Comparison of Broad Spectrum Turbulence Measurements, Gyrokinetic Code Predictions, and Transport Properties from the DIII-D Tokamak

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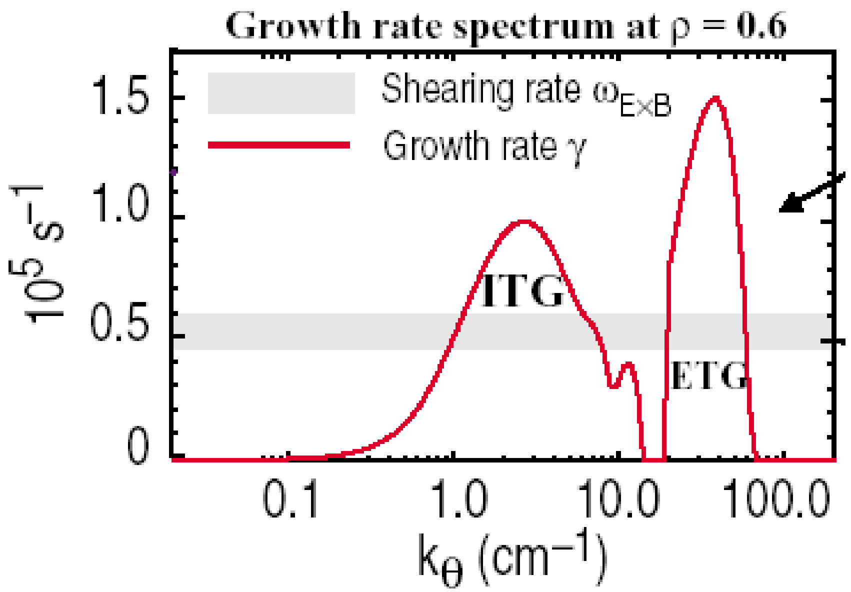
Overview of results

- First measurements of high-k turbulence (k~35 cm^{-1}, $k_\perp\rho_s \approx 10$) on DIII-D have been made.
  - Combined with low and intermediate-k measurements, these provide a new, more complete picture of turbulence behavior on DIII-D.
  - Clear turbulence signals at k~35 cm^{-1}, $k_\perp\rho_s \approx 10$ using new mm-wave backscatter.
  - $k_\perp\rho_s \sim 0.2\text{-}10$ a range relevant to ITG, TEM and ETG instabilities.
- GKS code shows plasma unstable to ITG, TEM, and ETG consistent with observed turbulent activity
  - however some differences between GKS and observations found.
  - High-k (k~35 cm^{-1}, $k_\perp\rho_s \approx 10$) turbulence increases with Te increase (with Ln, L_Te ~ constant) seemingly contrary to expectation.
- Both measured and calculated response to perturbations (NBI, ECH) varied with wavenumber, supporting need for broad wavenumber comparisons.

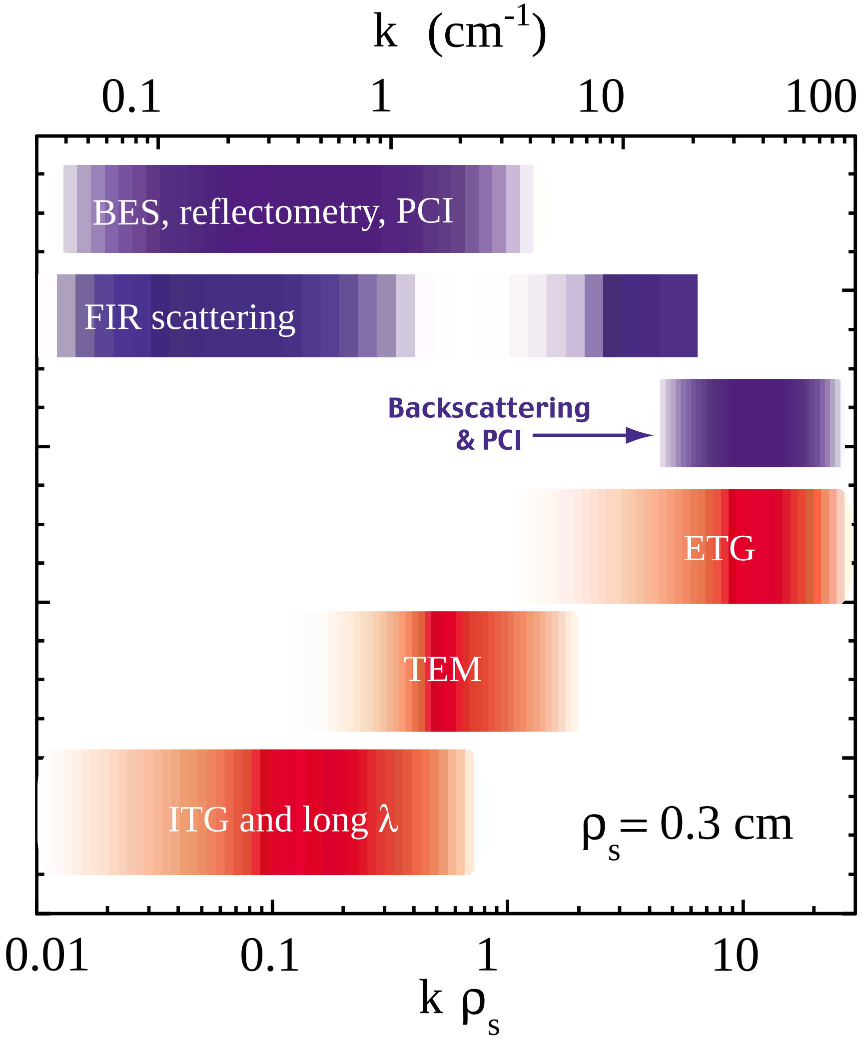
Motivation



Detailed comparison of transport properties and broad wavenumber range turbulence measurements to theoretical predictions is essential in developing this predictive capability.

- The understanding of anomalous electron and ion transport leading to development of a predictive transport capability represents a significant scientific challenge.
  - Provides confidence extrapolating to next-step devices.
  - Potentially lead to improved transport control ⇒ optimized pressure profiles and enhanced AT fusion performance.

Broad wavenumber diagnostic set being developed at DIII-D to address anomalous electron and ion transport



- Wavenumber region potentially occupied by ITG, TEM, and ETG type instabilities.
- **Diagnostic k-space large on DIII-D**
  - UCLA FIR scattering system upgraded to probe low (0-2 cm^{-1}) and intermediate wavenumbers (8-20 cm^{-1})
  - New concept high-k backscattering system added (~ 40 cm^{-1}) (UCLA).
  - U. Wisc. beam emission spectroscopy (BES), upgraded for improved sensitivity, probes 0 - 3.5 cm^{-1}
  - MIT phase contrast imaging (PCI) upgraded to probe core plasma, 0-30 cm^{-1}.
  - Fluctuation and correlation reflectometry probe 0 - 5 cm $^{-1}$.

Properties of FIR and mm-wave turbulence diagnostics

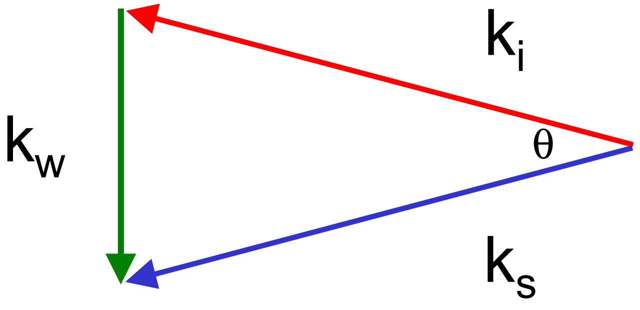
Diagnostic	k	k range (cm^{-1})	$k_\perp \rho_s$	Spatial resolution
Low-k FIR	k_θ	0-2	0-0.3	[-a, a] $-1 \leq \rho \leq 1$
Intermediate-k FIR	k_θ	8-15	2-5	varies with k, e.g. $-0.4 \leq \rho \leq 0.4$ $0.2 \leq \rho \leq 0.6$
High-k mm-wave backscatter	k_r	35-40	~10	~a/2 $\rho \geq 0.4$

Collective scattering principles

- Collective Thomson scattering is well-suited to study short wavelength turbulence – only known technique to probe such short wavelengths.

Momentum matching gives

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



Energy conservation gives

$\omega_i+\omega_w=\omega_s$ i.e scattered radiation Doppler shifted by propagation in lab reference.

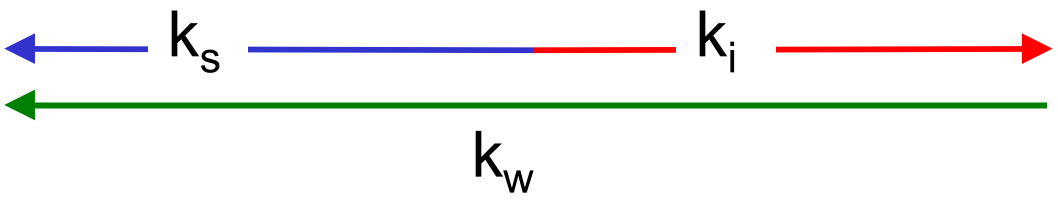
Bragg Law:

For $k_i \sim k_s$, can show that

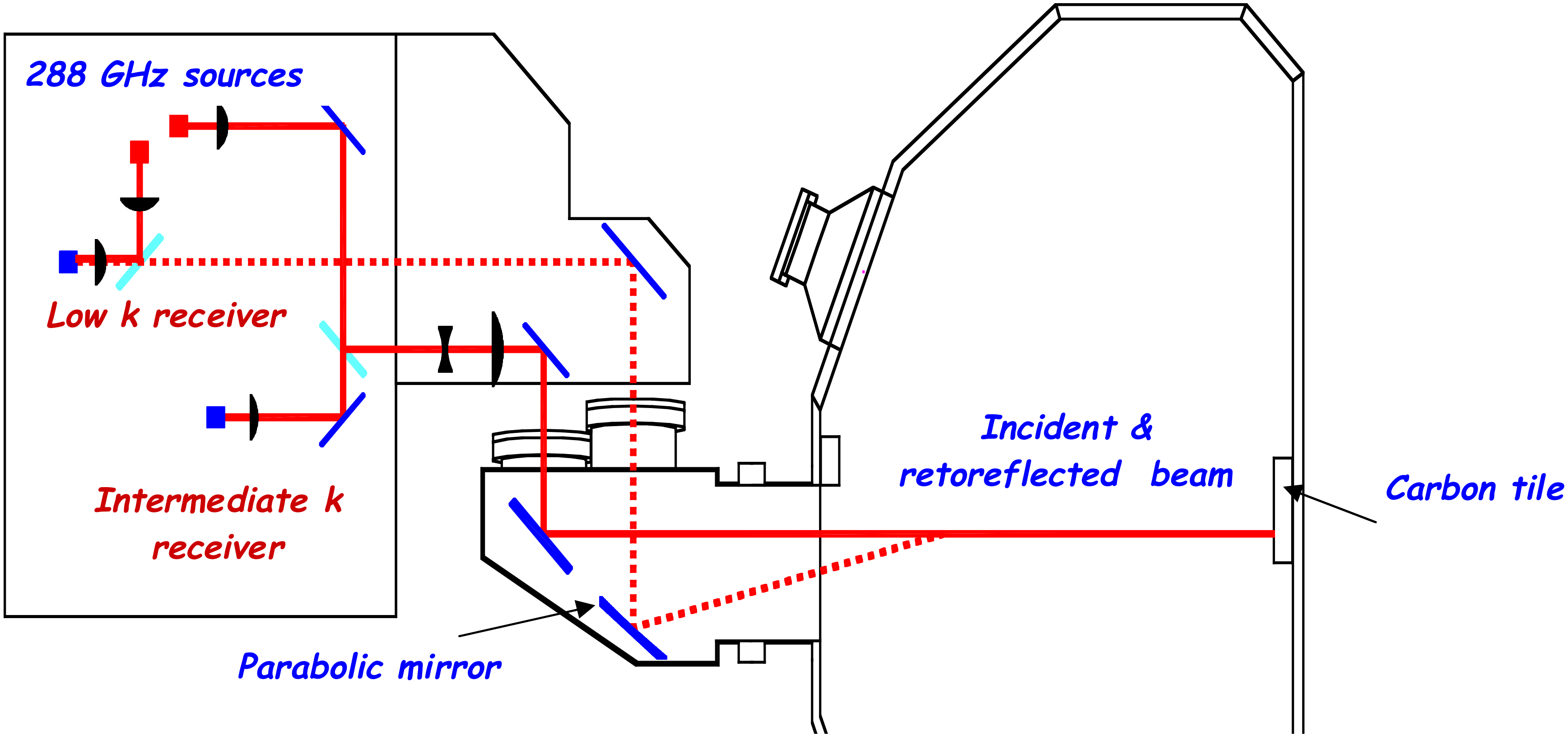
$\mathbf{k_w = 2k_i Sin\theta/2}$

Where θ is the scattering angle.

