Comparison of Edge Fluctuation Measurements from PCI, BES, Langmuir Probes, and Reflectometry on DIII–D

J.C. Rost[1], M. Porkolab, T.L. Rhodes,
R.A. Moyer, G.R. McKee, and K.H. Burrell

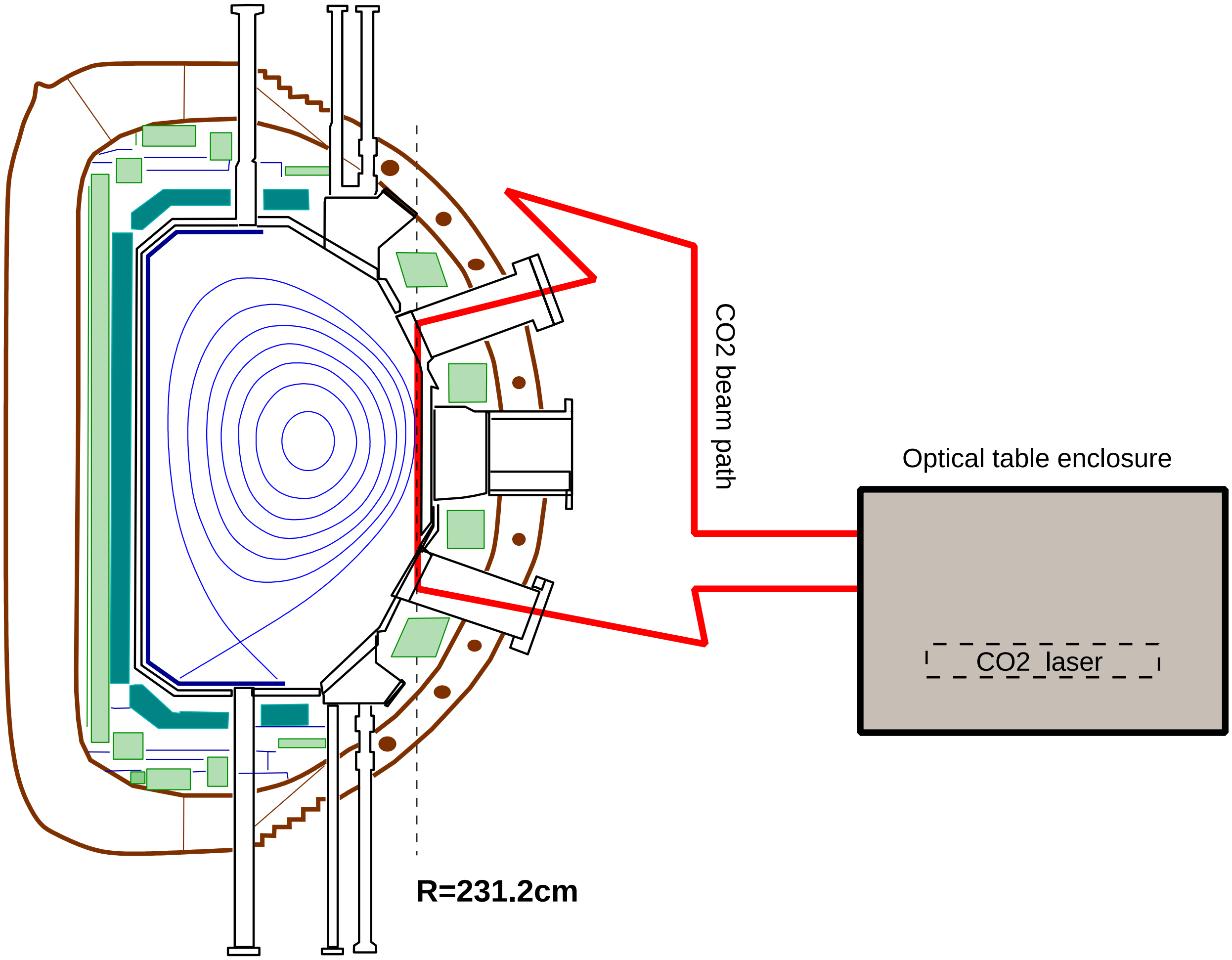
All material should be considered unpublished and provisional and should not be redistributed or presented without express permission of the authors.

