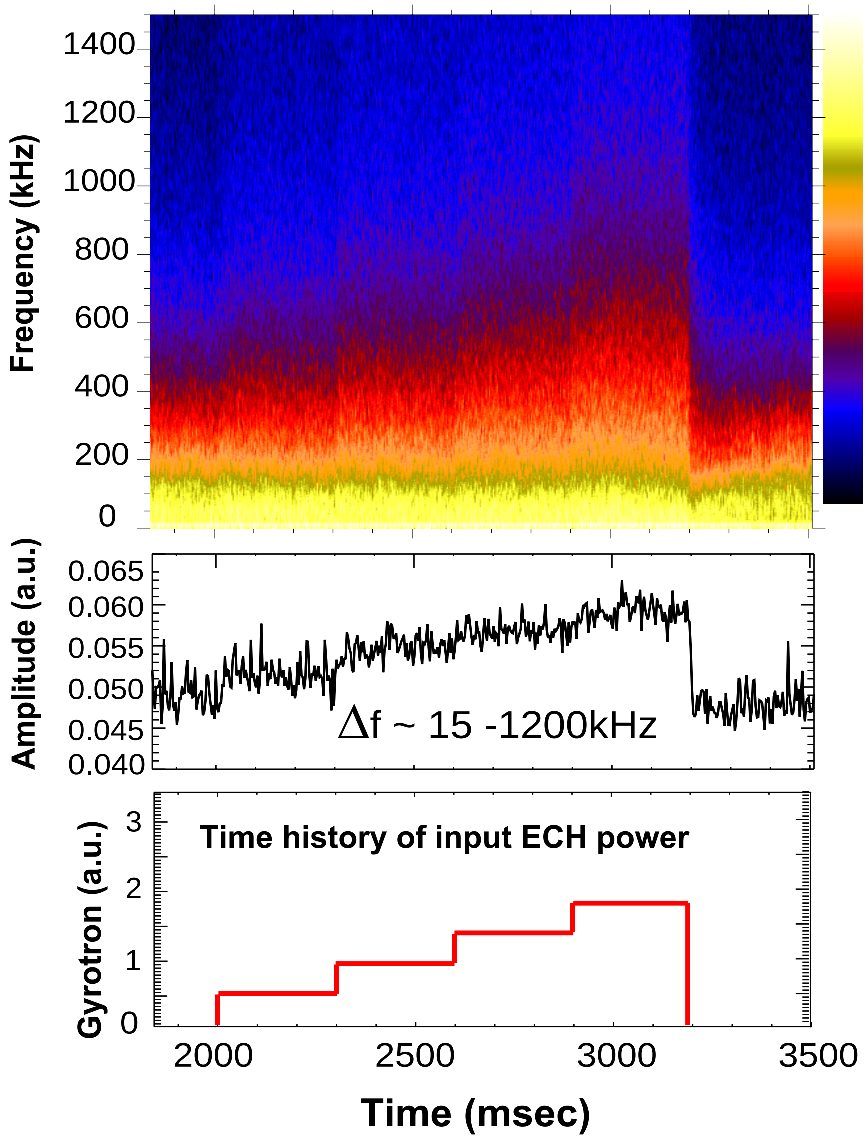
ECH affects both Te, dTe/dr & scale length LTe