When scattering is backward (~180°) probed wavenumber ~$2k_i$

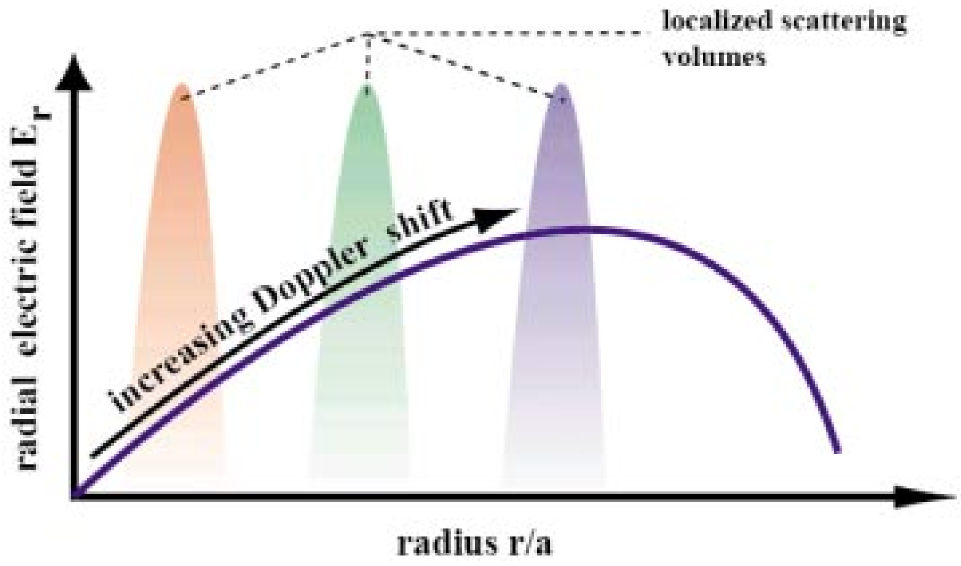


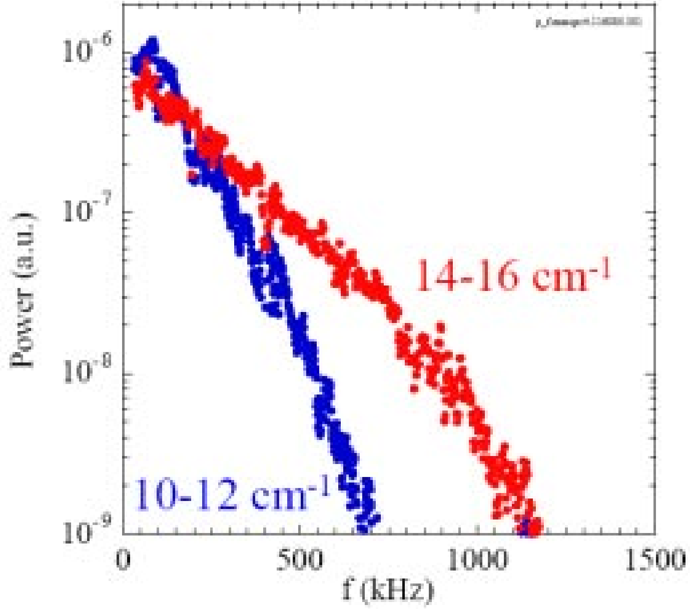
Low & intermediate k measurements via FIR scattering



- Forward scattering at 288GHz (λ ~1mm).
- Low and intermediate-k passed multiple validity tests: no cross correlation between signals, Doppler shifts consistent as k changed.

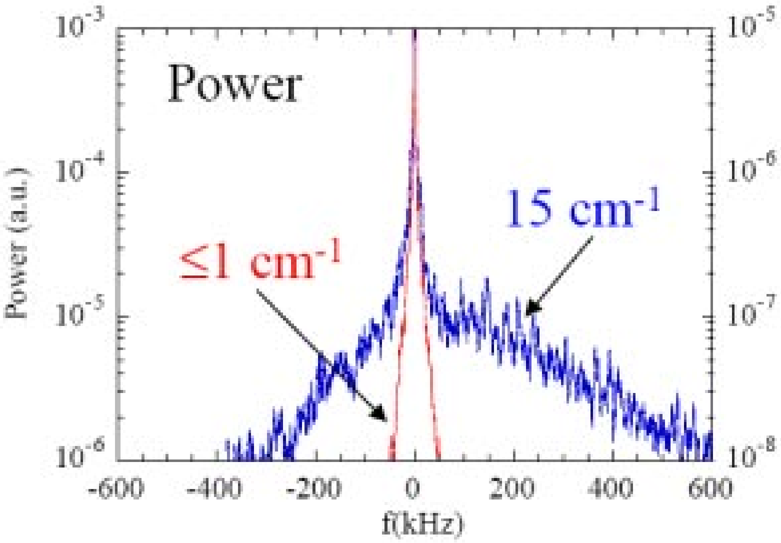
Validity tests of intermediate-k data

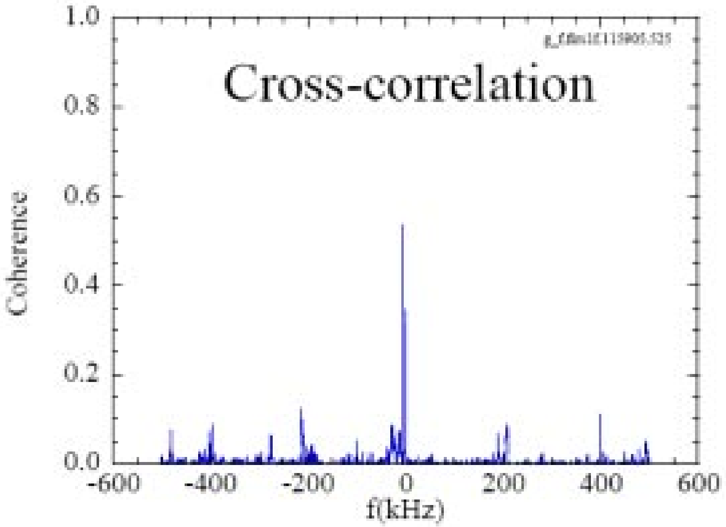




- Initial FIR data from Ohmic discharge.
  - Expect proportionally higher Doppler shifts as *k* is increased
- Size of scattering volume appx. same - overlap of volumes is ~ 10 cm.
- Spectral width at higher k larger than that at lower k by approx ratio of k’s.
- Consistent with Doppler shift $\Delta\omega = k \cdot v$ (dominated by ExB turbulent flow)

Low and intermediate-k power spectra have different widths and no correlation

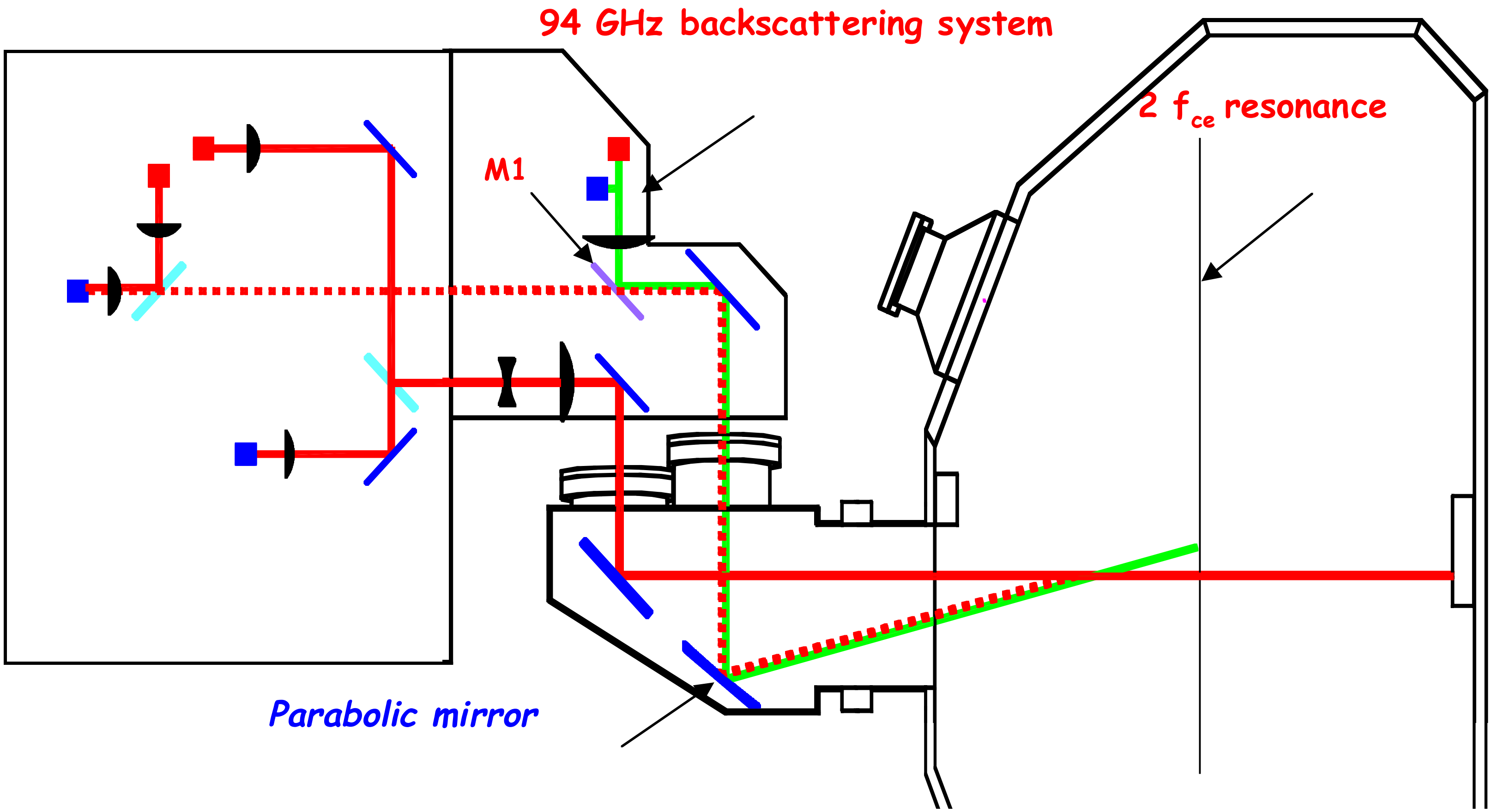




- Ohmic discharge, FIR data.
- Low-k is chord averaged while intermediate-k from ρ ≈ 0.4-0.8 .
- Intermediate-k spectrum wider in frequency space.
- Important test: No cross-correlation between low and intermediate-k signals:

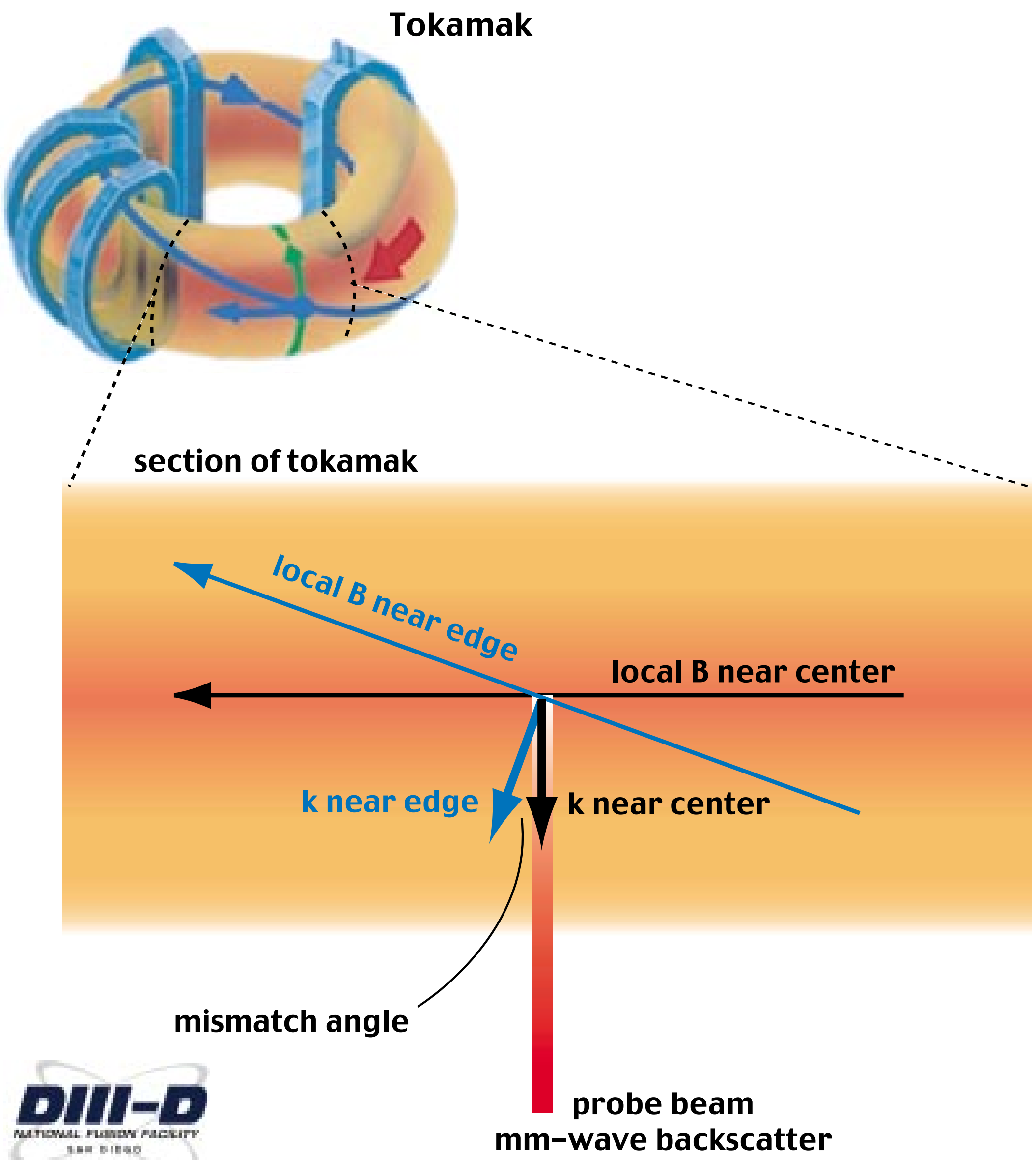
⇒**low-k not contaminating intermediate-k**, and vice-versa

