*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.174 (2004)*

Investigation of Broad Spectrum Turbulence on DIII-D Via Integrated Microwave and Far-Infrared Collective Scattering

W.A. Peebles[1], T.L. Rhodes[1], D.R. Mikkelsen[4], M. Gilmore[2], M. Van Zeeland[3], W. Dorland[5], J. Candy[6], J.C. DeBoo[6], E.J. Doyle[1], C.M. Greenfield[6], X.V. Nguyen[1], L. Zeng[1]

[1]*Electrical Engineering Department/PSTI, UCLA, Los Angeles, California, USA.*
[2]*Electrical & Computer Engineering Dept., UNM, Albuquerque, New Mexico, USA.*
[3]*ORISE, Oak Ridge, Tennessee, USA.*
[4]*Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA.*
[5]*Physics Department, University of Maryland, College Park, Maryland, USA.*
[6]*General Atomics, San Diego, California, USA.*

1. Introduction. Electron thermal transport remains strongly anomalous in fusion plasmas. Understanding this scientific challenge is important from both basic science and fusion plasma perspectives. Validation of transport predictions provides increased confidence as next-step devices emerge, and can lead to transport control, optimisation of pressure profiles and improved fusion performance. It is generally acknowledged that long wavelength turbulence in the form of ion temperature gradient (ITG: $k_\perp\rho_s \sim 0.1$) driven modes is likely responsible for anomalous ion transport. Anomalous electron thermal transport is often attributed to shorter scale, trapped electron (TEM: $k_\perp\rho_s \sim 1$) or electron temperature gradient (ETG: $k_\perp\rho_s \sim 10$) driven turbulence, which are little affected by E×B shear suppression. These shorter wavelength modes challenge the measurement capabilities of turbulence diagnostics and can only be observed via collective Thomson scattering. It is essential to monitor a broad turbulence wavenumber spectrum to make a clear connection with theoretical predictions and thereby improve understanding of the role that turbulence plays in anomalous transport. To specifically address this issue, turbulence measurement capabilities on DIII-D have recently been upgraded and, for the first time, data has been obtained over a broad spectral range ($0 < k_\perp\rho_s < 10$, $0\ cm^{-1} < k < 40\ cm^{-1}$). This paper outlines the measurement approach and describes preliminary results from lower single-null Ohmic plasmas where ITG, TEM and ETG modes are all predicted to be unstable. These preliminary experimental results exhibit frequency spectra that are generally consistent with linear gyrokinetic calculations. Detailed comparison with nonlinear gyrokinetic analysis is underway.

2. Measurement Approach. Turbulence measurement techniques that depend on correlation analysis to recover wavenumber spectra are limited by the spatial localization of the measurement. In collective Thomson scattering, on the other hand, energy and momentum conservation determine measurement properties. The scattering angle provides direct information on the turbulent wavenumber probed; the observed frequency shift of the scattered radiation gives the turbulent frequency in the laboratory frame of reference; and the scattered power is related to the fluctuation amplitude. On DIII-D, an upgraded far-infrared (FIR: $\lambda \sim 1$ mm) scattering system is utilized to probe low (~1 cm^{-1}) and intermediate (10–20 cm^{-1}) turbulent wavenumbers usually associated with ion temperature gradient and trapped electron modes respectively. This upgraded capability is integrated with a novel microwave (~100 GHz) back-scattering approach that probes very high wave numbers (~40 cm^{-1}) where electron temperature gradient (ETG) modes are created. This permits a broad spectral range of turbulence to be probed *simultaneously*, allowing detailed interdependencies to be uncovered and related to gyrokinetic code predictions. A schematic of the system installed on DIII-D is illustrated in Fig. 1.