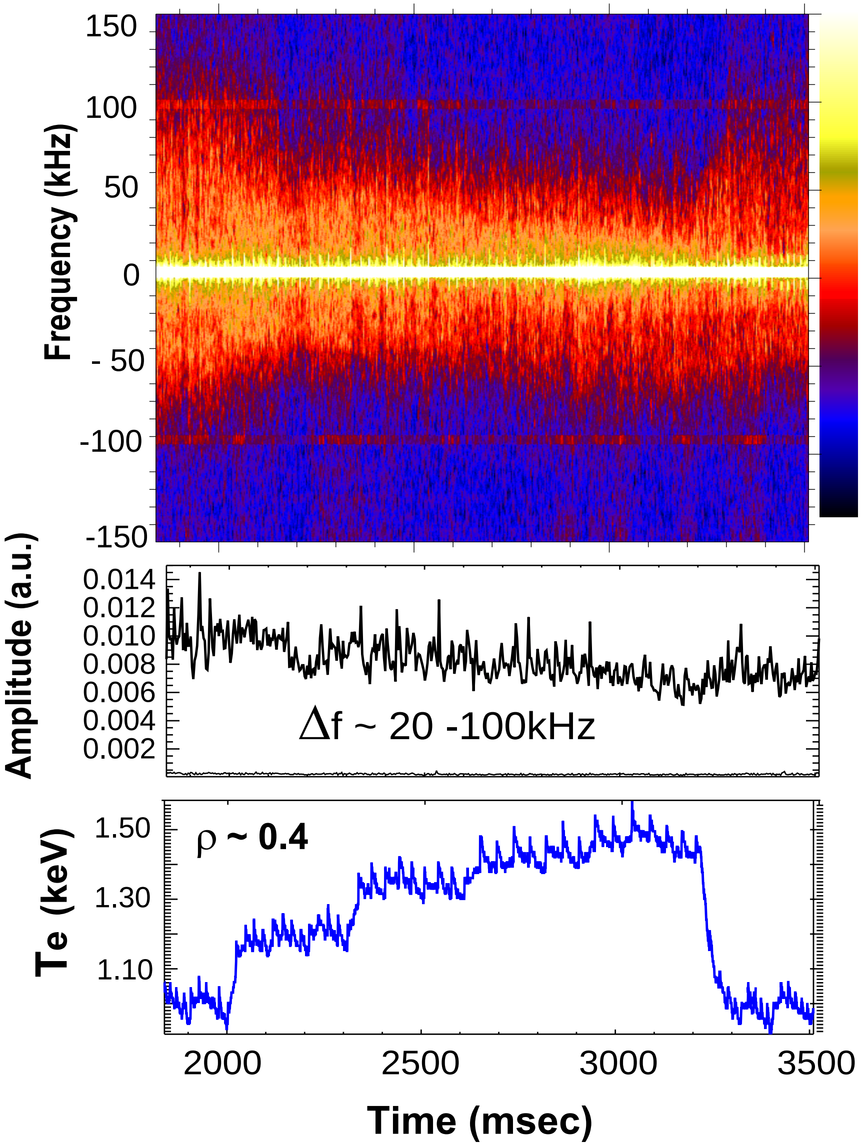
- ECH increased Te, dTe/dr, Te/Ti ratio while also modifying LTe the electron temperature scale length
- Electron density profile <u>also</u> changed
- Ion temperature tended to remain constant: Te/Ti ↑

High k increases significantly in outer plasma
low k slightly reduced or unchanged