94 GHz backscattering to probe high-k



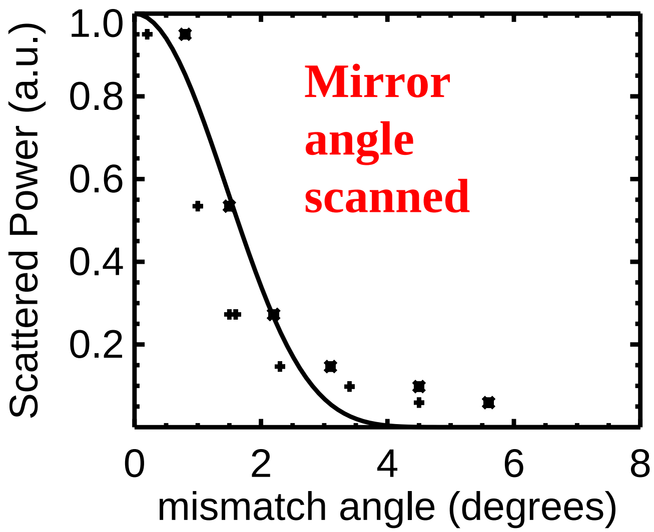
- 94 GHz radiation is shown in green and the 288GHz FIR in red.
- $2f_{ce}$ resonance layer used as beam dump for 94 GHz probe beam.
- High-k data passed multiple validity tests.

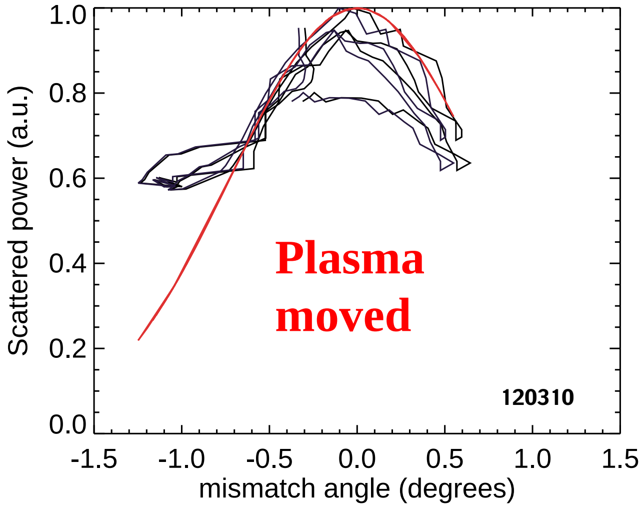
Multiple tests of mm-wave backscattering performed



- Backscatter signal clearly different from lower-k signals, e.g. showing none of coherent modes often seen at low-k.
- No coherency was found between the low-k FIR and backscattered signal.
- Concept of wavenumber matching provided excellent test of system performance.

k-matching requires both magnitude and direction to match



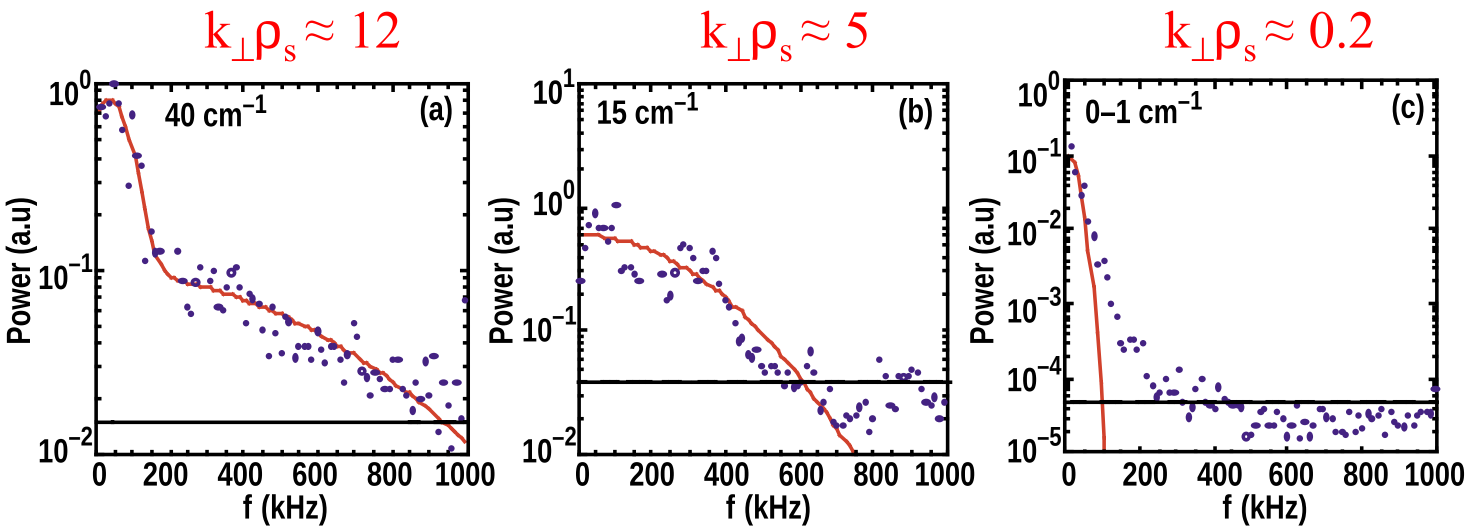


- In scattering theory, if wavenumber probed does not physically align in such a way as to satisfy the momentum balance then no scattering occurs.
- Instrument function given by [Slusher and Surko, PhysFluids1980]:

$$\mathbf{E}_s(\mathbf{R},t)=[\hat{R}\times(\hat{R}\times\hat{y})]\frac{a_0^2 r_0 E_0}{32\pi^3 R}\int d\omega\, d^3K\, dz\, \exp\left(-\frac{(K_x-k_x^s)^2a_0^2}{4}\right)\exp\left(\frac{-(K_y-k_y^s)^2a_0^2}{4}\right)$$
$$\times\{\exp[i(K_z+k_0-k_z^s)z]\exp[-i\omega_+(t-R/c)]n(\mathbf{K},\omega)+\mathrm{c.c.}\}$$

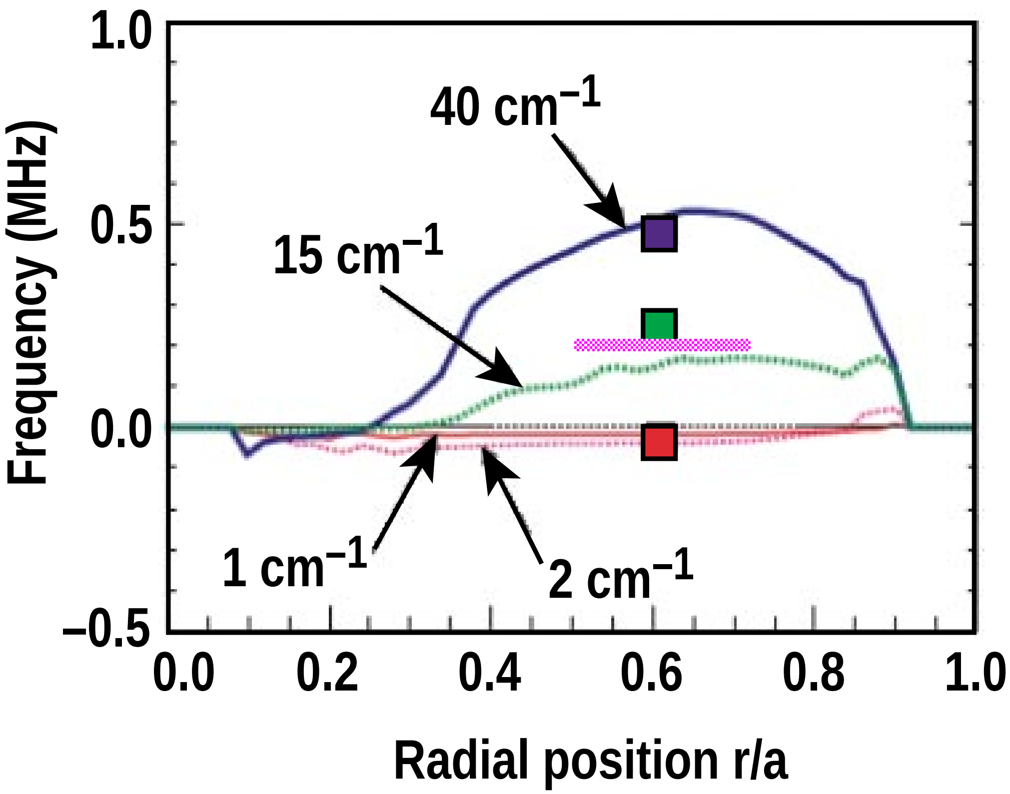
- Changed K_z by varying mirror angle and by moving plasma.
- Good agreement with theory expectation further confirming diagnostic operation

Initial measurements of low (0-1 cm^{-1}), intermediate (15 cm $^{-1}$), and high-k (40 cm $^{-1}$) density fluctuations performed


$k_\perp \rho_s \approx 12$ $k_\perp \rho_s \approx 5$ $k_\perp \rho_s \approx 0.2$

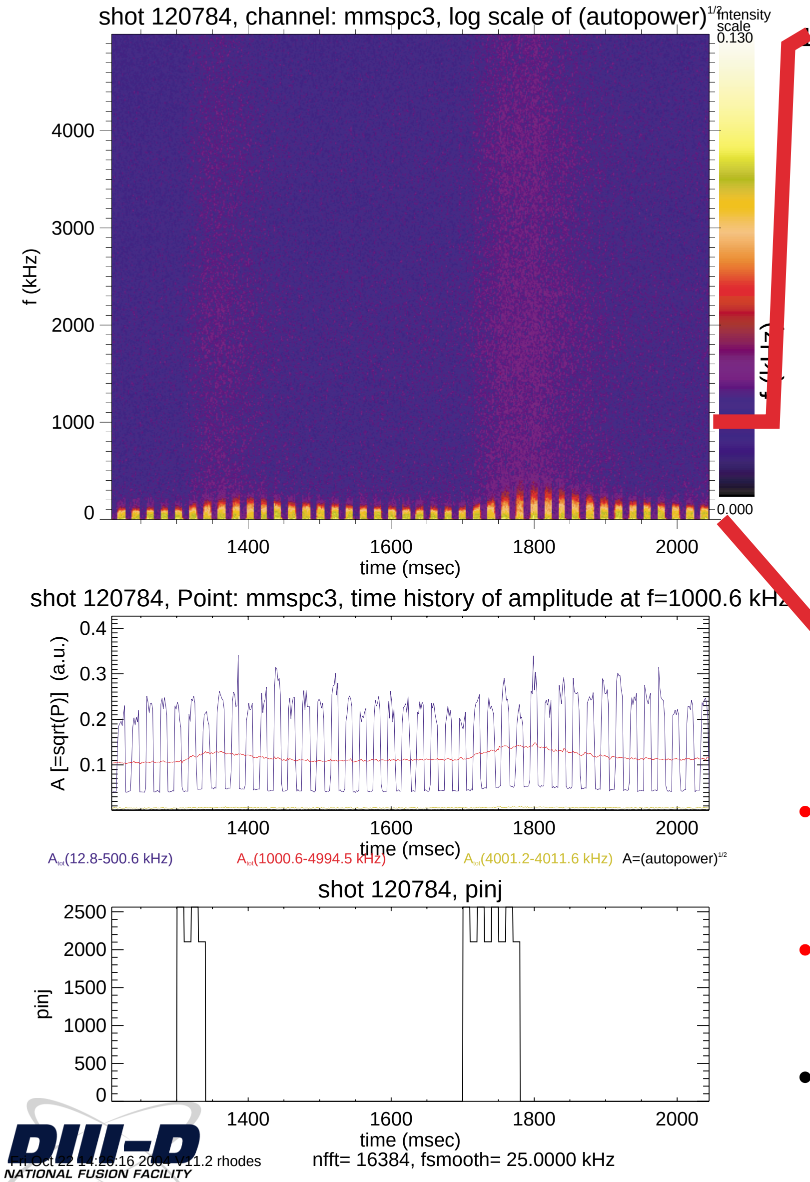
- Initial data in Ohmic, diverted plasma, I_p = 1 MA, $n_{e,avg} = 2.6\times10^{19}$ m^{-3}, B_T = 2.1 T.
- k range consistent with ITG, TEM and ETG type instabilities.
- Gaussian fits give ~50 kHz and ~490 kHz for the high-k, 260 kHz and 24 kHz respectively for intermediate and low-k.
  - The observed trend is for increasing frequency width with increasing wavenumber.

