Multichannel Scattering Studies of the Spectra and Spatial Distribution of Tokamak Microturbulence

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Detailed studies of low-frequency microturbulence are presented. We utilize a unique multichannel far-infrared ($\lambda = 1.22$ mm) laser scattering system capable of measuring the entire $S(k_\perp, \omega)$ spectrum during a single tokamak discharge. A statistical dispersion is unfolded for k_θ which exhibits a phase velocity $\simeq 3v_{De}$ at low k_θ with a distinct rolloff for $k_\theta \gtrsim 9$ cm^{-1}. In addition, a strong spatial asymmetry is observed in the k_θ density-fluctuation distribution which reverses with toroidal current direction.

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A nonperturbing technique for investigation of plasma microturbulence, such as the low-frequency density fluctuations potentially responsible for anomalous transport[1,2] in tokamaks, utilizes collective scattering of electromagnetic radiation.[3-6] The turbulent nature of the phenomenon to be explored along with discharge irreproducibility dictate the need to determine the complete time-resolved frequency and wave-number spectra during a single tokamak discharge. In this paper, the successful use of a unique multichannel scattering apparatus to perform detailed single-shot studies of tokamak microturbulence is reported. New results concerning the spectrum and spatial distribution of density fluctuations are presented. In particular, a statistical dispersion is unfolded for poloidal fluctuations together with a strong up-down spatial asymmetry in the fluctuation level which is observed to invert with reversal of the toroidal current direction.

The measurements were performed on the Texas Experimental Tokamak (TEXT), a device of $R = 1$ m major radius and $a = 0.27$ m minor radius. The discharge to be discussed has $I_p = 300$ kA, $\bar{n}_e = 3.5 \times 10^{13}$ cm^{-3}, $B_T = 2.8$ T, $T_{e0} = 950$ eV, $T_{i0} = 600$ eV, $Z_{\text{eff}} \simeq 1.8$, and $\tau_E \simeq 12$ ms. Data are taken during the plateau region (I_p, B_T, n_e) of sawtoothing discharges. The plasma current and toroidal field directions are parallel unless otherwise noted.

The multichannel far-infrared (FIR) laser scattering system employed for these measurements is described in detail by Park *et al.*[7] The apparatus simultaneously collects the frequency-shifted scattered radiation at six discrete angles ($0 \leqslant k_\perp \leqslant 15$ cm^{-1}) thereby enabling the entire $S(k_\perp, \omega)$ spectra[3] to be monitored throughout the duration of a single tokamak discharge. By translation of the system both horizontally and vertically the scattering volume may be centered at virtually any position within the plasma cross section. Single-channel heterodyne measurements have been performed (in addition to multichannel homodyne detection) in order to establish conclusively the wave-propagation direction. The output of the probe laser ($P_0 \simeq 8$ mW, $\lambda_0 = 1.22$ mm) is weakly focused along a vertical chord to a beam waist of $\simeq 2$ cm resulting in a measured wave-number resolution of $\Delta k_\perp = \pm 1$ cm^{-1}. The length of the scattering volume along the incident-beam direction is dependent upon the scattering angle and varies from a chord average at $k_\perp = 0$ to ± 8 cm (e^{-1} points of the scattered power) at $k_\perp = 12$ cm^{-1}.

Frequency spectra for a single discharge are illustrated in Fig. 1(a). The center of the scattering volume is

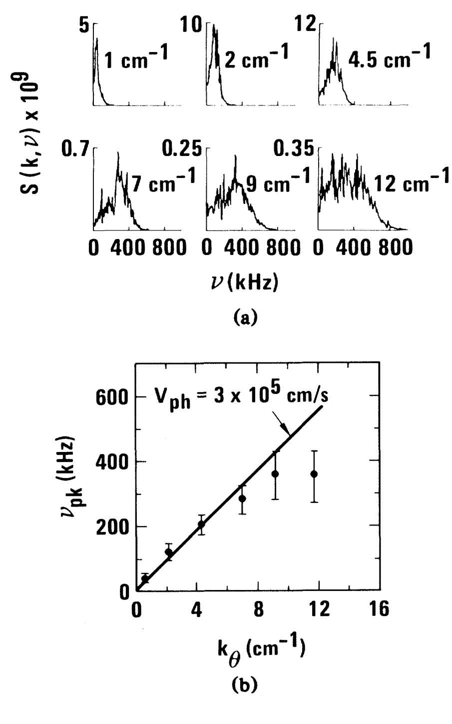

FIG. 1. (a) Multichannel frequency spectra measured during a single tokamak discharge. Fluctuations with poloidal wave number are probed. $\bar{n}_e \simeq 3.5 \times 10^{13}$ cm^{-3}, $B_T = 2.8$ T, $T_{e0} = 950$ eV, $T_{i0} = 600$ eV, $I_p = 300$ kA. (b) Single-shot statistical dispersion for k_θ density fluctuations. Note the distinct rollover at high k_θ.

situated at the plasma center and extends along a vertical chord whose length depends on $k_\perp$. The spectra are dominated by fluctuations with poloidal wave number. Four features are readily distinguished from the frequency spectra: (1) a distinct peak existing for a particular wave number; (2) a shift in the peak to higher frequencies as k_θ increases; (3) a broadening of the spectral linewidth with increasing k_θ; and (4) a significant decrease in the magnitude of the frequency power spectra for $k_\theta \geq 7$ cm^{-1}, as evidenced by the calibrated ordinate. Heterodyne measurements indicate that the fluctuations propagate almost completely in the electron diamagnetic drift direction. The fluctuation spectra were essentially constant throughout the plateau region of the discharge, consistent with unchanging density and temperature profiles.