[1] `rost@psfc.mit.edu`

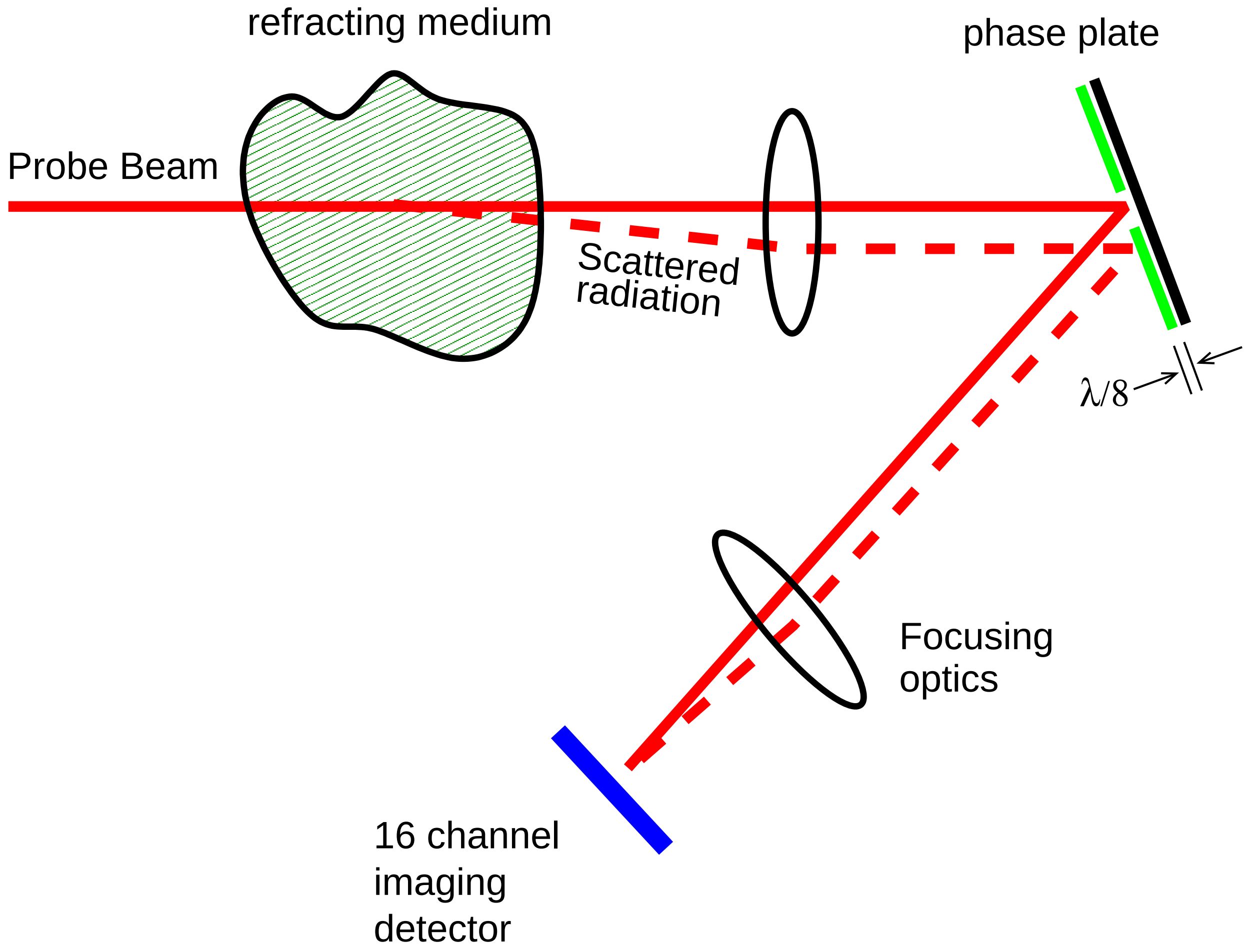
Abstract

Phase Contrast Imaging, Beam Emission Spectroscopy, reflectometry, and Langmuir probe diagnostics on DIII–D provide edge density fluctuation measurements that cover different but complementary regions of wave number space. Comparison of data collected from different diagnostics at the same time and location provides information about the k-space structure of the turbulence not available from a single diagnostic and thus better illuminates the underlying physics. Multiple measurement locations are used to extend the comparison across the LCFS.

PCI Location on DIII-D



Phase Contrast Imaging



PCI: the Equations

- CO_2 laser beam at 10.6 μm
- 8 cm beam width at midplane
- beam scattered with phase shift from plasma

$$\Delta\phi \propto \int n_e dz$$

- 16 channel detector
- no external reference beam

Fluctuations $\tilde{n}$ cause extra phase shift $\tilde{\phi} \propto \int \tilde{n}_e dz$

$$\mathbf{E}_0 \rightarrow \mathbf{E}_0 e^{i\tilde{\phi}(R)} \simeq \mathbf{E}_0(1 + i\tilde{\phi})$$

After phase plate, $\mathbf{E}_0$ shifted by i, reduced to δ. Field on detector:

$$|\mathbf{E}_D|^2 = |\mathbf{E}_0(i\delta + i\tilde{\phi})|^2 \simeq |\mathbf{E}_0|^2 \delta(\delta + \tilde{\phi})$$

- Easy to measure $\tilde{\phi}$ (AC) over δ (DC)

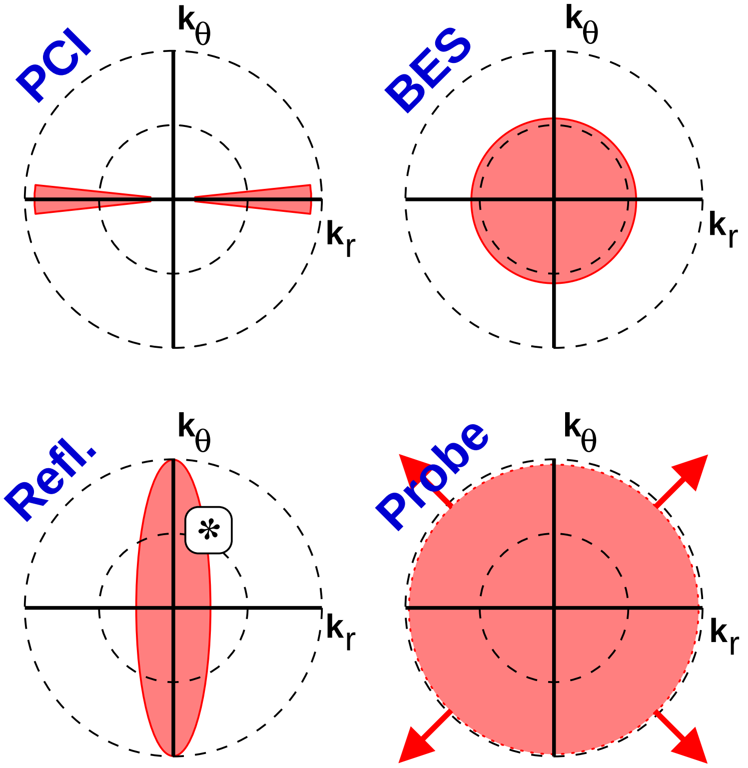
Diagnostics Combined are Better

- We study *transport* via *turbulence*
- One diagnostic sees only a part of the turbulence — limits in:
  - Frequency range
  - k-space range
  - Physical location
- First step to compare measurements at same location
- Valuable for:
  - Benchmarking details of computer/analytic models
  - Improving interpretation of diagnostics
  - More complete picture of turbulence

Making comparisons is not trivial: very small number of shots with 3 of these diagnostics acquiring data at same time and location.

- PCI fixed in place – large outer gap means PCI all in SOL
- BES needs a certain neutral beam (high-power); may not be consistent with other experimental needs
- Reflectometer measurement location depends on density profile, so can't be fixed in advance and changes with density (e.g. H-mode transition)
- Fast probe can go into LCFS only on low power plasmas (heat loading)
- Scale lengths very short in edge; positions must be identical to less than 1 cm.