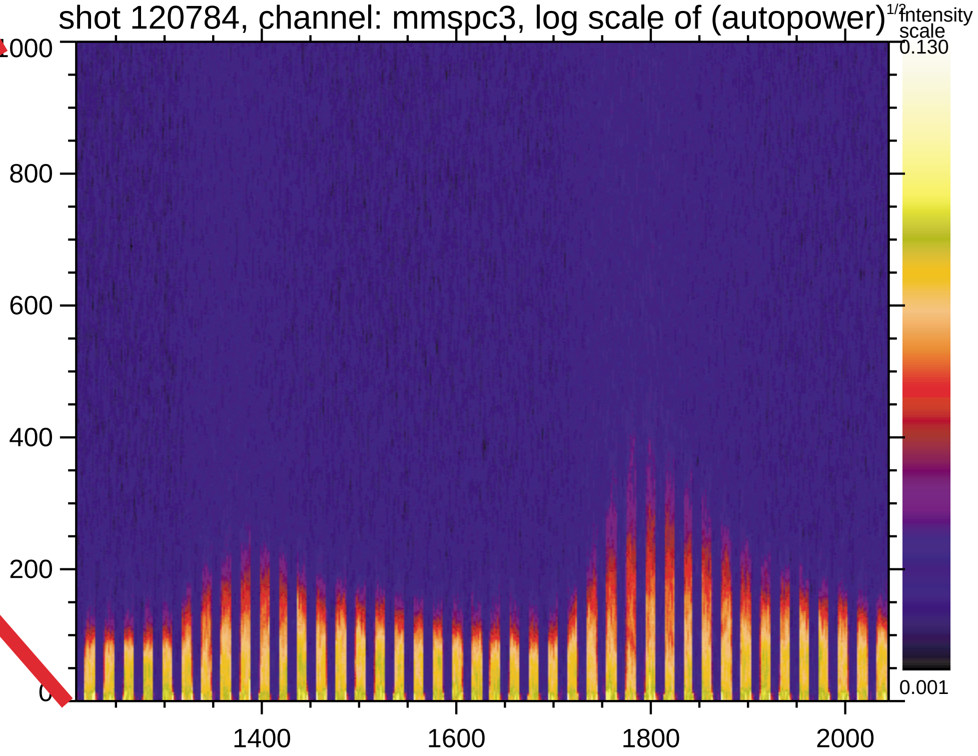
GKS linear stability code indicates these discharges unstable to a wide range of instabilities: ETG, ITG and TEM.



- Real frequency of unstable modes from GKS over radial range ρ = 0.1-0.9
  - for different k values.
- Colored squares indicate Gaussian widths of measured fluctuation spectra.
- Magenta line is electron bounce frequency, $\omega_b/2\pi \sim \varepsilon^{1/2}V_e/Rq$
- Data and predictions are seen to be similar.

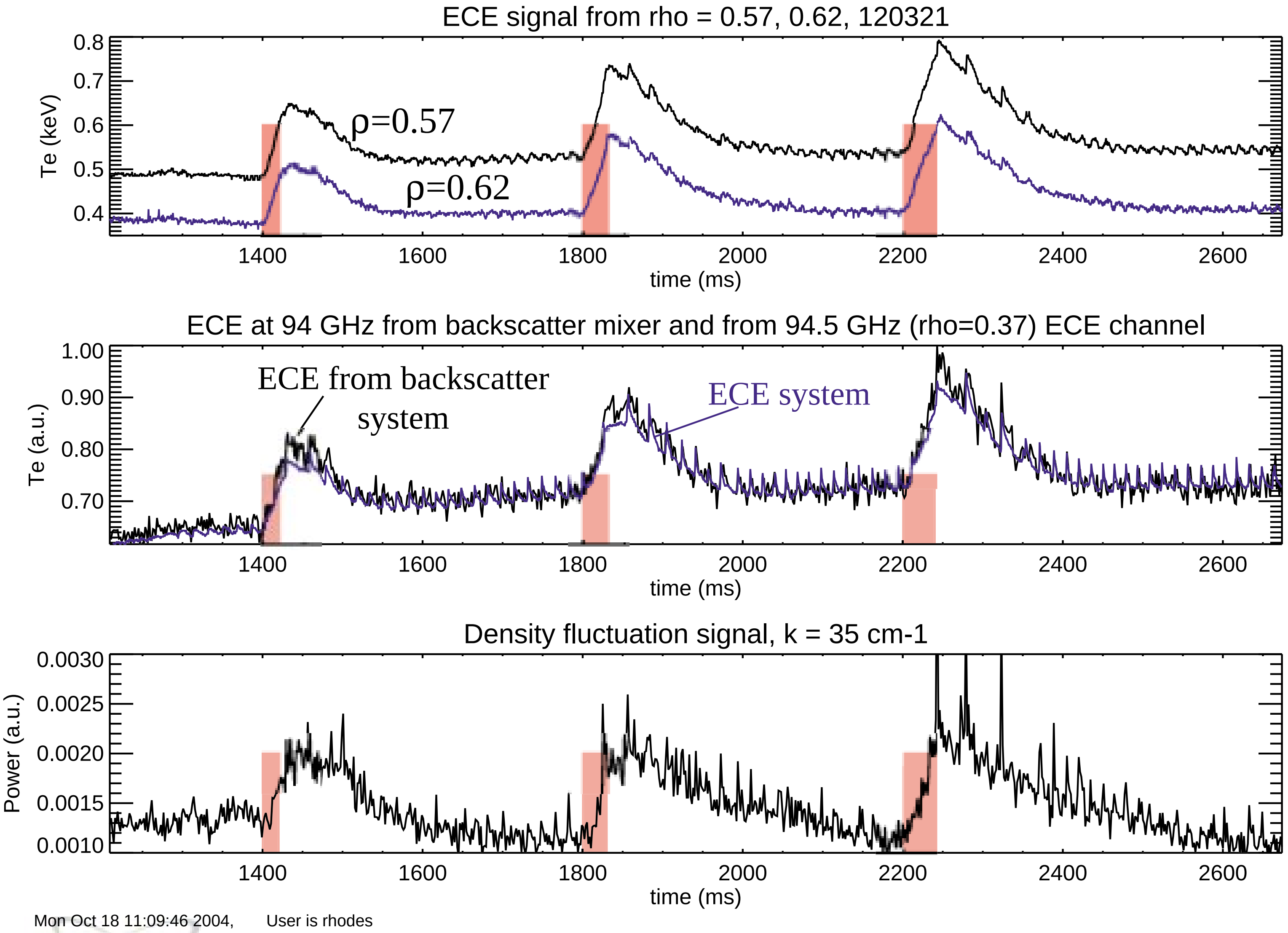
Modulated probe beam shows signal is not due ECE





- Backscatter is also a 94 GHz radiometer.
  - Some of signal is due to ECE
- Probe beam was modulated so that remaining signal is due to ECE.
- Turbulent signal clearly modulated while ECE signal is not.

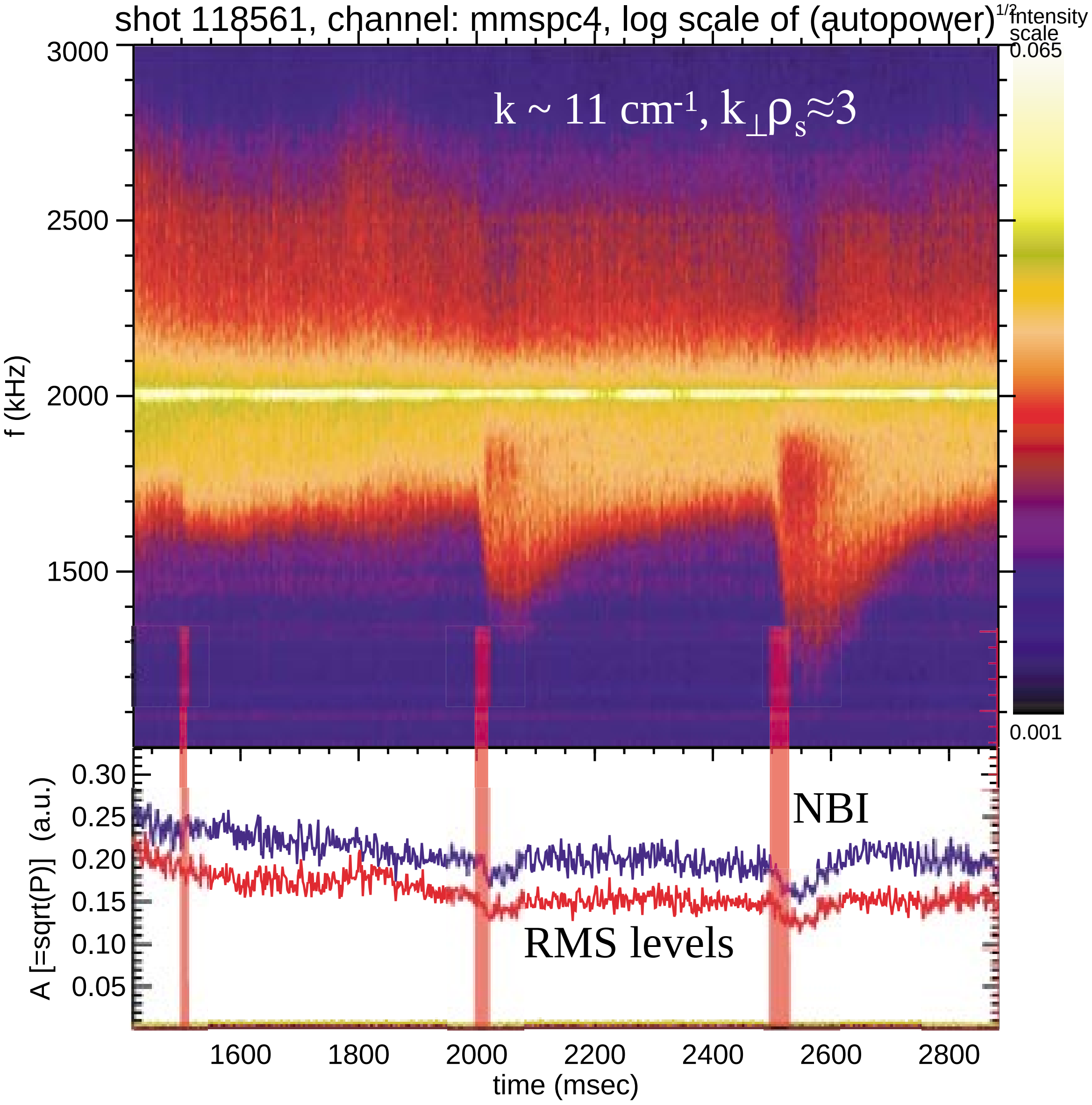
mm-wave backscatter signal not due to ECE



- ECE and mm-wave backscatter signals clearly different.
- mm-wave does see 94 GHz ECE which is similar to ECE system.

Short duration NBI used to affect turbulence and Te

- Intermediate-k (11 cm^{-1}, $k_\perp\rho_s\approx3$) turbulence decreases with NBI.
- Low-k (~1 cm^{-1}, $k_\perp\rho_s\approx.3$) and high-k (35 cm^{-1}, $k_\perp\rho_s\approx10$) turbulence increase with NBI.
- NBI increases T_e but little affect on other parameters.