High k increases in outer plasma



Low k slightly reduced

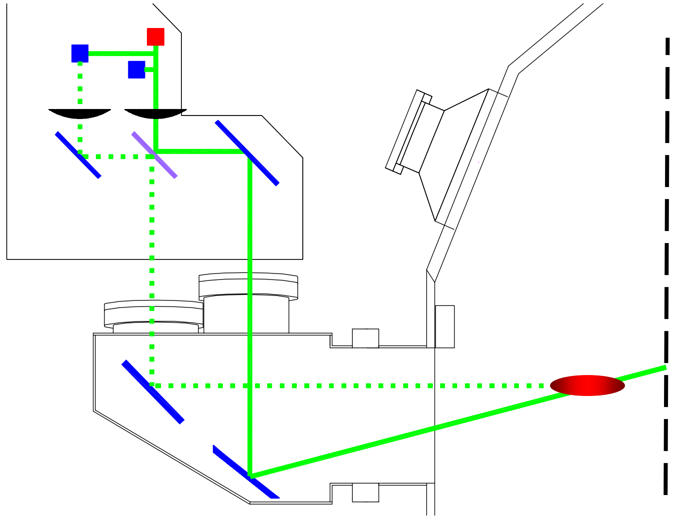


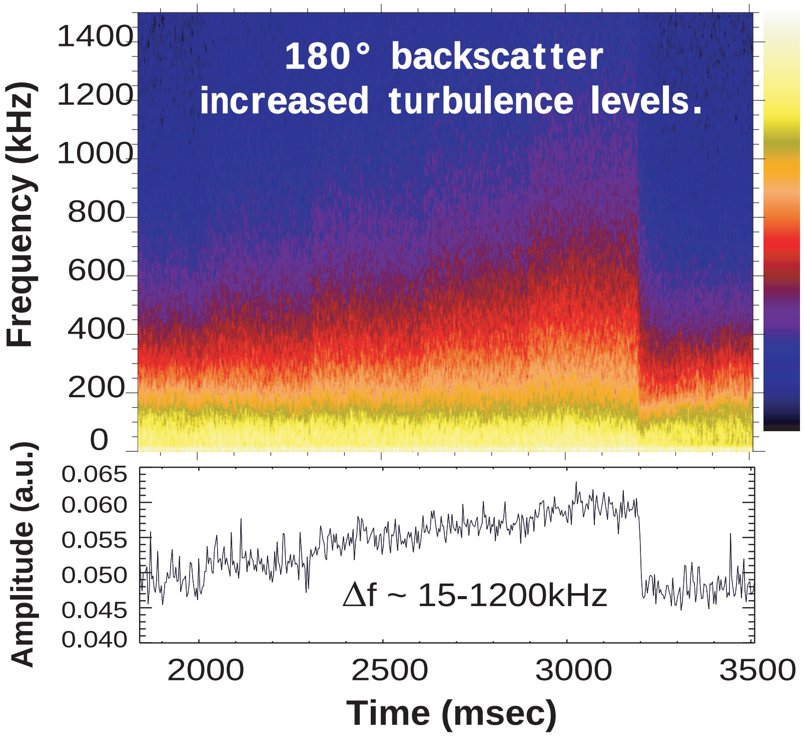
High k turbulence decreases in core (ρ ~0.4) plasma

Rearrange backscatter geometry to obtain a second view with improved spatial localization

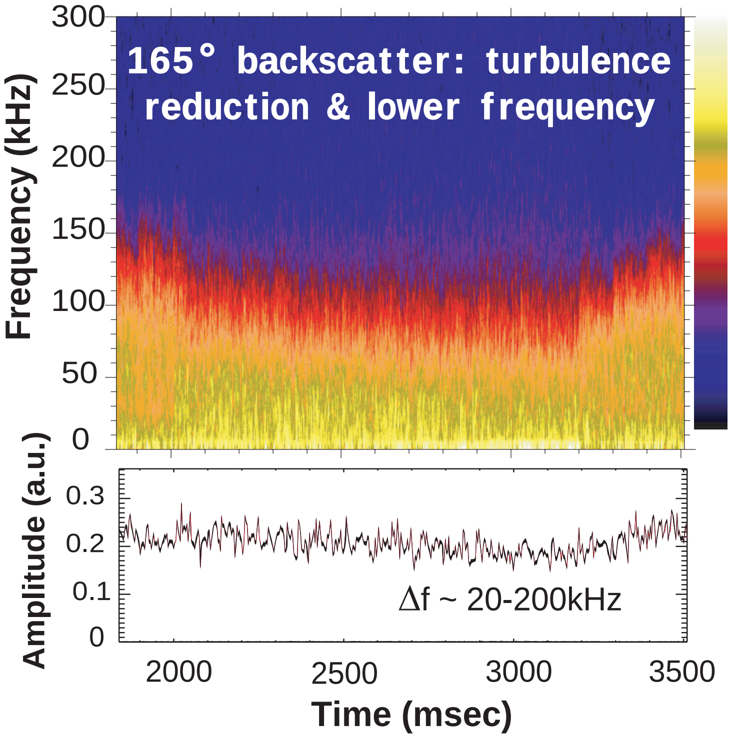
Note difference in frequency spectrum

Core signal narrows slightly whereas signal from outer plasma broadens





180° backscatter increased turbulence levels.



