Initial Density Fluctuation Measurements Using Fixed-Frequency Quadrature Reflectometers on DIII-D


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Abstract

Two fixed-frequency (42 and 65 GHz) quadrature reflectometers have recently been installed on the DIII-D tokamak for density fluctuation measurements. Both systems have horns that can be orientated to launch and receive either O- or X-mode cutoffs in order to probe different regions of the plasma. The reconstructed phase information successfully identifies MHD activity. For an \( m=3/n=2 \) tearing mode, the calculated density fluctuation levels from reflectometry using a 1-D phase screen model agree well with Beam Emission Spectroscopy (BES) measurements. Initial comparison of turbulent density fluctuation spectra in the edge pedestal with BES shows qualitative similarity; however there are differences in the details, which are under further investigation.

I. Introduction

It has long been recognized that reflectometer density fluctuation measurements have numerous advantages, e.g. highly localized measurement, highly sensitive, flexible spatial coverage, non-perturbative, and it is now anticipated to play a much enhanced role in the harsh burning plasma environment in the next generation devices like ITER. Reflectometer density fluctuation diagnostics have not been completely understood so far [1] and have been the focus of intense investigation. Recently, two fixed-frequency (42 and 65 GHz) quadrature reflectometers have been installed on the DIII-D tokamak. In this paper, density fluctuation measurements of MHD activity, and turbulent density fluctuation measurements in the edge pedestal using these reflectometers are presented and directly compared to Beam Emission Spectroscopy (BES) measurements with similar location and localization. The results show that the calculated density fluctuation levels of an \( m=3/n=2 \) tearing mode from reflectometry using a 1-D phase screen model agree well with BES measurements. Initial comparison of turbulent density fluctuation spectra in the edge pedestal with BES shows qualitative similarity, however there are differences in the details, which are under further investigation.

II. Fixed-Frequency Quadrature Reflectometer System on DIII-D

Figure 1 is a schematic plot of one of the two similar fixed-frequency quadrature reflectometer systems on DIII-D. The second system is similar with the exception of a different frequency. Most of the microwave power from the source, a Gunn Oscillator, is launched into the plasma by passing through a directional coupler and 2 isolators which are used to prevent reflected power into the source. The received reflection from the plasma cutoff layer mixes with the local oscillation from
the source, and the quadrature mixer output provides the complex electric field, \( E(t) = A e^{i\phi(t)} \) i.e. \( A(t)\cos\phi(t) \) and \( A(t)\sin\phi(t) \) where \( \phi \) i.e. is the phase delay between the launched microwave and its reflection from the plasma cutoff layer. The phase contains the density fluctuation information in the cutoff layer, e.g., the basic 1-D phase screen model predicts that the density fluctuation is proportional to the phase fluctuation, but they could have a more complicated relationship depending on the real geometry according to various models (see e.g. [1] and references therein).

The microwave and electronic components for each reflectometer are contained inside portable boxes. For initial tests, output waveguides are coupled to existing antennas normally used in the UCLA profile reflectometer systems [2]. Both systems have horns that can be orientated to launch and receive either O- or X-mode polarization in order to probe different regions of the plasma. The launch and receive antennas are in the outboard midplane of DIII-D.

A new algorithm [3] is applied to reconstruct the phase information from \( A(t)\cos\phi(t) \) and \( A(t)\sin\phi(t) \). It calculates the relative phase differences between two subsequent measurements and accumulates them to get the absolute phase. The method can be illustrated as follows. Assume two successive measurements \((x_i, y_i)\) and \((x_{i+1}, y_{i+1})\), where \(x_i\) and \(x_{i+1}\) are real parts (i.e. \(A(t)\cos\phi(t)\)), and \(y_i\) and \(y_{i+1}\) are imaginary parts (i.e. \(A(t)\sin\phi(t)\)), their phase difference can be derived [3] as:

\[
\delta\phi = 2\sin^{-1}\left[ \frac{x_i y_{i+1} - y_i x_{i+1}}{\sqrt{((x_i + x_{i+1})^2 + (y_i + y_{i+1})^2)(x_{i+1}^2 + y_{i+1}^2)}} \right].
\]

Note that this method can recover phase information if the phase variation between successive measurements is within \( \pm\pi \), which can be compared to the normal method which recovers the phase between \(-\pi/2\) and \(\pi/2\). High data sampling rates (normally 10 or 25 MHz) are employed to avoid phase jumps exceeding \(2\pi\) between successive measurements.

Beam Emission Spectroscopy (BES) [4] data will also be shown with similar location and localization for comparison in this paper. It measures a similar wave number range of \(k_\perp \approx 0\text{–}3\text{cm}^{-1}\).

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**Figure 1** A schematic plot of quadrature reflectometers on DIII-D
III. Coherent Density Fluctuation Measurements

MHD activity (e.g. tearing modes and compressional Alfvén eigenmodes) has been successfully identified from the phase information. An example of detection of a tearing mode is shown in Figure 2.