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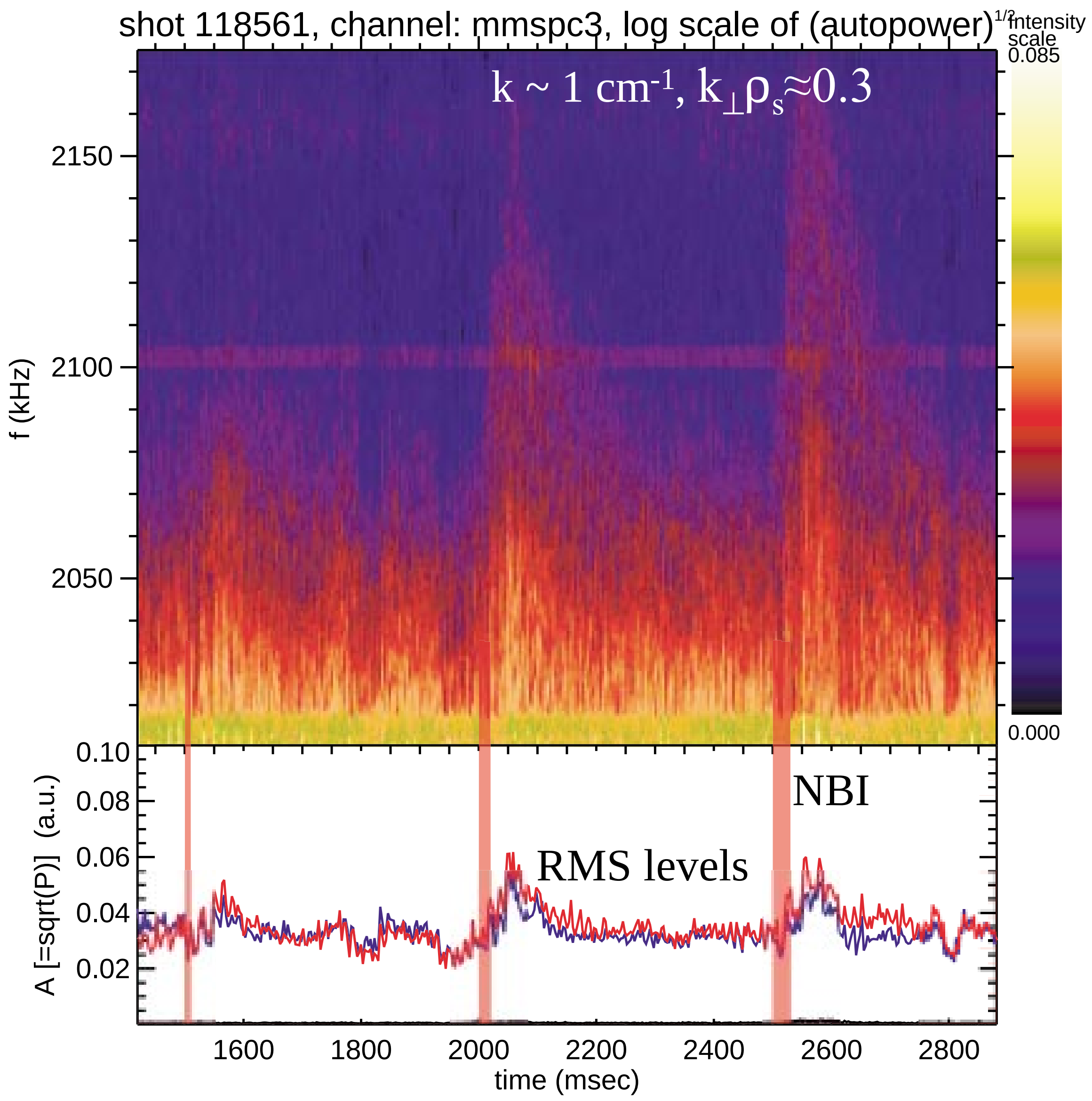
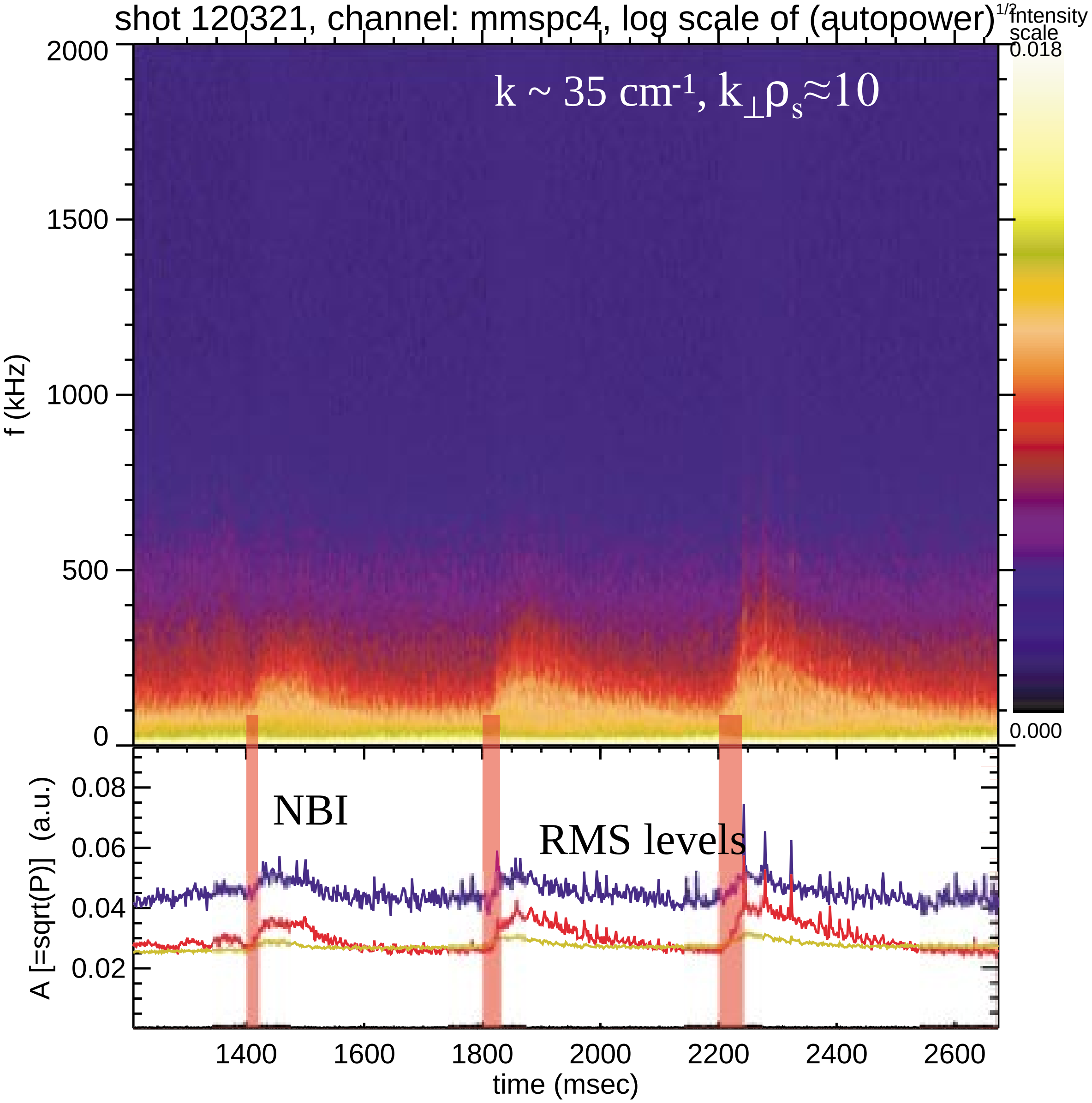
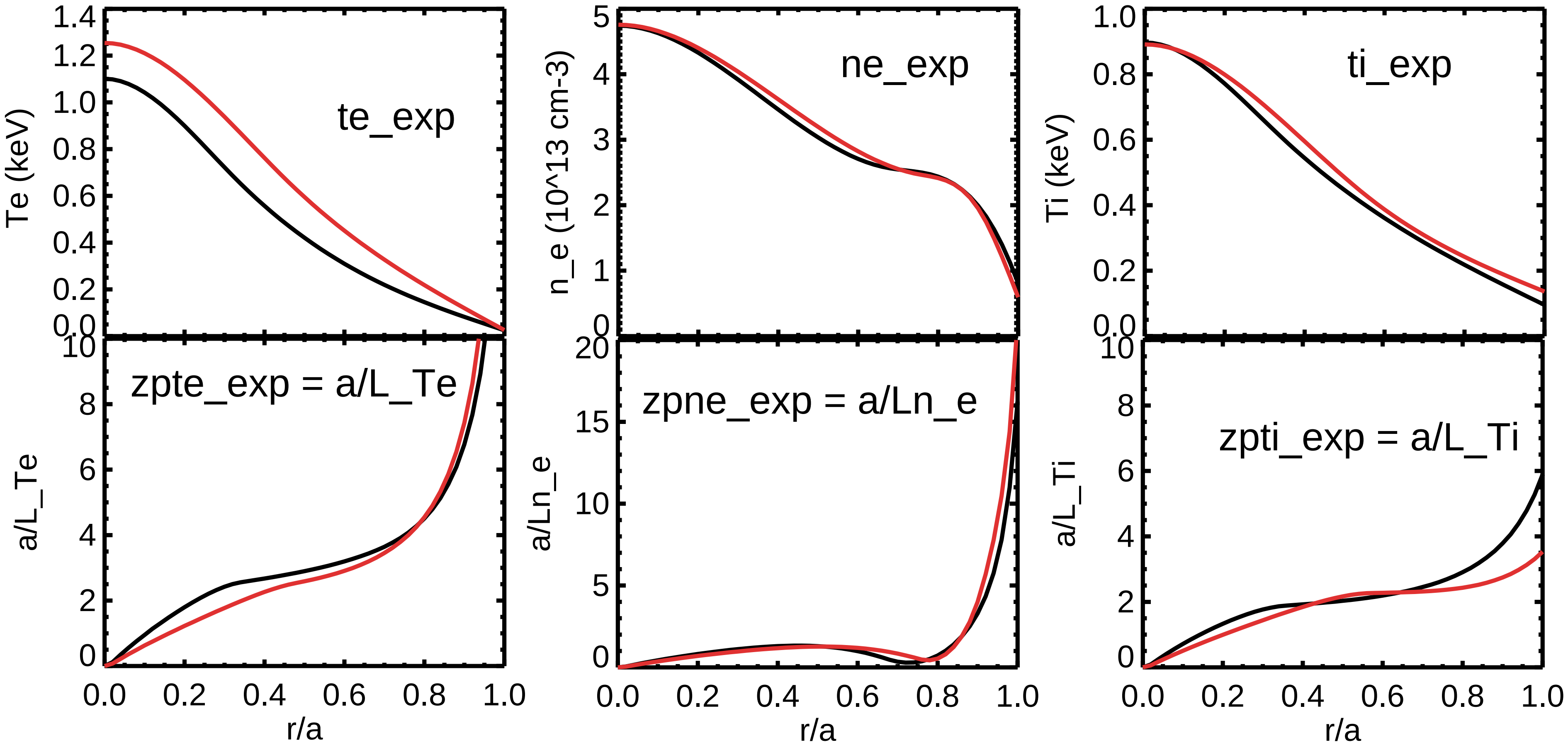


Short duration NBI used to affect turbulence and Te

- High-k (35 cm^{-1}, $k_{\perp}\rho_s \approx 10$ turbulence increases with NBI.

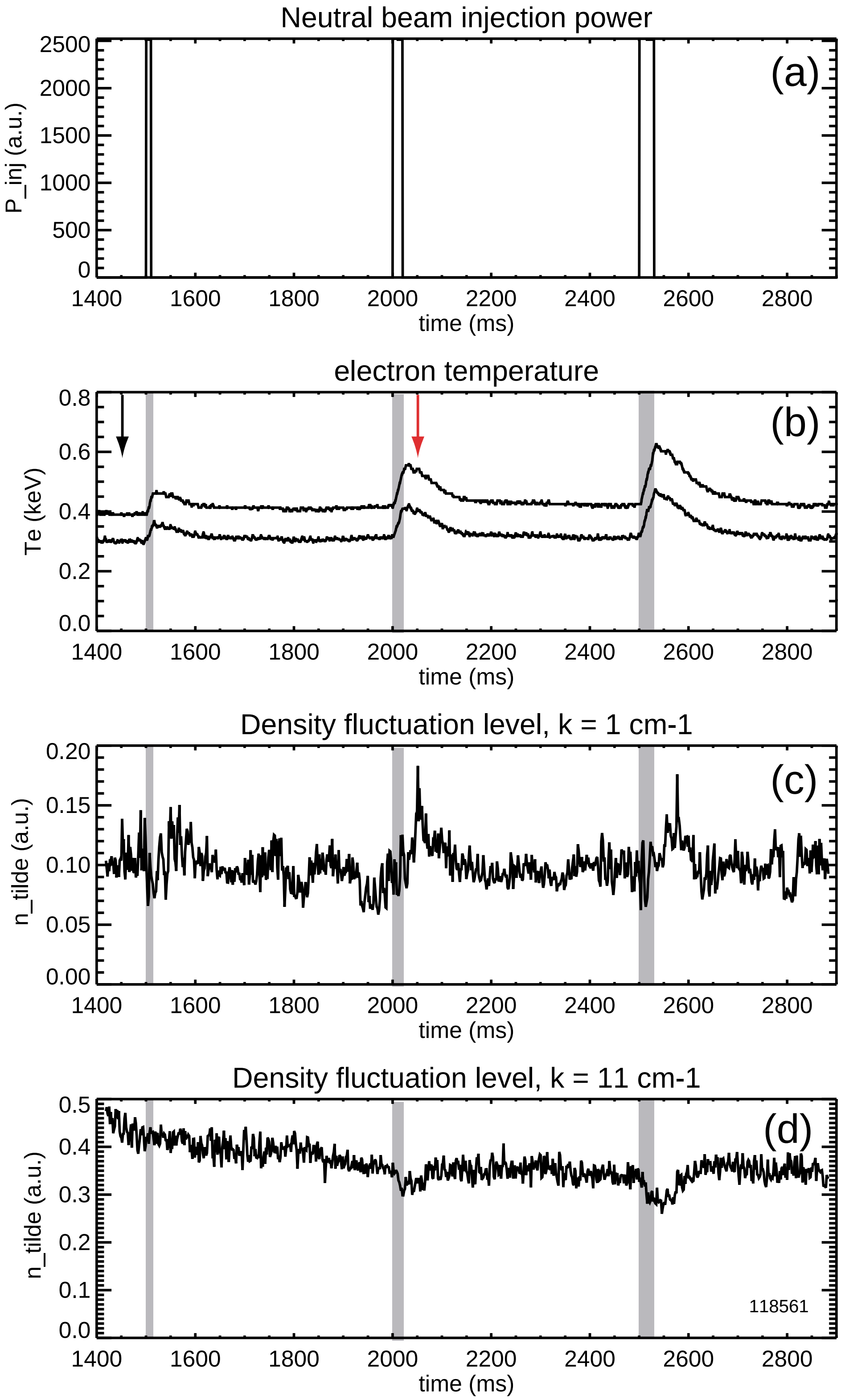


Short duration NBI affects mostly Te



- Little change in L_Te or other parameters with short duration NBI

Short duration neutral beams used to modify profiles and fluctuations



NBI

Te

ñ(k = 1 cm^{-1})