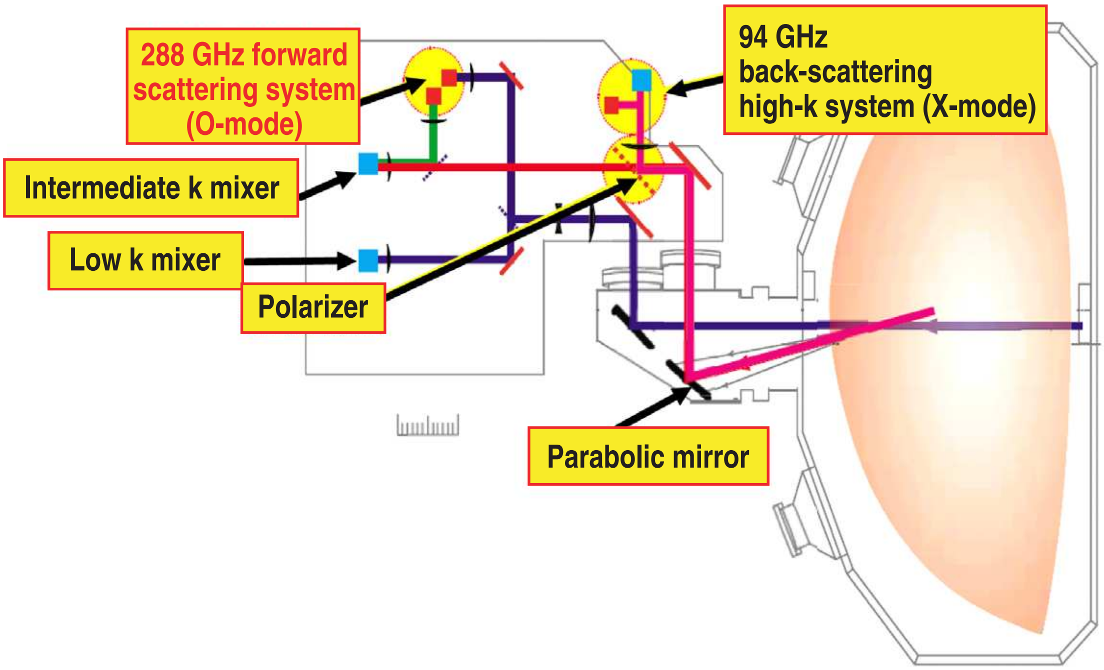

Fig. 1. Schematic illustrating scattering geometry together with integration of microwave backscattering and far-infrared forward scattering systems on DIII-D.

The FIR system consists of all-solid-state sources operating at 288 GHz. A 100 mW, 96 GHz Gunn oscillator is tripled to 288 GHz with output powers of ~5 mW. Fundamental waveguide Schottky diode mixers are utilized in quasi-optical receivers. Forward scattering at small angles (±1°) probes long wavelength turbulence (k ~ 1 cm^{-1}) while also allowing for interferometric phase measurement. A parabolic mirror is utilized to collect radiation scattered at larger angles allowing detection of wavenumbers from 10–20 cm^{-1}. One of the measurement challenges is the unambiguous observation of low level, high k turbulence in the presence of large amplitude, low k turbulence. A *back-scattering geometry* has been selected for this task since this provides strong

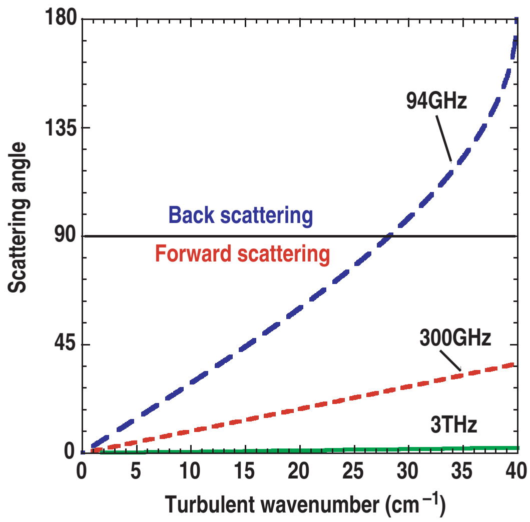

Fig. 2. Scattering angle plotted vs turbulent wavenumber for various incident electromagnetic frequencies.

discrimination against observation of large amplitude low k turbulence. In Fig. 2 scattering angle is plotted versus probed turbulent wavenumber for a variety of incident frequencies. As can be seen, at infrared incident wavelengths (~3 GHz) scattering angles are less than 1 degree, whereas in the FIR range (~300 GHz) scattering angles remain in the forward direction reaching ~36 degrees at 40 cm^{-1}. In contrast, for an incident frequency of 94 GHz, scattering angles switch from forward to backward (i.e. >90°) at wavenumbers exceeding ~28 cm^{-1} with pure-backscattering (180°) being necessary to probe 40 cm^{-1}. This provides excellent angular discrimination against observation of large amplitude, low k turbulence. The use of X-mode launch polarization also allows the $2f_{ce}$ resonance to be used as an effective "beam-dump", internal to the plasma, further improving discrimination. Incident and forward scattered radiation are strongly absorbed at the $2f_{ce}$ resonance, whereas backscattered radiation from high-k turbulence is easily collected. The backscattering system utilizes a high power (200 mW) 94 GHz source combined with standard receiver and coupling components. As in the FIR system, quasi-optical optics are employed with the incident beam focused to a beam waist (w_0) of ~2 cm.