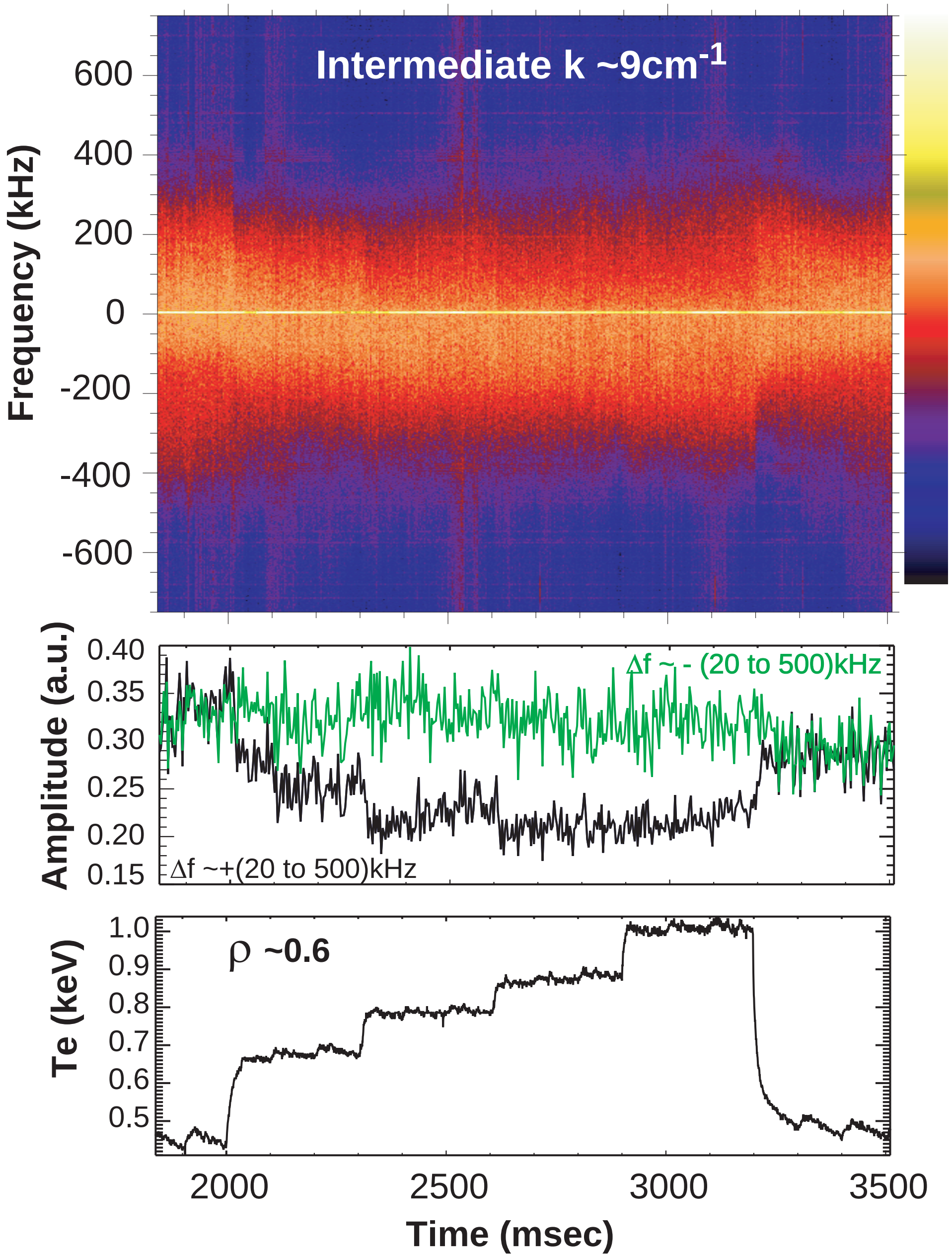
165° backscatter: turbulence reduction & lower frequency