$k_\perp \rho_s \approx 0.3$

ñ(k = 11 cm^{-1})

$k_\perp \rho_s \approx 3$

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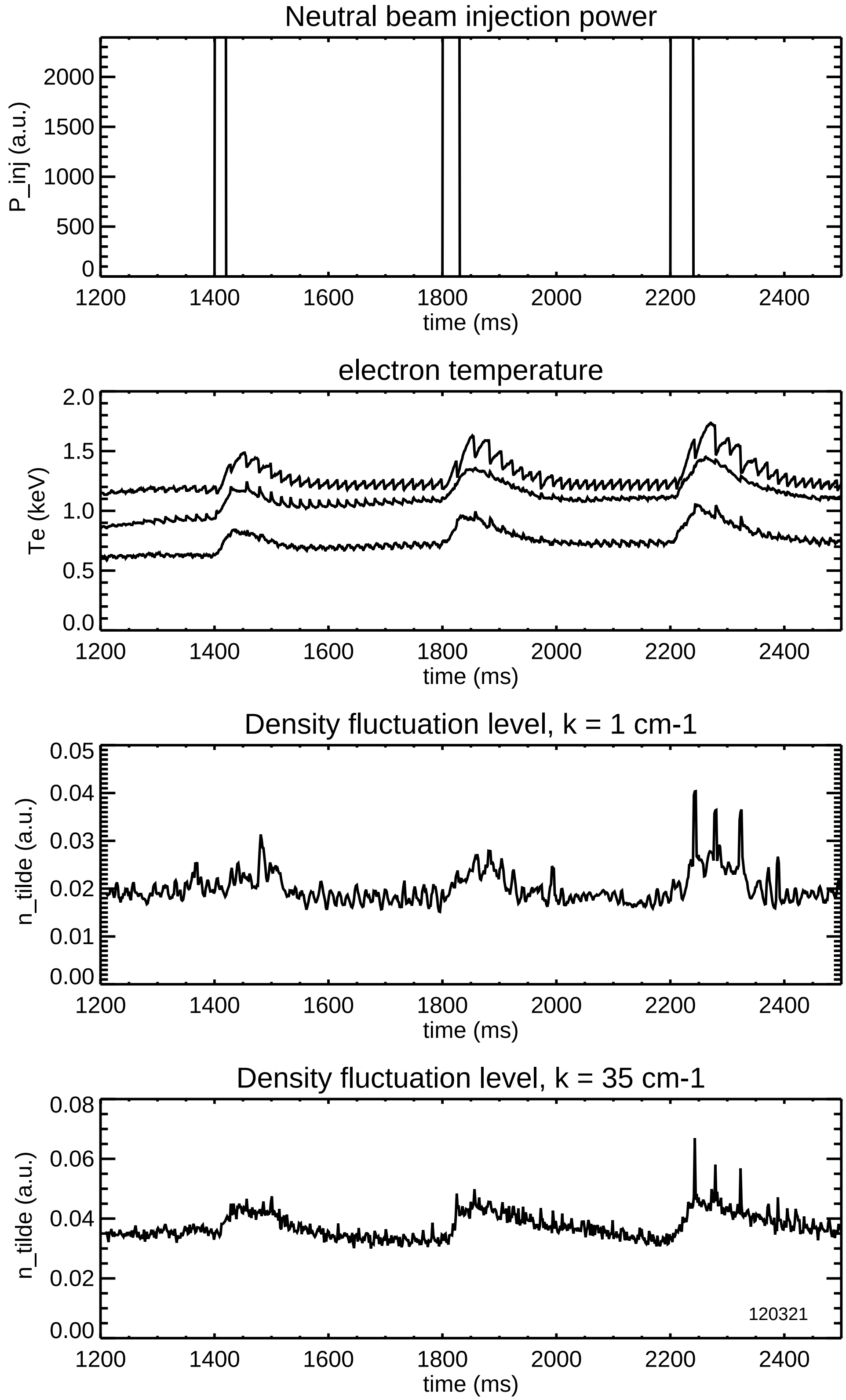
Different discharge showing high-k



NBI

Te

$\tilde{n}(k = 1\ cm^{-1})$

$k_{\perp}\rho_s \approx 0.3$

$\tilde{n}(k = 35\ cm^{-1})$

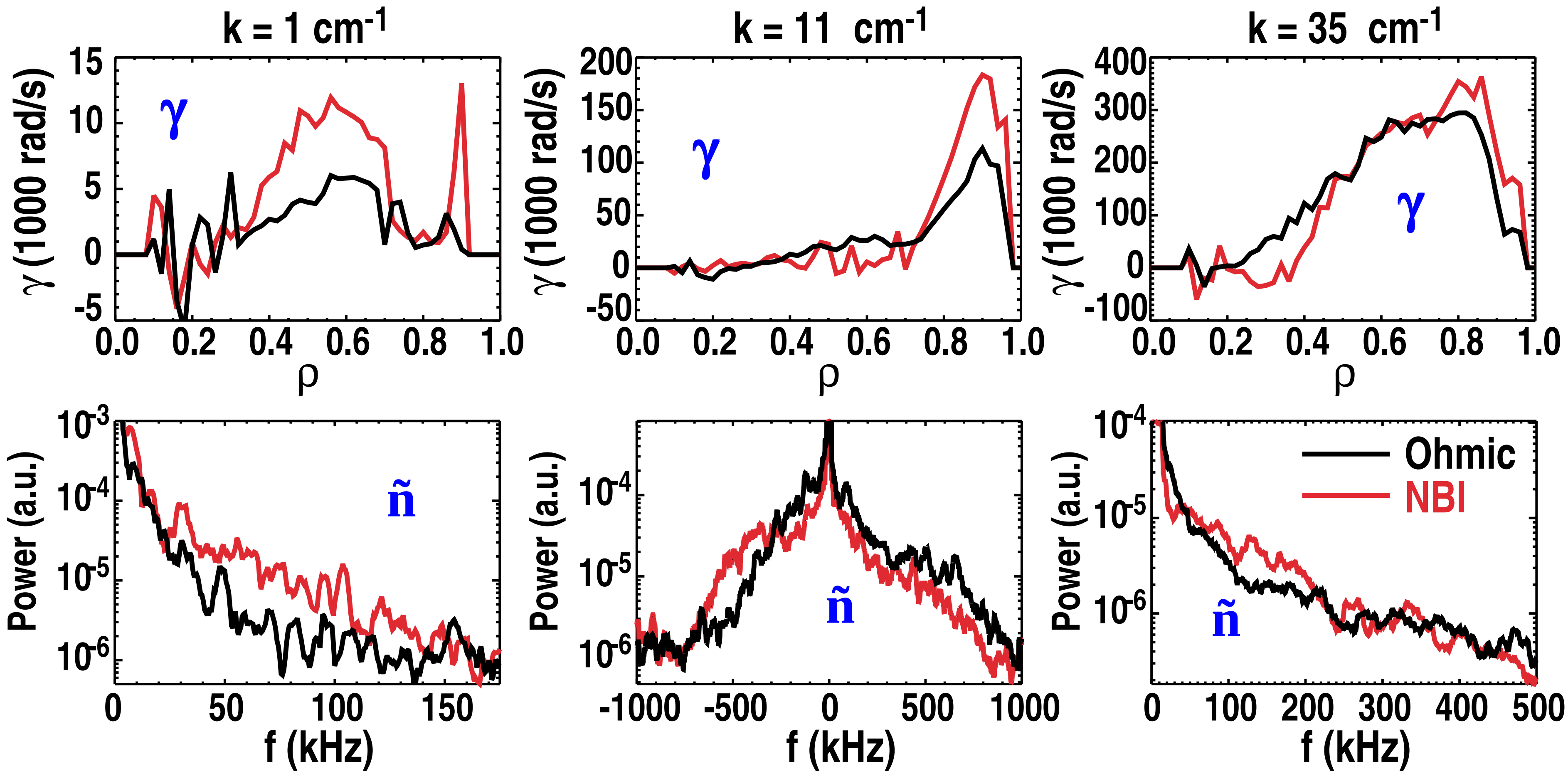
$k_{\perp}\rho_s \approx 10$

Fluctuations respond differently depending upon wavenumber

- RMS levels are integrated across the frequency range where the fluctuations appear.
- RMS levels are seen to respond quite differently,
  - with the low-k increasing to a maximum after the beam turns off
  - intermediate-k decreases to a minimum.
  - Interestingly the high-k fluctuations also increase

Response to short duration NBI: both ñ measurements and GKS predictions vary with wavenumber

$k_\perp \rho_s \approx 0.3$ $k_\perp \rho_s \approx 3$ $k_\perp \rho_s \approx 10$



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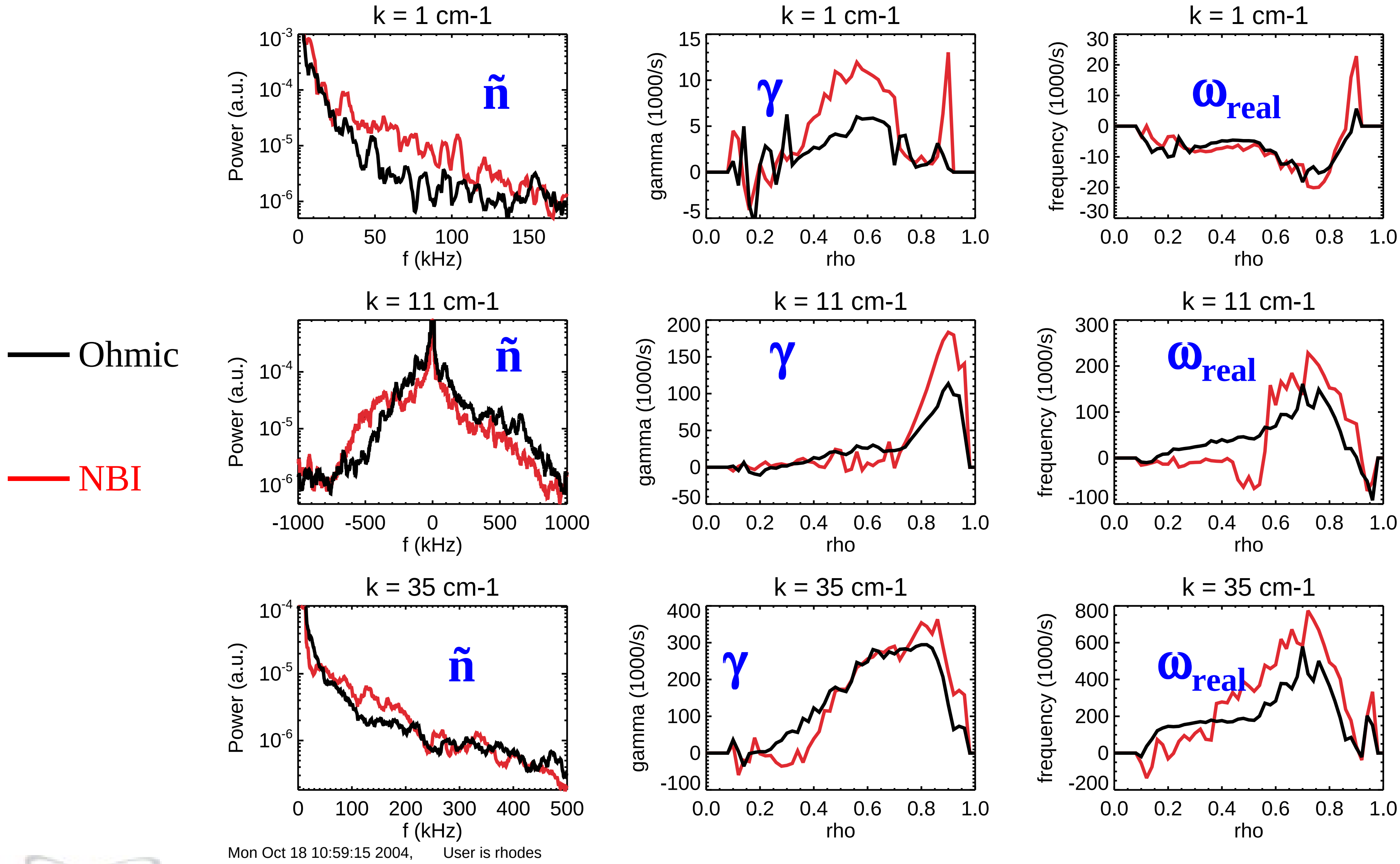

