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

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## Abstract

Phase contrast imaging (PCI), beam emission spectroscopy (BES), reflectometry, and Langmuir probes provide different but complementary measurements of the density fluctuations in the edge of the DIII-D tokamak plasma. In particular, the PCI is sensitive to modes with  $k_\theta \ll k_r$ , while the BES and probe response depends less on the angle of  $\vec{k}_\perp$ .

On plasma discharges in which these diagnostics collect data from the same location at the same time, comparison of the signals gives more information about the turbulence than a single measurement. Comparing measurements from L- and H-mode plasma phases, we found that the L-mode frequency spectra (10–250 kHz) from BES, PCI, and reflectometry have identical shapes. However, the H-mode spectra differ significantly, with the  $k_\theta \ll k_r$  modes suppressed the most. This suggests that the edge fluctuations are nearly isotropic in L-mode but highly anisotropic in H-mode. Other comparisons at the last closed flux surface in two similar low power plasma discharges differing by a factor of four in density showed power spectra with a more complicated structure.

## I. Introduction

Understanding heat and particle transport via density fluctuations may be key in designing a plasma fusion reactor. Any single diagnostic can only measure a restricted set of the characteristics of the turbulence, including limits in frequency and wave number range and measurement location. Consequently, employing several of these diagnostics simultaneously gives a better picture of the turbulence than any of these alone.

The advances in computer simulations of plasma transport are leading to mature models describing plasma fluctuations[1], including models specific to the plasma edge[2]. The type of comparisons presented here are needed to assess the validity of the modeling results. Furthermore, the general results of the computer models can improve our understanding of the diagnostic measurements and thus allow us to better interpret the observations.

In this work, we compare measurements of density fluctuations in the plasma edge acquired with the phase contrast imaging (PCI) interferometer[3], the beam emission spectroscopy (BES) diagnostic[4], the reflectometer system[5], and fast scanning Langmuir probes[6] on the DIII-D tokamak[7]. While the strengths and limitations of each diagnostic may be found in the references, the most important difference for this study is that BES and probes are equally sensitive to all  $\vec{k}_\perp$  wave number directions, while PCI responds to the  $k_\theta \ll k_r$  range of wave number space, and reflectometry responds to  $k_r$  components but more so to  $k_\theta$  components. Note that this implies that the PCI data is minimally affected by Doppler shifts caused by plasma rotation.

We note that acquiring data for these comparisons is not a trivial exercise. The PCI and probe measurements are not available for all plasma shapes. The BES requires that a particular neutral beam heating source be used, which precludes use of the fast scanning probe. The position of fluctuation measurements by the reflectometer depends on the density profile, and may not be specified in advance.

In order that the features compared be well-defined, we examine turbulence frequency power spectra of the various diagnostics. We interpret the results in terms of the different  $k$ -space response of the diagnostics.

## II. L–H Transition

Valuable data for this comparison was acquired on a DIII-D experimental run day dedicated to studying the L–H transition. The plasmas were sawtooth-free, double null diverted discharges, with  $n_e = 4 \times 10^{19} \text{ m}^{-3}$  and 7.5 MW of neutral beam power.

Comparisons of data from PCI, BES, and reflectometry made 100 ms before the transition and 140 ms after the transition are shown in Fig. 1. No absolute calibration of the signals was used. Multiplication factors were used to align the L-mode signals, and the *same* multiplicative factors were used for the H-mode data.

The L-mode spectra are identical in shape. The minimal hypothesis is that the edge turbulence at this time is isotropic.

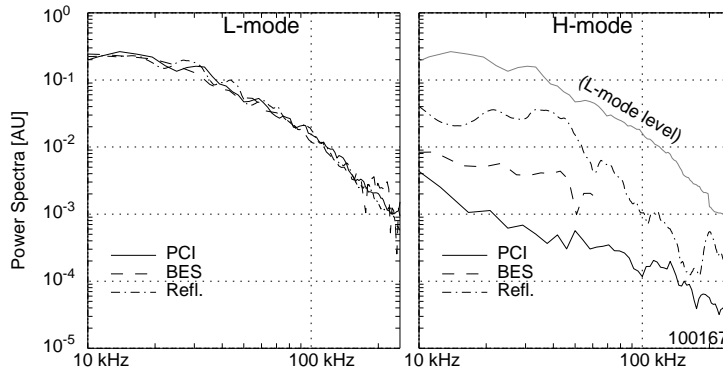


Figure 1: *PCI, BES, and reflectometer fluctuation power spectra in L- and H-mode*

Comparing the H-mode data to that from L-mode shows that the components to which the PCI is sensitive are most strongly suppressed. This may be a direct effect of the increased edge velocity shear in the H-mode edge[8]. Velocity shear breaking up the edge turbulence can move energy into higher  $k_r$ , above the PCI limit (in the current configuration) of approximately  $6 \text{ cm}^{-1}$ . Another possible interpretation is that the instability drives the finite  $k_\theta$  modes which couple nonlinearly to modes at  $k_\theta \sim 0$  (this behavior is predicted by models of core fluctuations[9]). Hence a decrease in the finite  $k_\theta$  modes results in a larger decrease in the nonlinearly driven  $k_\theta \sim 0$  modes.