ECH: Intermediate k also slightly reduced

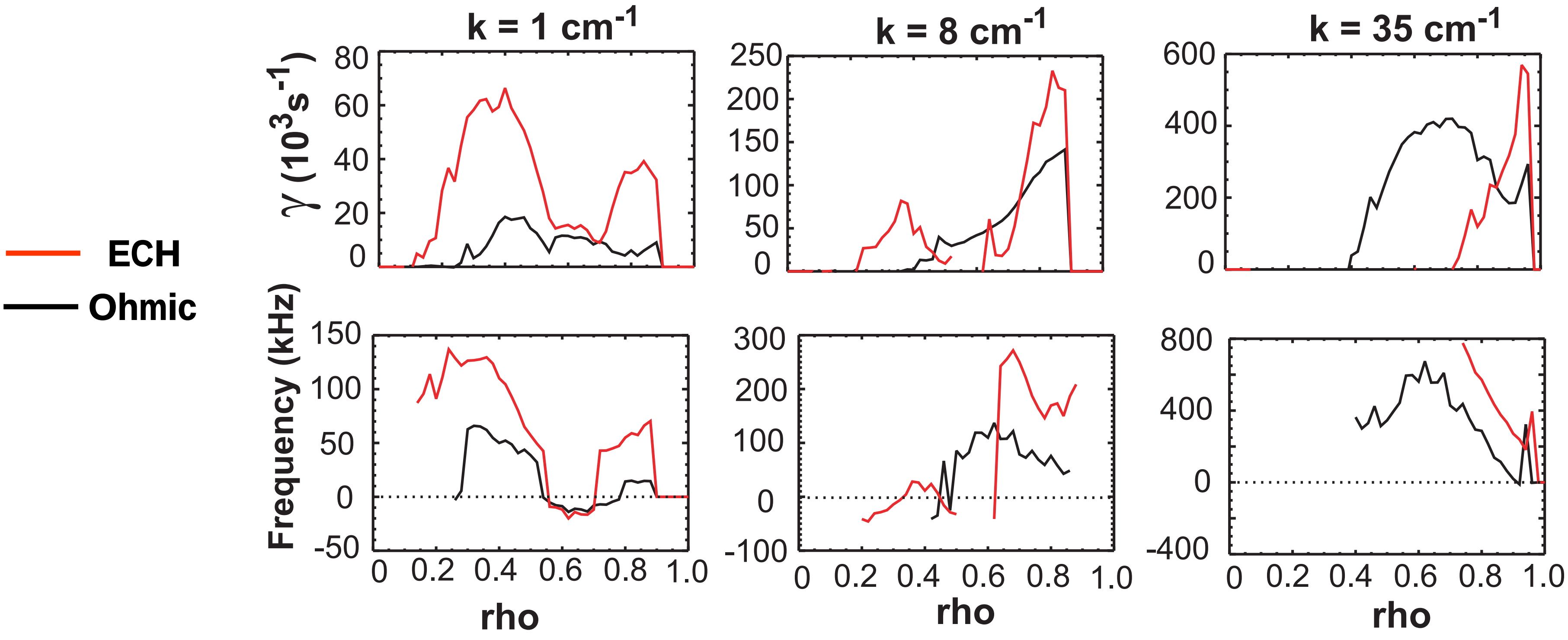
Scattering location for 9cm^{-1} centered at ρ ~ 0.3 with localization of ~ 40cm.