Diagnostic Response in Different Regions of k-space

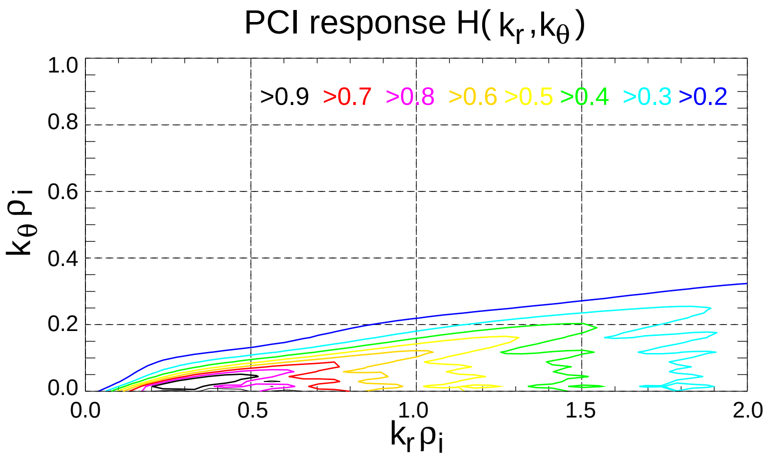


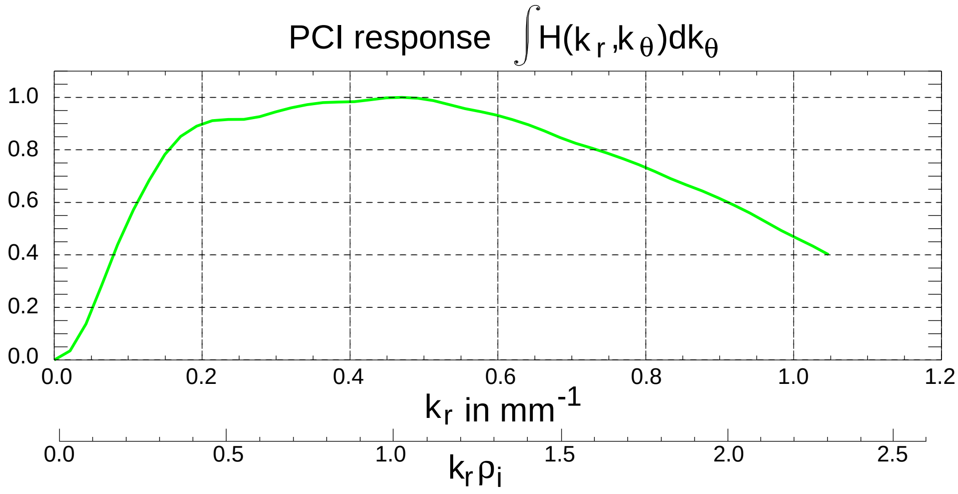
Not to scale.

- Different diagnostic measurements describe different parts of k-space.
- Shape of region important!

$*$ k-space reflectometer response is not completely understood, and is an area of active experimental and theoretical study. See Rhodes *et al*, Plasma Phys. Control. Fusion **40** (1990) 493.

Details of PCI k-space Response


PCI response $H(k_r, k_\theta)$


PCI response $\int H(k_r, k_\theta) dk_\theta$

- Low k cutoff due to scattering technique
- High k cutoff from detector spacing via (adjustable) magnification
- Measures approximately $S(k_r, k_\theta = 0)$
- Response approximately **flat** in region of interest

Example: Isotropic turbulence

- $S(k_r, k_\theta, \omega) = S(k, \omega)$
- PCI signal

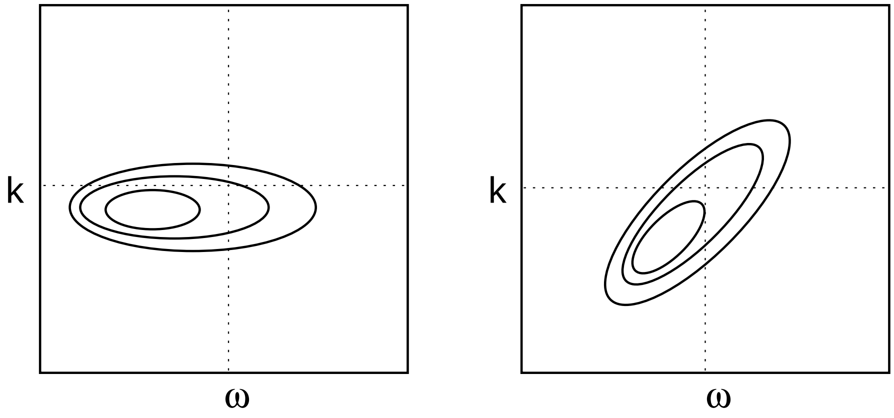
$$S(\omega) \propto \int_{k_1}^{k_2} S(k, \omega) dk$$

- Probe/BES signal

$$S(\omega) \simeq \int S(k, \omega) dk_r dk_\theta = 2\pi \int k S(k, \omega) dk$$

- Often $S(k, \omega)$ peaks at some $\bar{k}(\omega)$, $i.e.$ approximate dispersion relation
- For isotropic turbulence, expect PCI $S(\omega)$ **not** to match BES, probe in many cases