### III. Density Scan

Data for comparison of diagnostics was also obtained during a DIII-D experiment studying ITG turbulence[10]. Calculations for these limited, nearly circular plasmas predicted that the ITG instability was stable in the core at the low density, but unstable at higher density. PCI, reflectometer, and Langmuir probe data from the last closed flux surface (there may be no direct correspondence between the edge turbulence and the instabilities in the core plasma) at two very different densities,  $n_{e0} = 0.9 \times 10^{19} \text{ m}^{-3}$  and  $n_{e0} = 4 \times 10^{19} \text{ m}^{-3}$ , is shown in Fig. 2.

In contrast to the L-mode plasma shown in Fig. 1, the spectra from the three diagnostics do not have the same shape; the relative amplitude of the spectra from the different diagnostics varies by two orders of magnitude between 10 kHz and 100kHz. However, all three follow the same trend: the

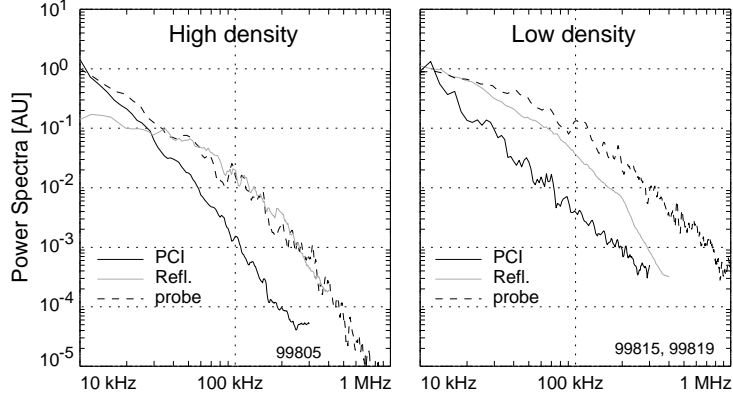


Figure 2: *PCI, reflectometer, and Langmuir probe fluctuation power spectra at the LCFS, with arbitrary normalization. Right-hand plot includes data from two identical shots. Spectra are more heavily smoothed at high frequencies for clarity.*

fall off of the power spectrum becomes steeper at higher density. Assuming a functional form of  $S \propto 1/f^\gamma$  near 100 kHz, the spectra varied as  $\gamma = 2$  in the low density shot, but obeyed  $\gamma$  of 3–4 at higher density (PCI data throughout the experiment showed that  $\gamma$  increased smoothly with plasma density). The Langmuir probe data, absolutely calibrated, shows that the high density discharge had a larger RMS amplitude of fluctuations, but that the lower density plasma had more power in fluctuations above 100 kHz.

While the spectra are more complicated than in the previous section, the evidence does suggest the following interpretation. In the high density case, the  $k_\theta \sim 0$  components as seen by the PCI dominate the turbulence, and so the probe spectrum follows the PCI spectrum. However, at higher frequencies the turbulence is dominated by the poloidal components, and the reflectometer and probe spectra are similar. The low frequency components may be due to small radial oscillations in the plasma position, which would show up in the PCI and probe data.

In the lower density discharge, the reflectometer and probe spectra have similar shapes, while the PCI spectrum is steeper at low frequencies. There are several features apparent in the graph, however, which defy simple explanation.

## IV. Conclusions

The comparisons of measurements made by several edge fluctuation diagnostics show that the wave number spectra have a complex structure. Better knowledge of structure of the spectra can help in understanding phenomena such as H-mode transport barriers. The description of the variation of the spectra in different plasma conditions is a necessary part of benchmarking the fluctuation details of turbulence models, analytic or computational. One goal of this work is to document the fluctuations in a way appropriate for these detailed comparisons.

This work also highlights difficulties in the interpretation of fluctuation data. While the turbulent transport generally decreases with decreased fluctuation level, we have seen that different spectral components of the fluctuations increase or decrease by different amounts as the overall fluctuation amplitude changes. Thus a more detailed knowledge of which spectral components generate the transport in a given regime is needed to correlate quantitatively changes in transport and fluctuation amplitude. Similar problems arise with another parameter of the turbulence used in transport studies, namely the autocorrelation time, which is roughly the inverse of the width of the fluctuation spectrum[11]. In the data presented, the autocorrelation time inferred from different diagnostics varies significantly.

We believe that the work presented here shows the importance of employing a complementary set of diagnostics to fully characterize plasma turbulence.

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