Measurement is a core measurement rejecting edge plasma- similar to second backscatter view

Small, but abrupt, frequency change –consistent with E field measurements



GKS growth rate calculations for ECH plasma vary in space and with wavenumber

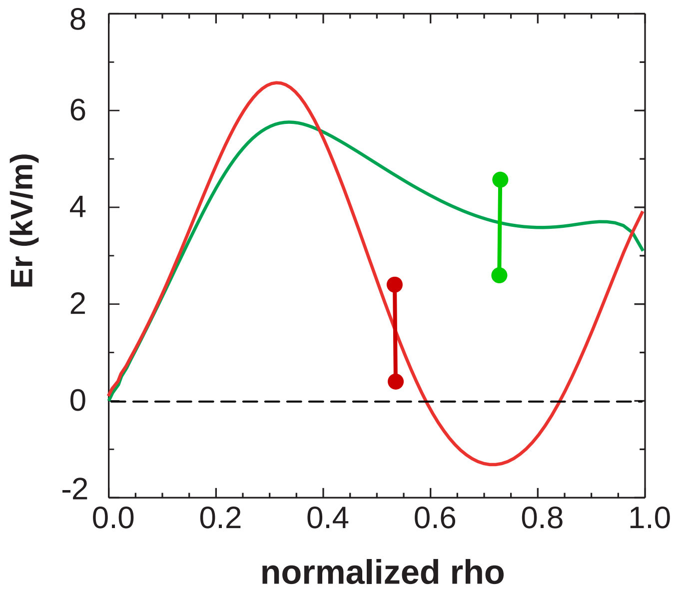


Experiment	Low k	Intermediate k	High k
Outer plasma	small ↓ ✗		↑ ✓
Core plasma		small ↓ ✓	small ↓ ✗

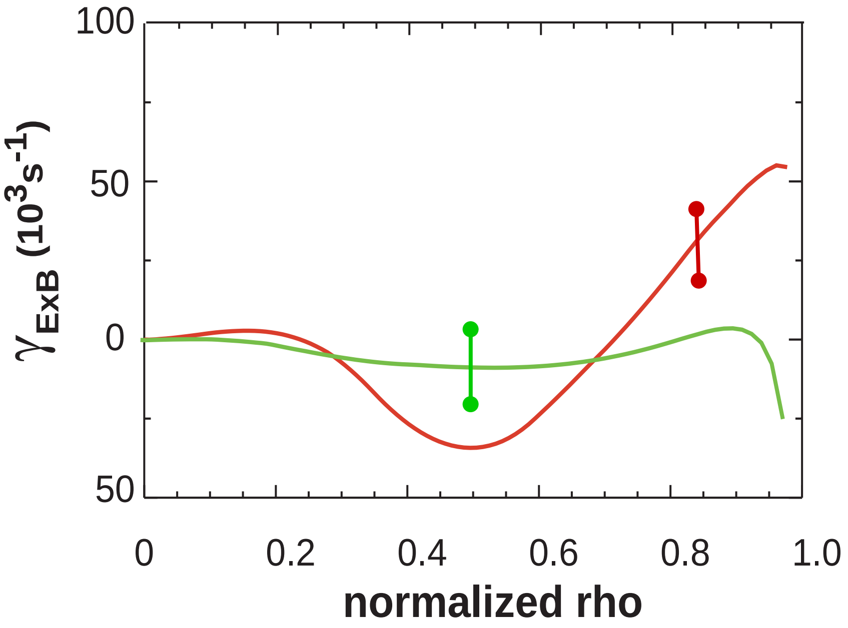
Note: effect of ExB shear flow not included

Modification of radial electric field during ECH consistent with observed turbulence spectrum