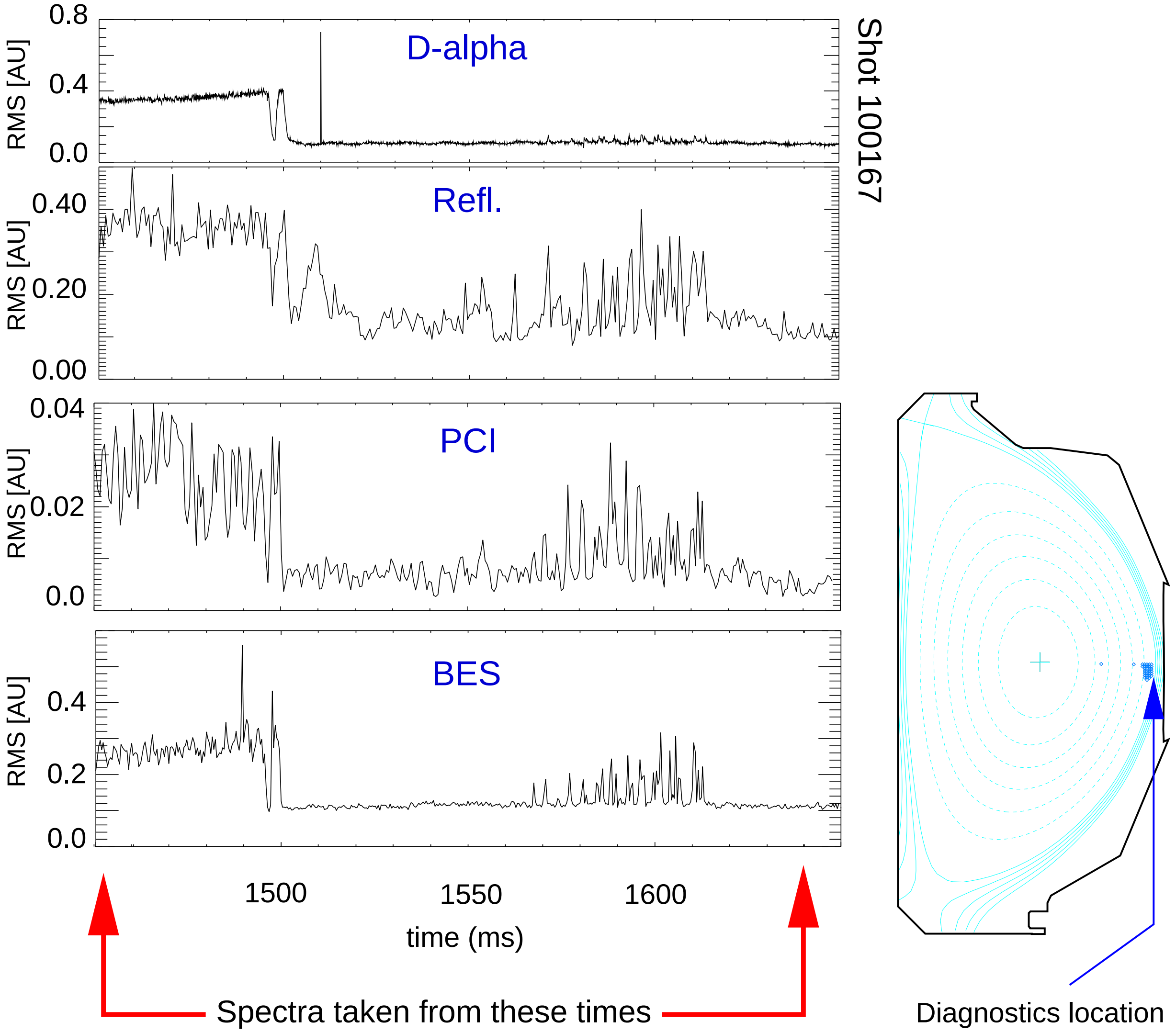
Sample S(k,ω) contour plots



$S(\omega)$ independent of k response

$S(\omega)$ changed if higher k cut off

L–H Transition Experiment

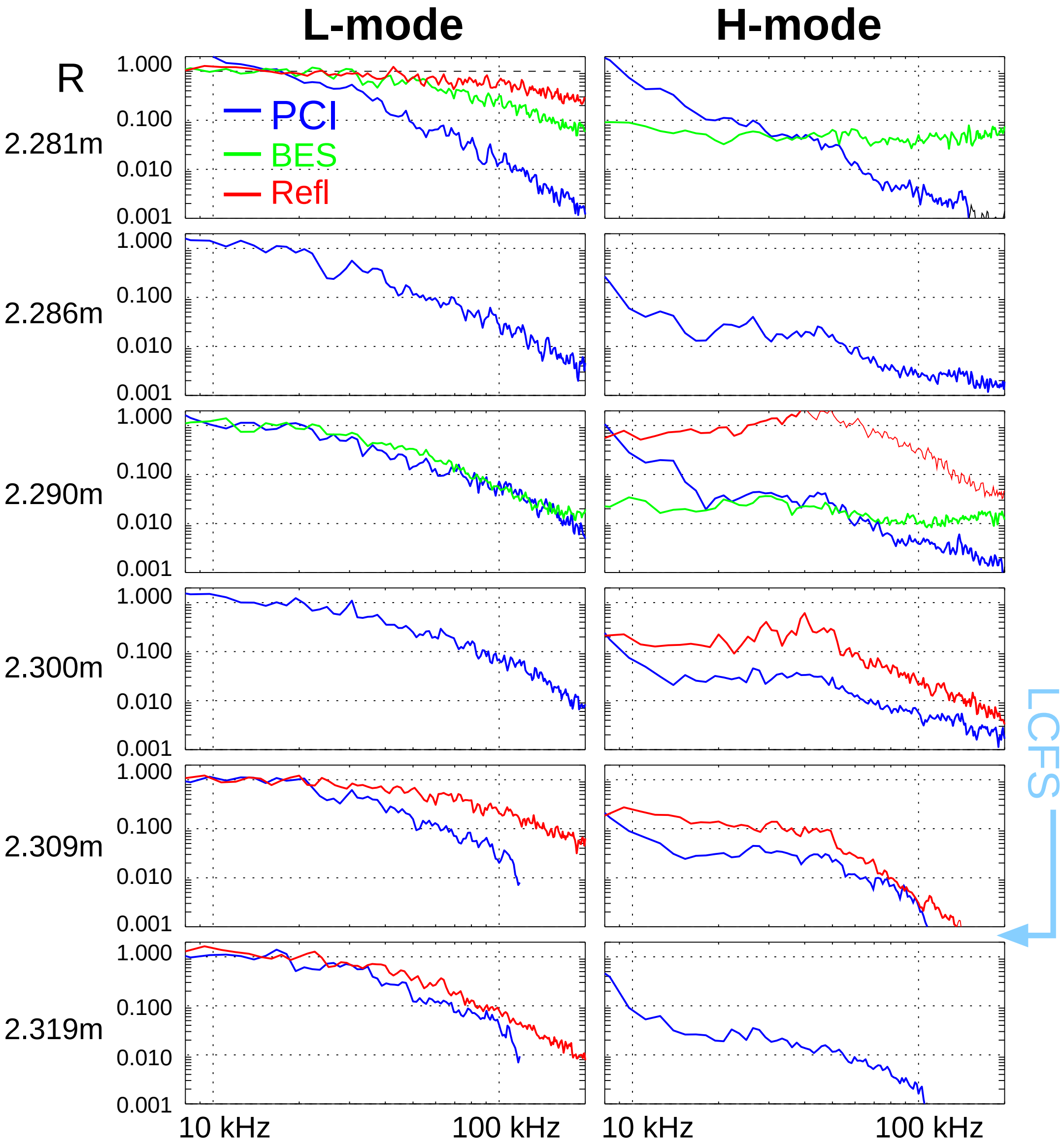


Spectra taken from these times

Diagnostics location

- Sawtooth-free, double null diverted
- $n_{e0} = 4 \times 10^{19}$ m^{-3}, NB power 7.5 MW
- Well-known drop in fluctuations in H-mode observed with all diagnostics

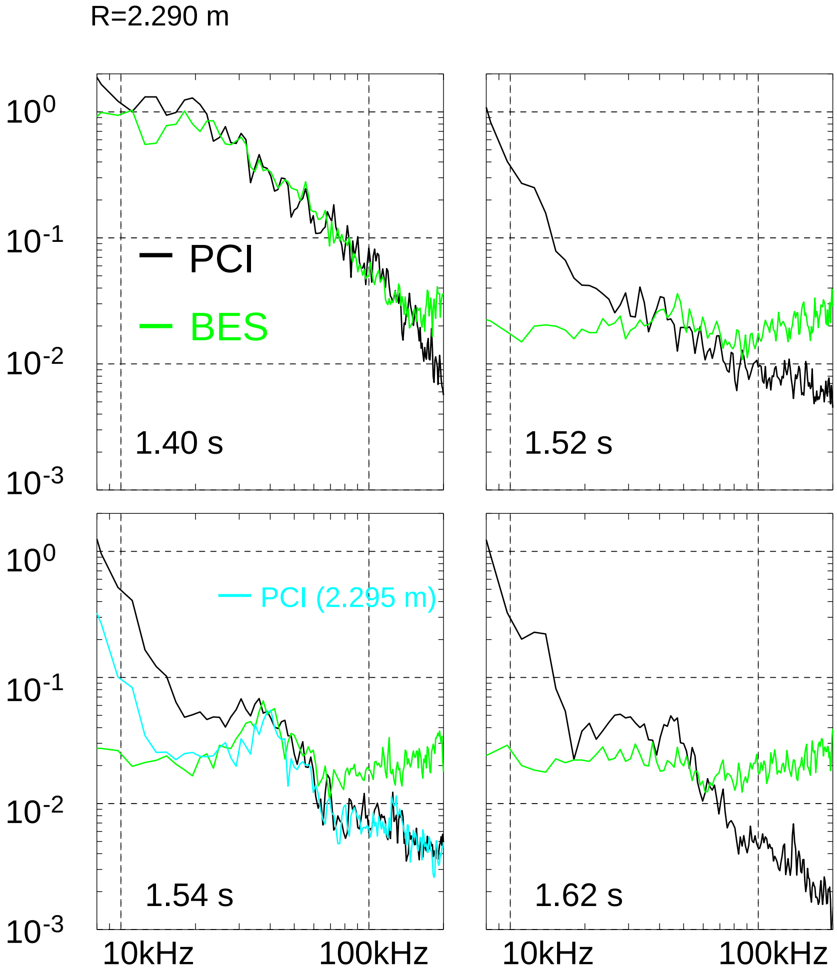
L–H Transition Experiment



- Arbitrary normalization at 1.40 s
- Same normalization kept on other plots

PCI vs. Integrated BES

Add up a vertical set of BES channels to approximate PCI response



PCI and integrated BES also match: additional evidence that $S(k_\theta = 0, \omega) = S(\omega)$