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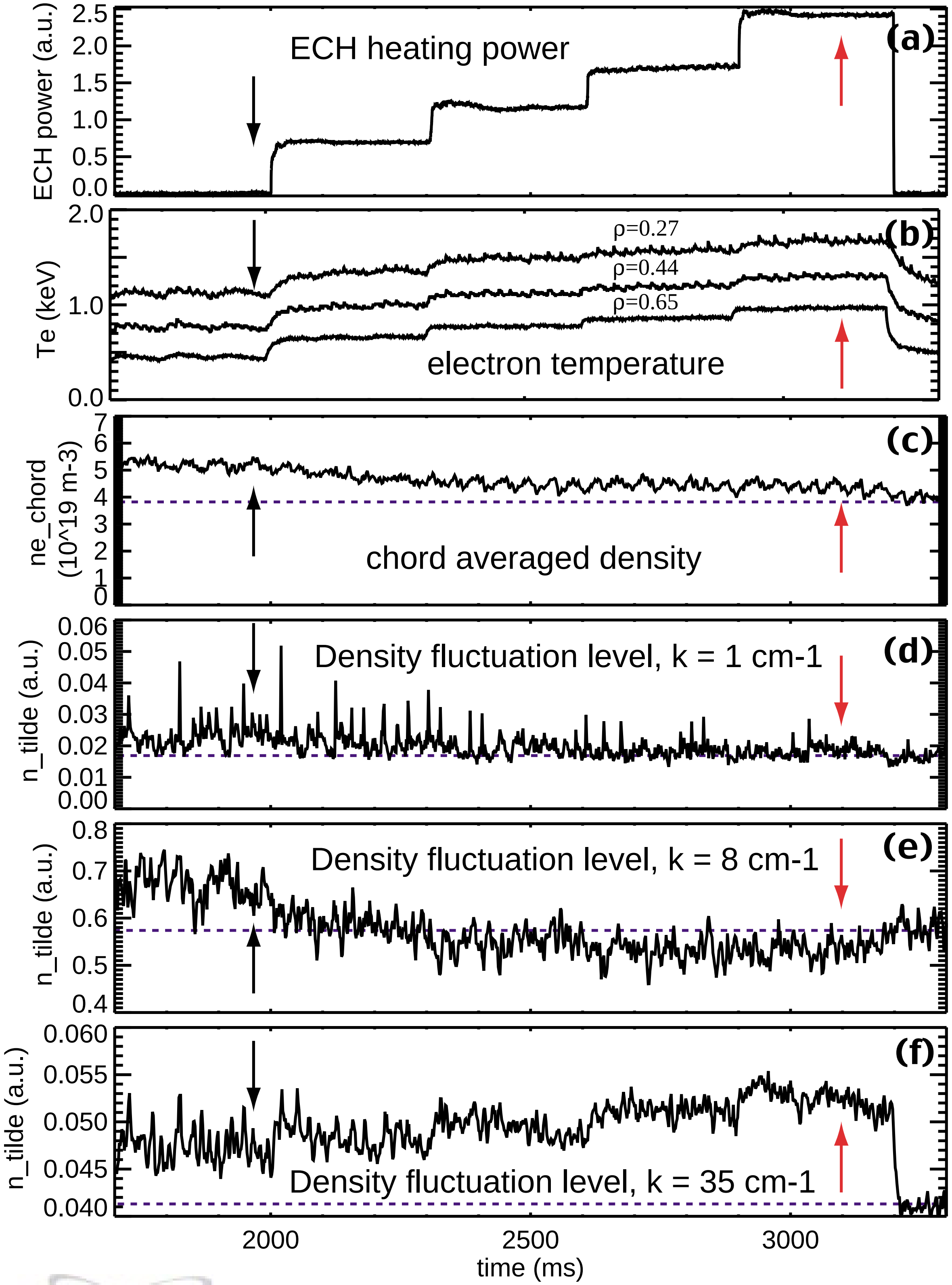
Response to short duration NBI: high and intermediate k measurements differ from expectation

- GKS calculations for low-k ($k_{\perp}\rho_s \approx 0.3$) show an increase in growth rate over much of radius consistent with observed fluctuation increase.
- Intermediate-k ($k_{\perp}\rho_s \approx 3$) decreases with NBI but GKS predicts increase at edge and possible decrease in core.
- High-k ($k_{\perp}\rho_s \approx 10$) increases with NBI but GKS shows little change.
    - Only change in plasma is increase in Te so that increase in high-k seemingly contrary to expectation.

Electron cyclotron heating (ECH) modifies profiles (n_e and T_e) and fluctuations



ECH power

Te

n_{chord}

$\tilde{n}$ $k_{\perp}\rho_s \approx 0.3$

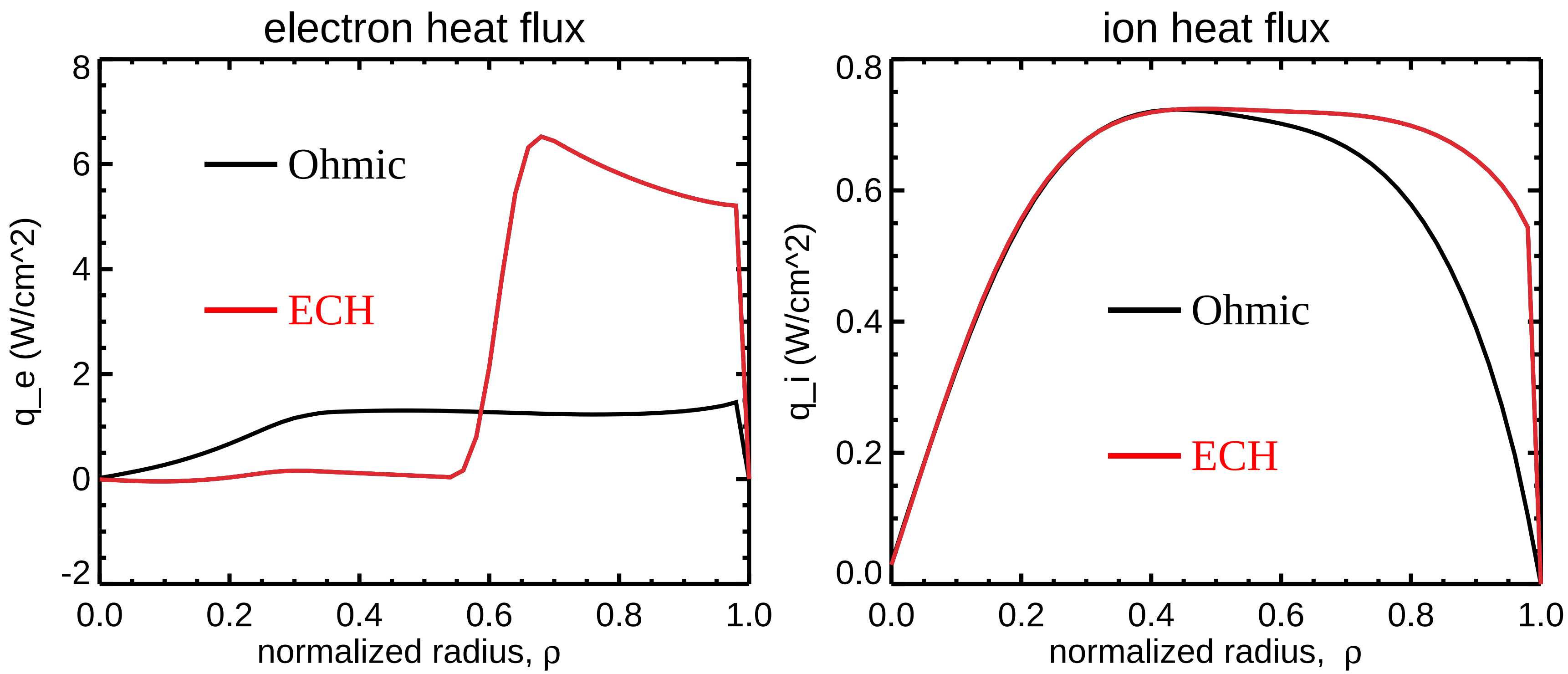
$\tilde{n}$ $k_{\perp}\rho_s \approx 2$

$\tilde{n}$ $k_{\perp}\rho_s \approx 10$

Electron cyclotron heating (ECH) resulted in different changes for different wavenumbers

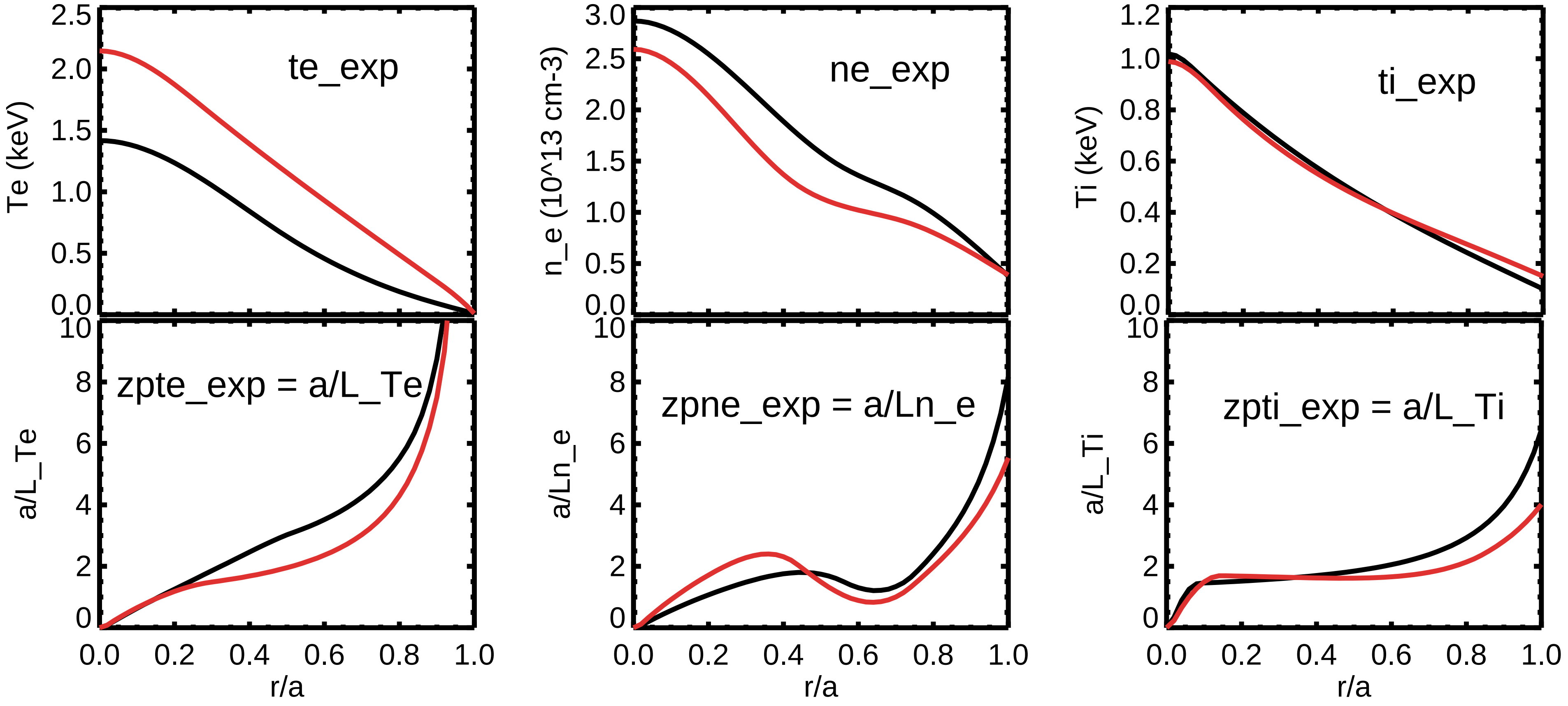
- Integrated fluctuation signals from low-k did not change appreciably with ECH
- Intermediate-k decreases (~10%)
- high-k increases (~10-15%).
- The high-k fluctuation level decreases rapidly after ECH turn-off, similar to the Te signal from the outer part of the plasma
- It should be noted that Ti did not change appreciably during the ECH.

With ECH electron heat flux increases for ρ ≥ 0.55



- Increase in q_e correlates with increase in high-k fluctuations, intermediate-k centered at ρ=0 so decrease in q_e might also be consistent.
- Ion heat flux also increases, but to a smaller extent, doesn't appear to correlate well with little or no change in low-k fluctuations.