Electric field profiles



ExB shearing rate



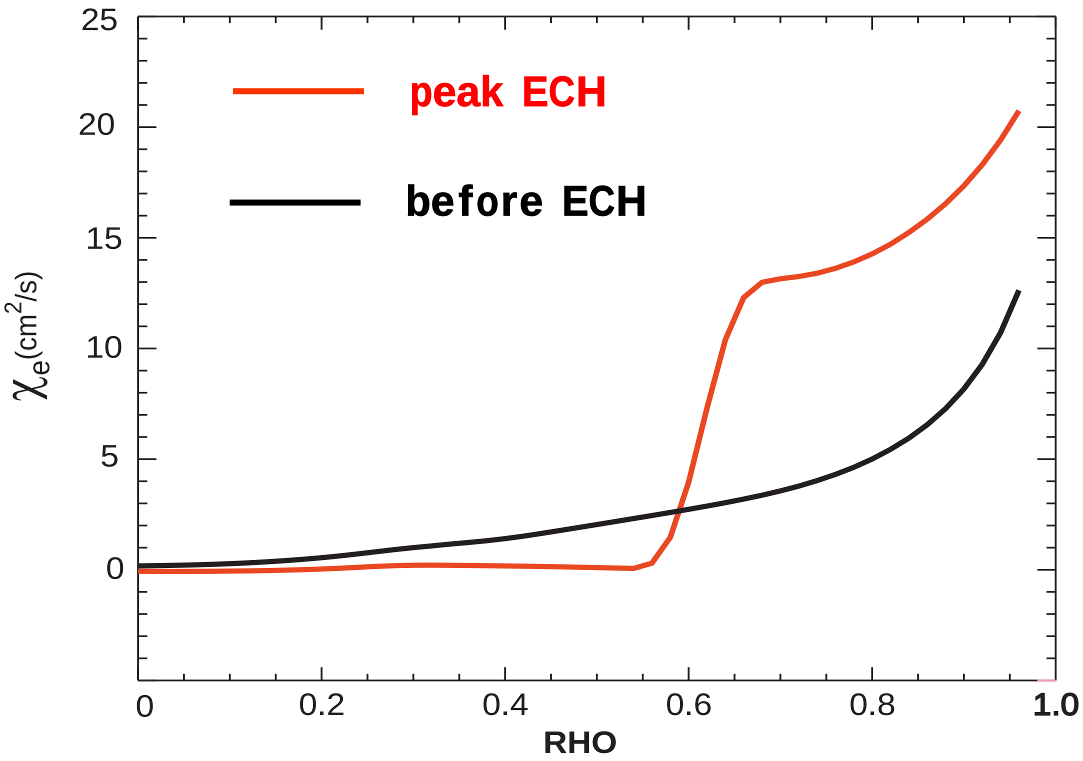
E field profile change causes

(1) Reduction of ExB spectral shift of low k_θ turbulence in outer plasma – may explain frequency narrowing of spectra

(2) Increased shearing rate helps to balance increased growth rate turbulence levels at longer wavelengths (~ 50% of growth rate)

Need non-linear calculations including ExB shear, zonal flows, etc.

Electron thermal diffusivity increases for $\rho \geq 0.6$



- ECH deposition at r ~ 0.65.
- Significant **increase in electron thermal diffusivity** in outer region:
- **Consistent** with **high-k fluctuation increase** in outer plasma

Discussion

GKS calculations for **low-k ($k_\perp \rho_s$~0.3)** appeared inconsistent with observations

ExB shear suppression in outer region may explain.

Shearing rate comparable to growth rate.

Growth rates for k = 35 cm^{-1} ($k_\perp \rho_s \approx 10$) increase near edge ($\rho > 0.85$) – consistent with experiment.

Increase in **electron thermal diffusivity consistent** with **high-k fluctuation** increase in this region of plasma

However, GKS indicates stability in core plasma, where experiment only shows small reduction

Summary

- **First measurements of high-k turbulence (k~35 cm^{-1}, $k_\perp\rho_s$~ 5-10)**
  - combined with **low** and **intermediate-k** measurements, these provide a **new, more complete picture of turbulence behavior on DIII-D**
  - **essential** to observe $k_\perp\rho_s$ ~ 0.2 - 10, a range relevant to ITG, TEM and ETG instabilities, to connect to gyro codes and achieve understanding
- GKS code shows plasma unstable to ITG, TEM, and ETG - generally consistent with observed turbulent activity
  - however some **clear differences** between GKS and observations **were found.**
  - **motivates need for comparison with fully nonlinear gyrokinetic calculations**
- **Tools now exist to perform detailed comparisons**

Monitoring broad wavenumber turbulent spectrum essential to achieve full understanding