Figure 2 (a) Photodiode time history, contour plot of fluctuation spectrum (log scale) from (b) B from a magnetic loop, and (c) 65 GHz reflectometer at O-mode polarization, (d) density fluctuation levels versus time from reflectometer (solid line) and BES (filled rectangles).

Figure 2(b) is a contour plot of the magnetic fluctuation spectrum measured by a magnetic loop, showing the existence of an \( m=3/n=2 \) tearing mode (m and n are the poloidal and toroidal mode numbers respectively) between 25-30 kHz in the time window of 4000-4100 ms of shot 121962. This is an H-mode discharge with frequent ELMing activity as indicated by the photodiode time history in Figure 2 (a). Figure 2(c) is a contour plot of the phase fluctuation spectrum measured by 65 GHz reflectometer at O-mode polarization and clearly illustrates detection of the mode. It should be pointed out that from the Thomson Scattering density profile measurement between ELMs that the reflectometer detection locations are almost constant, i.e. at \( \rho \sim 0.8 \), but during the occurrence of the ELMs, the edge density profiles are affected and does cause the detection location to move radially inward/outward, as can be seen from the spectrum change in Figure 2(c), especially around 4010, 4028, 4052, and 4080 ms.
Using the basic 1-D phase screen model [1], the density fluctuation level induced by the mode can be calculated as \( \delta n/n_e = \delta \phi/(2 k_o L_n) \), where \( \delta \phi \) is the phase fluctuation level, \( k_o \) is the vacuum wave number of the source wave, and \( L_n \) is the density scale length. The solid curve in Figure 2 (d) is the result of the calculated density fluctuation level for the \( m=3/n=2 \) mode. With a time resolution of 0.655 ms, \( \delta \phi \) is obtained from integrating the mode spectrum shown in Figure 2(c) over 22-30 kHz and subtracting the turbulent density fluctuation background which is calculated by integrating the spectrum over 30-38 kHz due to the fact that the spectrum is quite flat in the frequency range of 22-38 kHz. \( L_n \) is calculated from the Thomson scattering density measurement with 12.5 ms time resolution but interpolated to the time grid of \( \delta \phi \). For comparison, measurements from BES were plotted as red rectangles with each averaged over a 10 ms time window. These BES measurements (and those shown in the following part of this paper) were obtained with the recently upgraded BES system [5]. The two diagnostics agree well with a few exceptions. The observed discrepancies could be related to 1) the possible uncertainty in the calculated turbulent density fluctuation background; 2) the afore mentioned effect of ELMs during which the actual \( L_n \) may have changed dramatically from the value interpolated from the sparse Thomson scattering density measurement; and 3) the mode amplitude has changed substantially as the detection location moves.

IV. Turbulent Density Fluctuation Measurements in Edge Pedestal Region

Initial analysis has also been done for the broadband density fluctuations in the edge pedestal. Figure 3(a) is a density profile measured by Thomson scattering, showing a case where the 65 GHz O-mode detection location is in the edge pedestal region. The raw data, \( A(t)\cos(\phi(t)) \) and \( A(t)\sin(\phi(t)) \) (data sampled at 25 MHz) are plotted in Figure 3(b) for \( t=4000-4002 \) ms. The figure shows a fairly well defined annulus, indicating a good phase measurement. The auto-power of the phase fluctuation for these data is plotted in Figure 3(c). The spectrum decays with an index of -3.3 in the frequency range of 85-800 kHz, again indicating non-random phase measurement (phase runaway would tend to increase the index to -1). Figure 3(d) shows the density fluctuation spectrum from BES measurement at the same location of \( \rho \sim 0.8 \) but averaged over a much longer time scale (4000-5000 ms). The plasma is in a steady-state condition in this time period. It is evident that the two diagnostics show qualitative similarity in the density fluctuation power spectrum, but a difference in the details can also be found. The difference might be due to several reasons, e.g., the 1-D phase screen model may not be applicable in this case, different instrument response and the difference of the averaging time windows of the two diagnostics, etc. For a better understanding, a 2-D full wave calculation [6] of the density fluctuation level and fluctuation spectrum is underway.

V. Summary and Conclusion

In summary, two fixed-frequency (42 and 65 GHz) quadrature reflectometers have recently been installed on the DIII-D tokamak for density fluctuation measurements. The reconstructed phase information successfully identifies MHD activity. For an \( m=3/n=2 \) tearing mode, the calculated density fluctuation levels using a 1-D phase screen model agree well with BES measurements. Initial comparison of turbulent density fluctuation spectra in the edge pedestal with BES shows qualitative similarity, however there are differences in the details. A 2-D full wave calculation of the density fluctuation level and fluctuation spectrum is underway for a better understanding.
Figure 3 (a) Density profile from Thomson scattering measurement, (b) raw data $A(t)\cos\phi(t)$ and $A(t)\sin\phi(t)$, auto-power spectrum from (c) reflectometer, and (d) BES measurement where $f^{-3.3}$ line has been added for the reader’s convenience in comparing with the data in Figure (c).

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References