ECH affects both n_e and T_e and their scale lengths



- Little change in Ti with ECH

Response to ECH: both ñ measurements and GKS predictions vary with wavenumber

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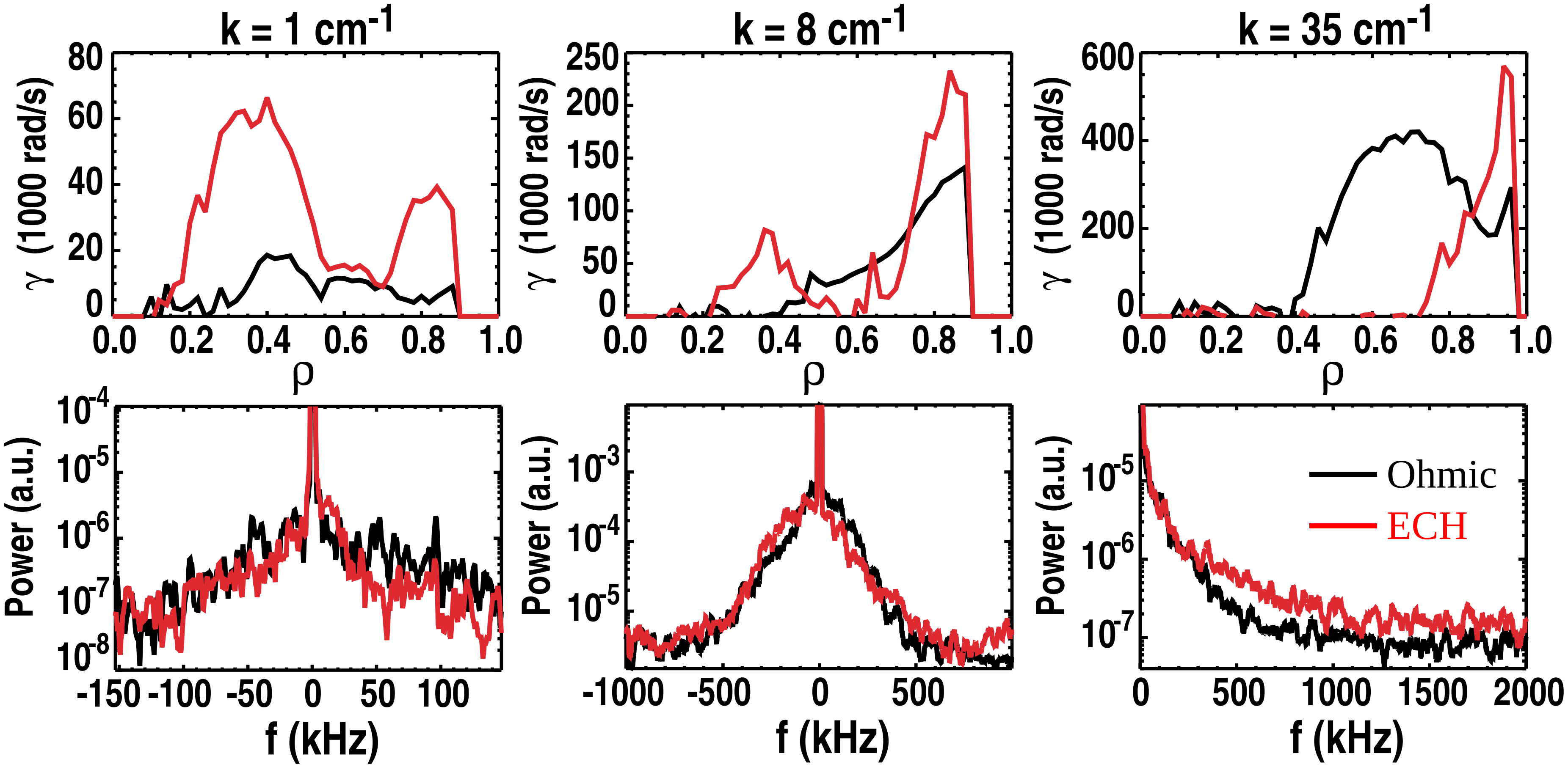

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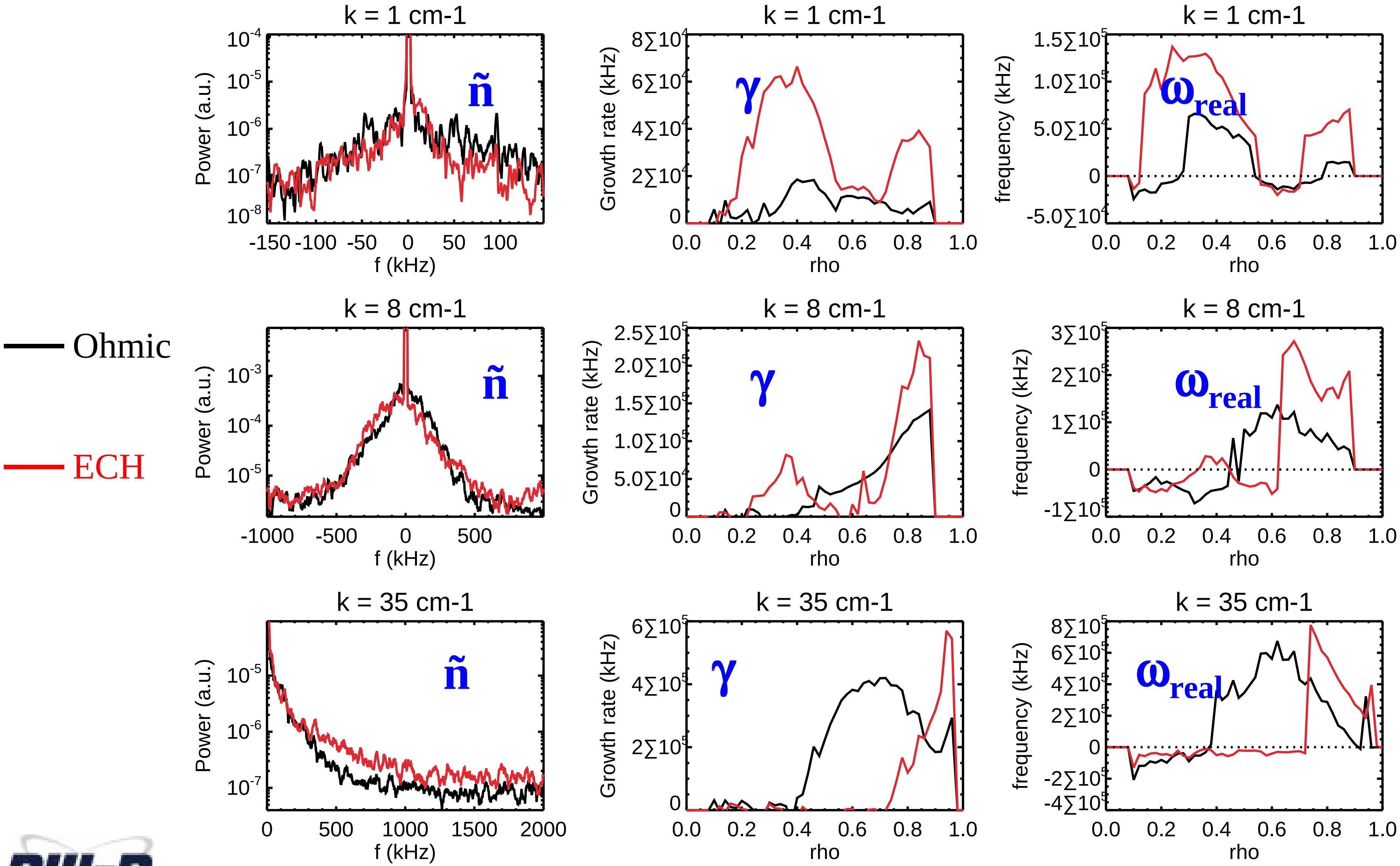

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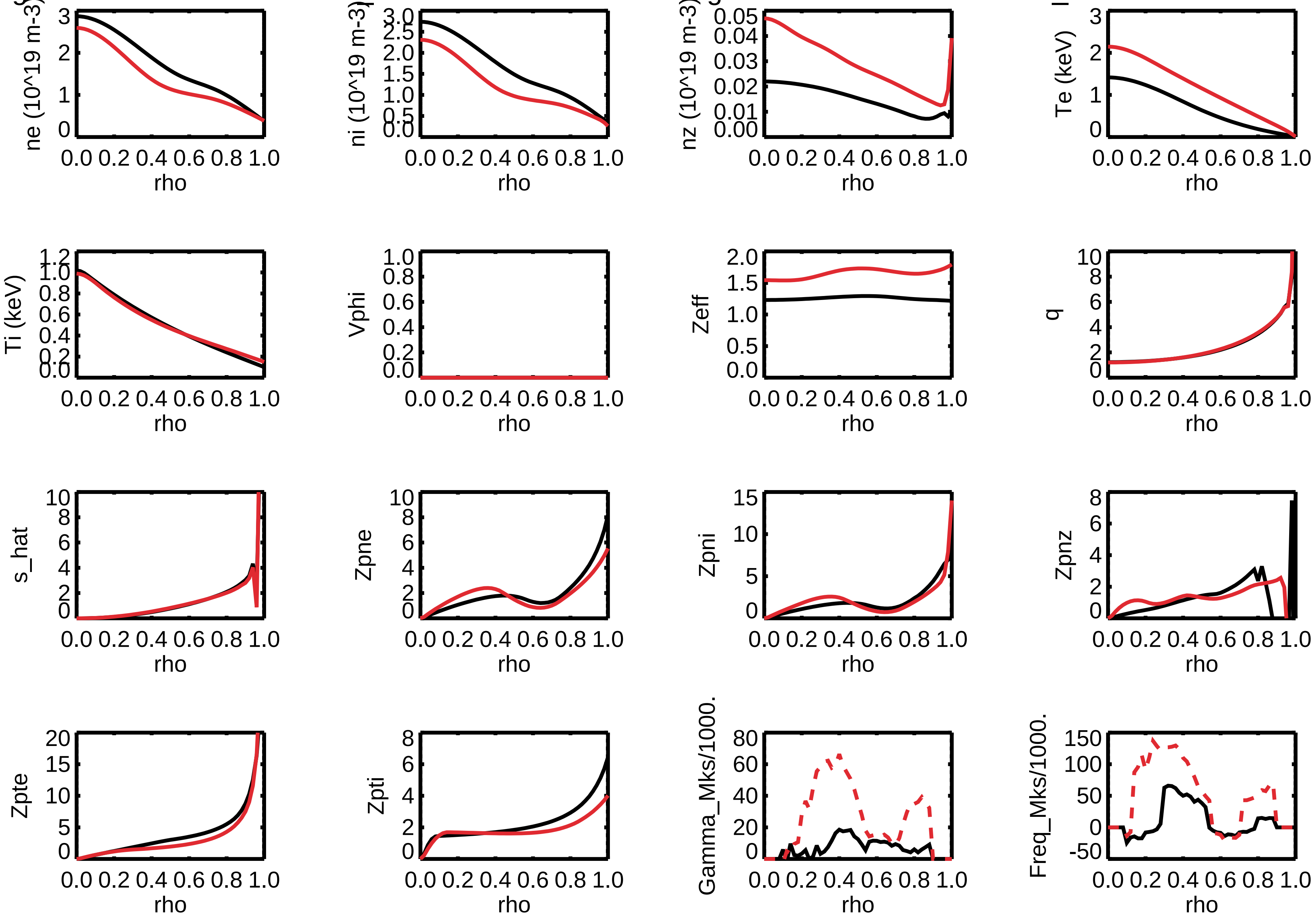

Response to ECH: both ñ measurements and GKS predictions vary with wavenumber

- GKS calculations for low-k ($k_\perp\rho_s \approx 0.3$)) appears different from observations but Er' needs to be accounted for.
- Growth rates for intermediate-k ($k_\perp\rho_s \approx 2$) both decrease and increase with ECH.
  - Observed signal comes from different radii so different frequencies may be associated with different radial positions, indicating a radial variation in fluctuation response.
- Growth rates for k = 35 cm^{-1} ($k_\perp\rho_s \approx 10$) decrease in core and increase near edge.
  - Experimental data shows an increase which appears inconsistent with the signal coming from a radial extent of $\rho = 0.4$ to 1.0 .
  - Very interesting observation with more work needed to fully understand it.
- Changes in electron heat flux roughly correlate with high-k fluctuation changes.
  - Ion heat transport does not appear to correlate with low-k fluctuations.

Summary

- First measurements of high-k turbulence ($k \sim 35\ \mathrm{cm}^{-1}$, $k_\perp \rho_s \approx 10$) on DIII-D have been made.
  - Combined with low and intermediate-k measurements, these provide a new, more complete picture of turbulence behavior on DIII-D.
  - Clear turbulence signals at $k \sim 35\ \mathrm{cm}^{-1}$, $k_\perp \rho_s \approx 10$ using new mm-wave backscatter.
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- Both measured and calculated response to perturbations (NBI, ECH) varied with wavenumber, supporting need for broad wavenumber comparisons.