H-mode: Conclusions

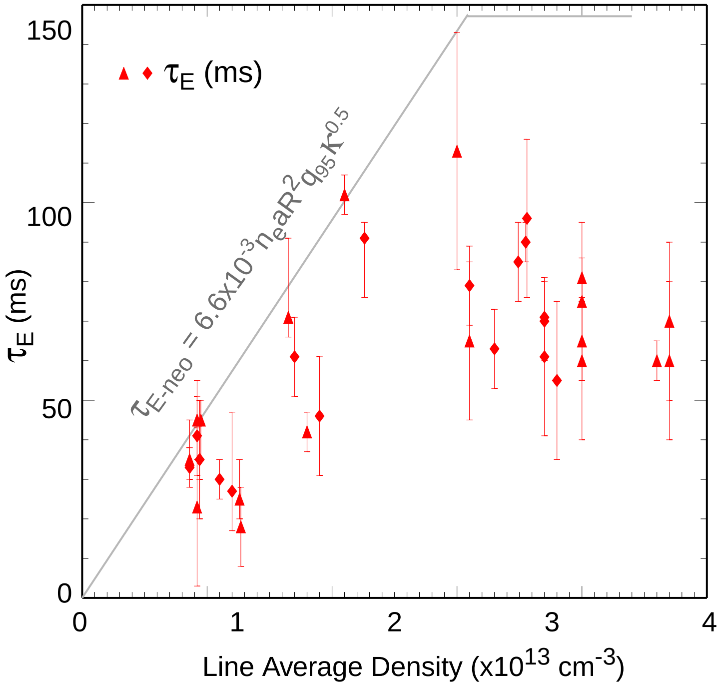
BES and PCI spectra match near LCFS

- Average k_r is the same (0.25 mm^{-1}) for all ω (in contrast to ITG experiments below). . .
- Therefore varying k response does not affect measurement of radial modes

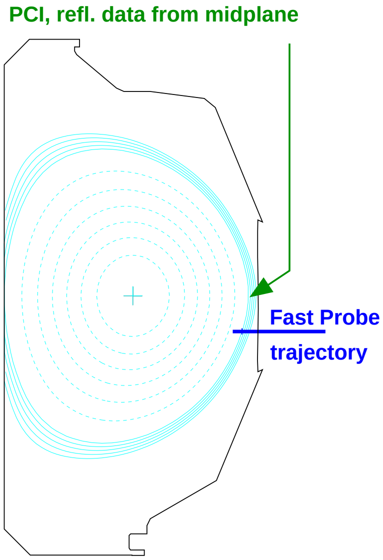
Reflectometer spectra do not match

- Spectra wider in ω hence autocorrelation time *shorter*
- Less decrease in amplitude than PCI, BES
  - Question of normalizations with change of $n_e(r)$ over transition
- Poloidal modes (Doppler shift) smaller contribution to $S(\vec{k})$ than radial modes