3. Initial Results. Preliminary data from backscattering (k = 40 cm^{-1}) in LSN Ohmic plasmas indicate a broad scattered frequency spectrum (Δf > 500 kHz). In contrast, low k (~1 cm^{-1}) and intermediate k (~15 cm^{-1}) data from FIR scattering indicate spectral widths of ~25 kHz and ~250 kHz respectively. No cross correlation is observed between the different scattered signals. Calculations using the GKS linear stability code indicate that these discharges are unstable to a wide range of instabilities: ETG, ITG and TEM. The lines in Fig. 3 show the predicted real frequencies of the unstable modes over the radial range r/a = 0.1–0.9 for the different k values. Note that negative real frequencies indicate propagation in the ion diamagnetic direction, consistent with ITG while positive frequencies are consistent with electron type modes, e.g. TEM and/or ETG. Figure 3 indicates that the predicted frequencies at 40 cm^{-1} are larger than those at 15 cm^{-1}, which are in turn larger than the 1 cm^{-1} predictions. The measured spectral halfwidths are indicated by the markers in Fig 3. This ordering is reasonably consistent with experimental observations. The predicted frequencies at 15 cm^{-1} are somewhat smaller than those observed experimentally but it should be noted that the linear GKS calculations of the mode frequencies are only an indication of the fully developed turbulent spectra. In addition, the GKS code calculates poloidal wavenumber characteristics and the high-k data (40 cm^{-1}) represents principally radial k. If the fluctuations are isotropic in k_r-$k_\perp$ then the simulation and experiment are directly comparable. However, if there is a significant anisotropy, for example due to streamer activity, then nonlinear simulations are needed to estimate the expected frequency range of the back-scattered signal. Nonlinear simulations (GS2) are underway which will address this issue, as well as providing a more accurate experiment-simulation comparison. These simulations will extract the data using simulated experimental diagnostics (e.g. spatial and k resolutions) in order to match the real world experiment as closely as possible.

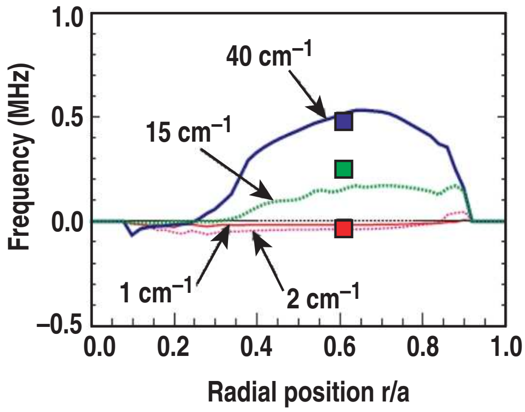

Fig. 3. Linear GKS calculations of the real frequencies of turbulent modes at 1,2,15 and 40 cm^{-1} using profiles from the discharge described in the text. Markers indicate spectral halfwidths for the measured turbulent spectra at their respective k. Note that the low k data is line-averaged, the intermediate k has $1/e^2$ spatial extent of ~30 cm and the high k data comes from the region radially outward from the $2f_{ce}$ resonance layer at r/a =0.5.

4. Summary. Upgraded turbulence measurements on DIII-D cover a broad portion of the turbulent wavenumber spectrum where ITG, TEM and ETG modes potentially exist. Preliminary data in Ohmic plasmas are found to be consistent with linear gyrokinetic code calculations. Nonlinear gyrokinetic calculations are underway to allow more accurate comparison with emerging experimental data. In the near future it is planned to perform high k backscattering measurements using a steerable antenna where both radial and poloidal wavenumbers can be investigated. This will allow any evidence for spectral anisotropies to be uncovered and compared with theoretical predictions.

This work was supported by the U.S. Department of Energy under DE-FG03-01ER54615, DE-AC02-76CH03073, SC6832401, DE-AC05-76OR00033, DE-FG02-93ER54197, and DE-FC02-04ER54698.