Density Scan in ITG Experiments

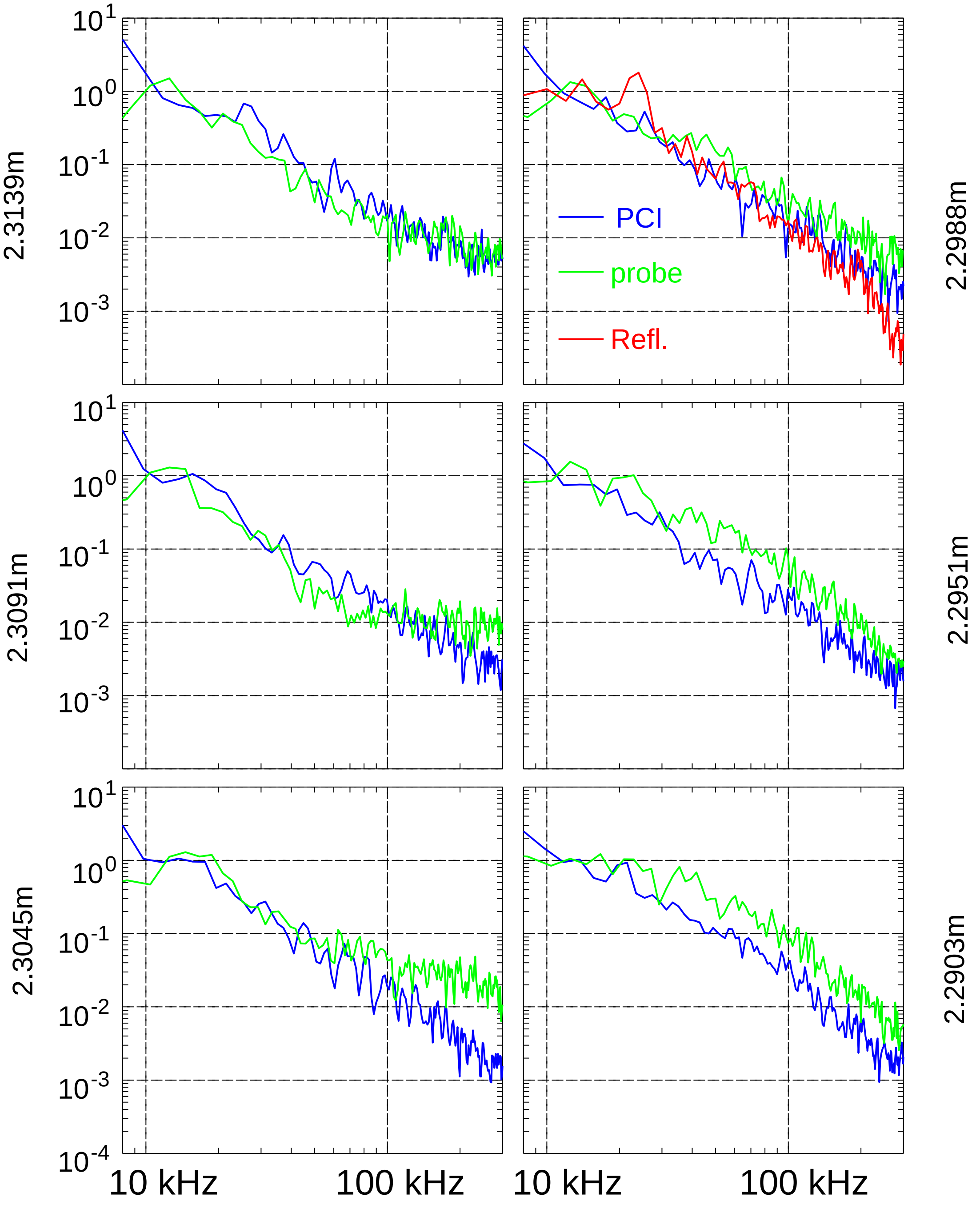


Energy Confinement Time versus Line Average Density



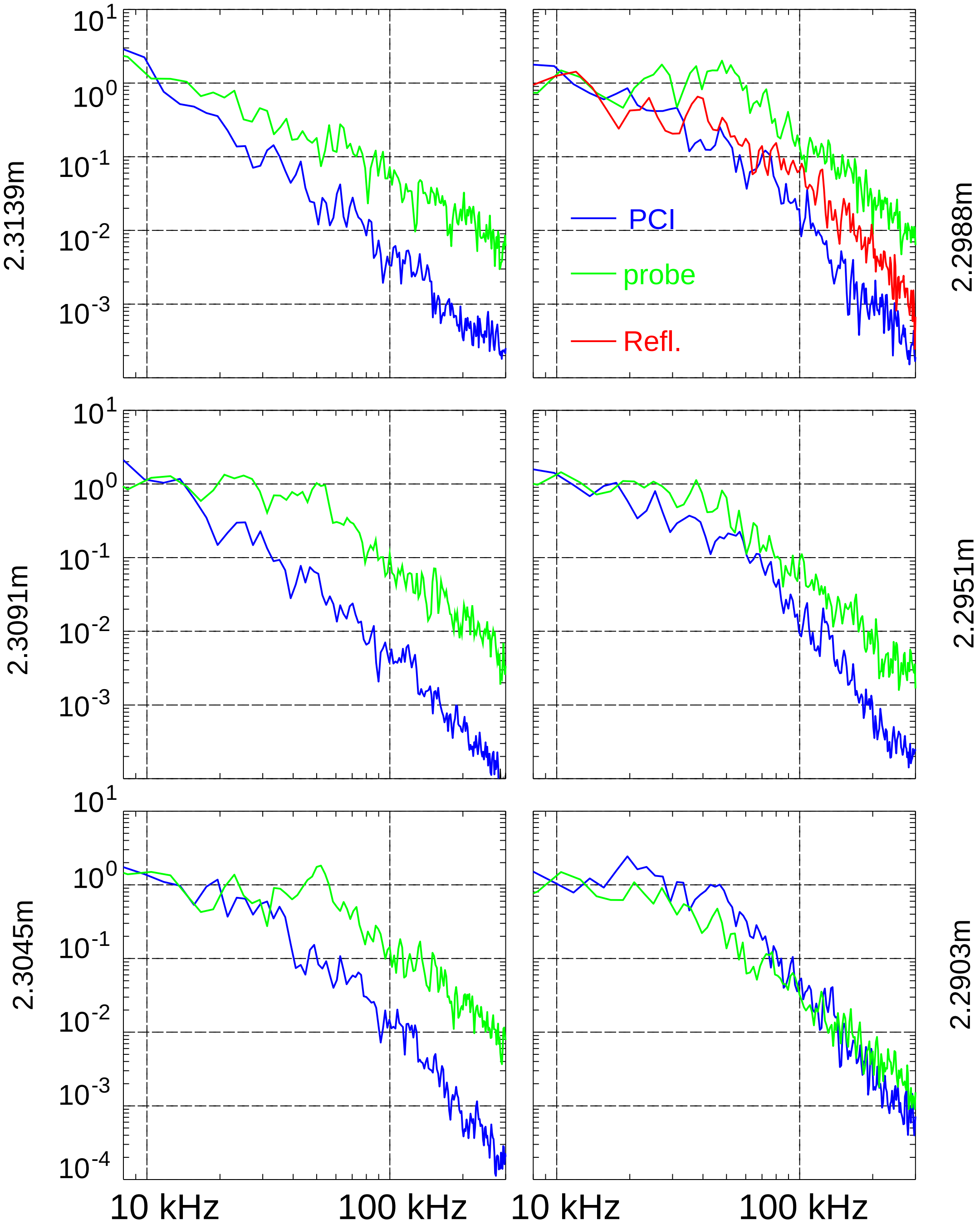
- Limited, nearly-circular plasmas
- Codes say ITG unstable only at high density
- Turbulence data from PCI, reflectometer, and fast scanning Langmuir probe at LCFS
- Spectra at lowest and highest density

Power spectra vs. R, Low Density

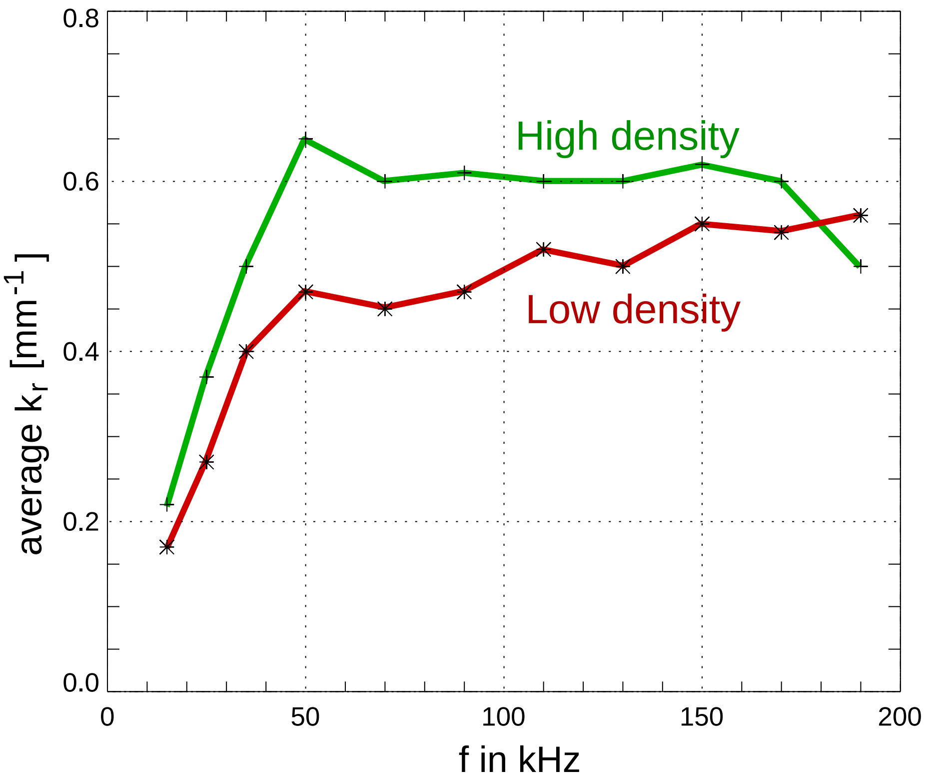


Probe position mapped to midplane R using EFIT

Power spectra vs. R, High Density



Cutoffs in k Affect Power Spectrum



- Find approximate dispersion relation for the turbulence $k_r(\omega)$
- In high density, hit high k_r cutoff at 50 kHz
- PCI spectrum above 50 kHz reduced b/c missing spectral components
- Maybe $\bar{k}_r \propto T^{1/2} \longrightarrow \bar{k}_r\rho$ constant

Conclude: High k components are large part of turbulence above 50 kHz at higher density.

Probability Distribution Function

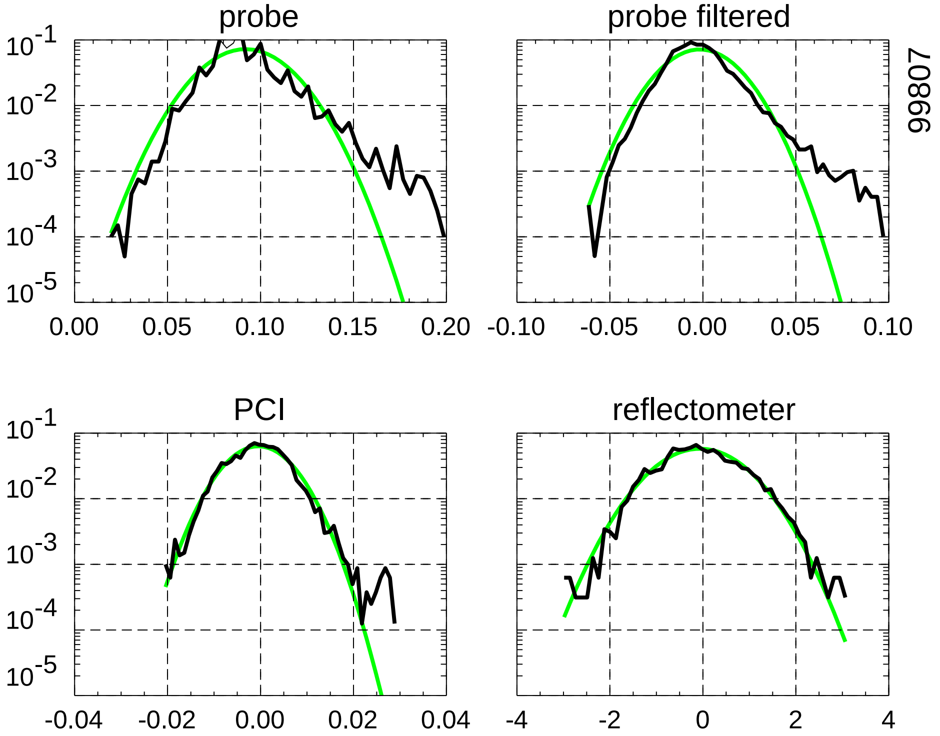
PDF $\mathcal{P}(z)$ of a signal $x[n]$ gives probability that

$$z - \Delta z < x[n_0] < z + \Delta z \qquad \text{for any } n_0$$

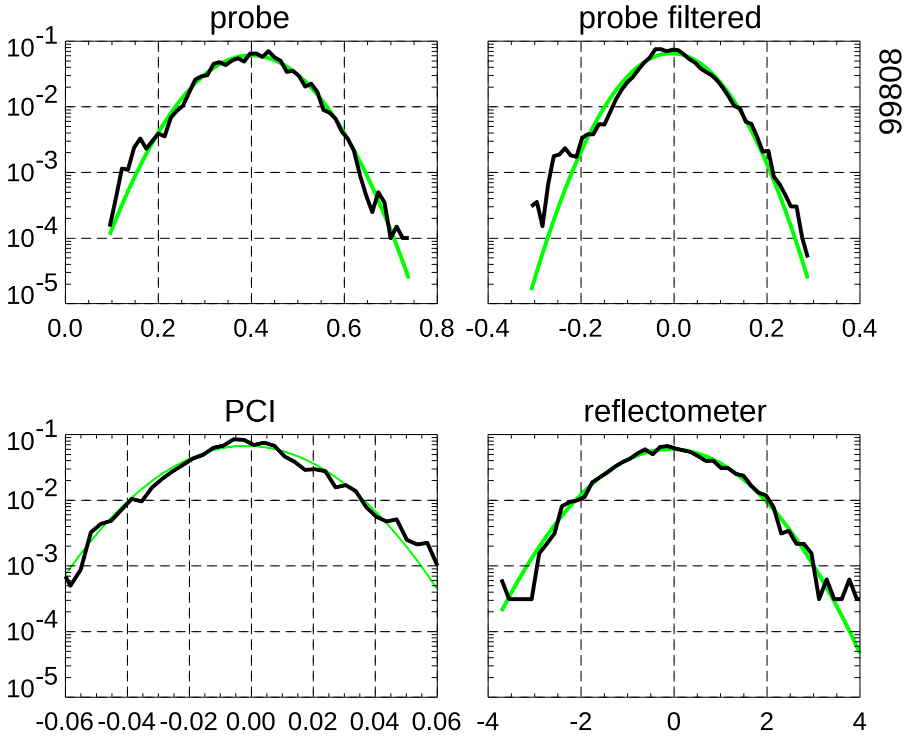
- Different points of view
  - Power spectrum separates frequency components
  - PDF is nonlinear, correlations between frequency components important
- PCI response limited at ~ 8 kHz, so look at PDF of *filtered* data for fair comparison
  - High pass at 10 kHz (brick wall)
  - Low pass at 100 kHz (brick wall)
  - Effect on PDF not well understood
- Probe data clearly skewed, PCI & refl not
- Avalanche-like transport gives skewed PDF
- Strong turbulence gives symmetric PDF
- Green line is a Gaussian

PDF: low density

Do Not Distribute



PDF: high density



PDF: Results

Skew only on probe signals

- Skew to large at low density (seen often)
- Some skew to small at high density
- Skew also on *filtered* data, so it should be seen on PCI, refl.
- PCI, refl are missing the *largest* events! Which events cause most transport?

Why skew only on probe?

- $\tilde{T}_e$? ($I_{\mathsf{sat}} \propto nT_e^{1/2}$)
- Do other diagnostics miss spectral components that generate the largest $\tilde{n}$ on probe? (Power spectra look the same.)

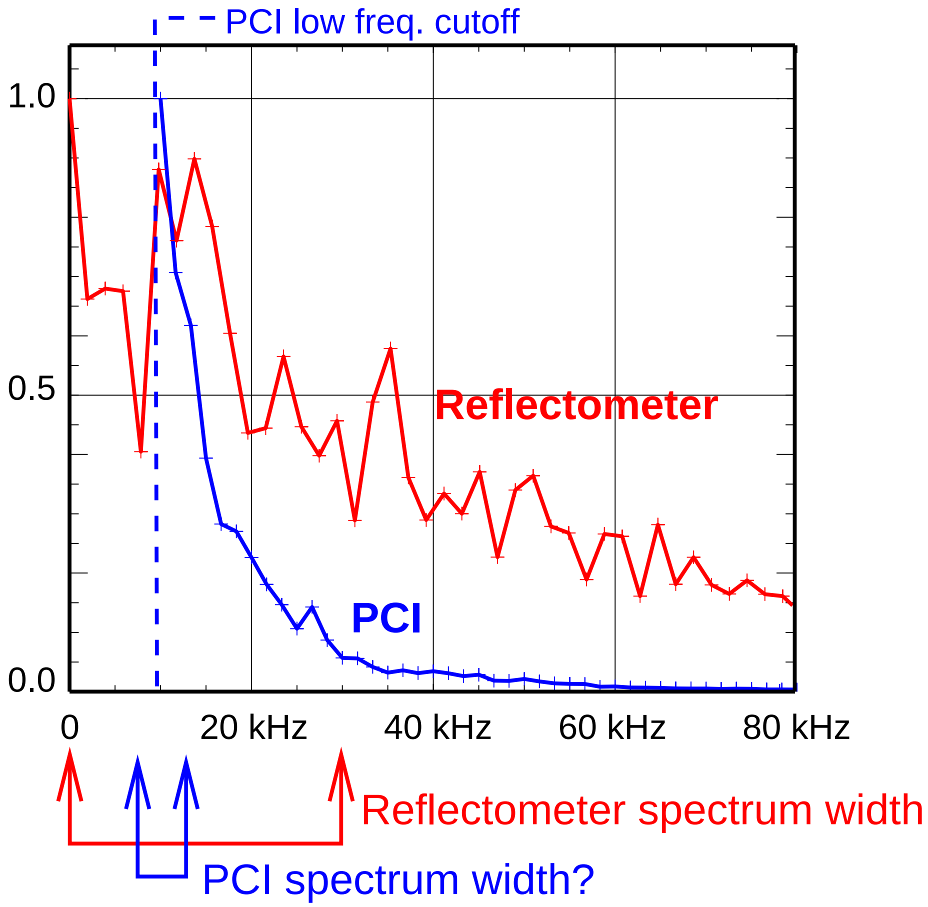
Correlations and Power Spectra

- Autocorrelation time and radial correlation length are quantitative turbulence parameters used in transport studies.
- Correlation function $C(\tau) \propto \int x(t)x(t-\tau)$ and power spectrum are a *Fourier transform pair* (See e.g. Bendat & Piersol)
- Example:

$$S(\omega) = \frac{1}{1+\omega^2\tau_c^2} \quad \Longleftrightarrow \quad C(\tau) = \exp(-|\tau|/\tau_c)$$

- Autocorrelation time τ_c is also inverse of width of power spectrum! $(1/2\pi f_c)$

Different Diagnostics Must Measure Different Correlations



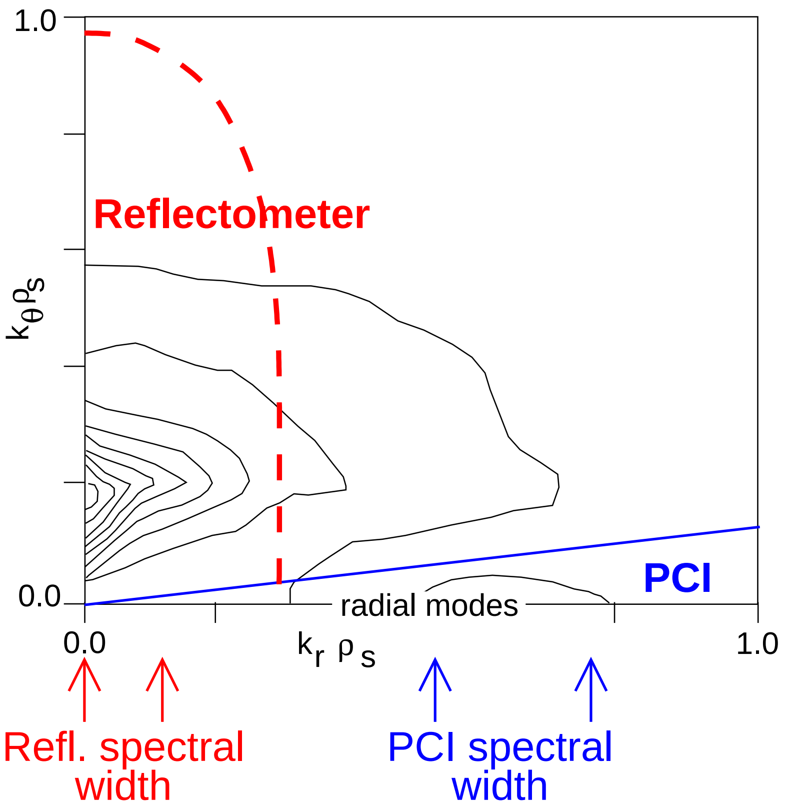
Autocorrelation times and “high density” shot:

- Reflectometer spectrum width ~ 30 kHz
- PCI, probe spectral width < 10 kHz

Therefore

- Reflectometer autocorrelation time $\sim 5\ \mu$s
- PCI, probe autocorrelation time $> 15\ \mu$s

Different Diagnostics Must Measure Different Correlations



(Response shown is only *qualitative*)

- Reflectometer sees width of main peak
- PCI sees width of “radial modes” peak
- Different correlation lengths from different parts of the spectrum

Concepts such as autocorrelation time and radial correlation length are too simplistic to describe plasma turbulence.

Conclusions and Future Work

- Turbulent spectra have complex structure in k-space
- Using diagnostics with complementary k-space sensitivity allows us to study this structure
- Diagnostic response directly affects measurement of turbulence parameters; amplitude, correlation length, autocorrelation time
- Need to understand what parameters to extract to usefully quantify turbulence.
- Extending this work
  - Examine more discharges
  - Make full use of capabilities of these diagnostics
  - Include more diagnostics in comparison
- Ready to start serious detailed comparisons with edge turbulence models
  - Must include k-space response, frequency response, and volume effects correctly
  - Distinct features that model must reproduce
    - $\bar{k}_r(\omega) \propto \omega\sqrt{T}$ vs. $\bar{k}_r(\omega)$ constant
    - Dominance of poloidal modes in high power plasma
    - Skew PDF of modeled Langmuir probe signals (and density dependence) and no skew of PCI, reflectometer