By plotting of the peak frequency ($\nu_{pk} = \omega_{pk}/2\pi$) as a function of wave number (k_θ) a statistical dispersion relation[8] may be produced as shown in Fig. 1(b). The measured dispersion can be approximated by a linear dependence of frequency on wave number for $k_\theta < 9$ cm^{-1} with a corresponding phase velocity $v_{ph} \simeq 3\times10^5$ cm/s. However, extrapolation of this linear dispersion to $k_\theta \simeq 12$ cm^{-1} would indicate $\nu_{pk} \simeq 500$ kHz which is clearly in contradiction with experiment, where a rolloff at high k_θ is noted.

This dispersion is observed consistently over a wide range of plasma parameters. Raising (lowering) the plasma temperature by varying I_p or n_e acts to increase (decrease) the measured phase velocity. Qualitative agreement with linear drift waves is obtained as the electron diamagnetic drift frequency, ω_e^*, is given by

$$\omega_e^* = k_\theta v_{De}(1 + k_\theta^2 \rho_s^2)^{-1},$$

where $v_{De}(= k_B T_e/eB_T n(dn/dr))$ is the electron diamagnetic drift velocity and ρ_s is the ion Larmor radius at T_e. A rolloff in the dispersion is predicted as a result of finite ion inertia effects and agrees well with observations. A discrepancy arises because $v_{De} \simeq \frac{1}{3} v_{ph}$. At no point across the plasma cross section, not even at the edge (where the measured density scale lengths are small), can v_{De} for linear drift waves approach the experimentally determined value. The spectral broadening indicated in Fig. 1(a) is found to scale linearly with poloidal wave number and $\Delta\nu/\nu_{pk} \simeq 1$. Such observations are characteristic of a strongly turbulent system and are consistent with the theoretical work of Diamond *et al.*[9] The observations made from Fig. 1 differ from earlier measurements[7,10,11] in that a clear dispersion is observed whose phase velocity is a factor of 3 larger than that expected for drift waves.

Plasma rotation induced by a radial electric field provides a possible explanation for the observed discrepancy with a simple drift-wave picture. However, a number of observations suggest this is not the case. For example, the rolloff in the measured dispersion at high $k_\perp$ is inconsistent with bulk plasma rotation arguments where a $\mathbf{k}_\perp \cdot \mathbf{v}_{rot}$ relation would be expected. Also, scattering measurements during periods of magnetohydrodynamic activity indicate the existence of a large amplitude, low frequency, coherent ($\Delta\nu/\nu_{pk} \simeq 0.2$) spectral component in addition to the normal microturbulence spectrum. This coherent mode is observed at different frequencies (20–40 kHz) for various wave numbers during the same shot. Heterodyne detection often indicates the presence of a standing-wave mode. The absence of any Doppler shift suggests the effect of plasma rotation to be negligible. Nevertheless, spectroscopic measurements are required to answer this question definitively.

The spatial distribution of the poloidal-wave-number fluctuations is investigated by a scanning of the scattering volume along a vertical chord through the plasma center. The center of the scattering volume is translated beyond the plasma edge so that the spatial resolution of the system is confirmed *in situ* by observing the decay in the scattered signal. Only small variations in the shape of the frequency spectrum are observed,which indicates that v_{ph} is relatively unchanged across the plasma [i.e., at plasma top and bottom the measured dispersion is within the error bars of Fig. 1(b)]. This is consistent with drift-wave type fluctuations since ω_e^* is roughly constant over most of the plasma cross section.[12] The unvarying spectral linewidth also implies that $\Delta\nu$ is not a result of the extended length of the scattering volume but is indeed a real feature of the microturbulence—an observation in agreement with Mazzucato.[12] Figure 2 illustrates the spatial distribution of the frequency-integrated scattered power for $k_\theta \simeq 9$ cm^{-1} (scattering volume length $\simeq \pm 11$ cm). Curve *a* indicates data for I_p, B_T parallel. As expected, the scattered power peaks towards the plasma edge but surprisingly is roughly an order of magnitude larger at the top than

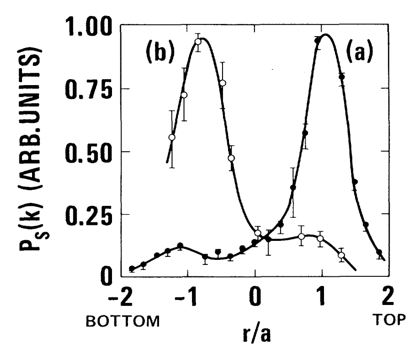

FIG. 2. The spatial distribution of the scattered power ($k_\theta = 9$ cm^{-1}) along a vertical chord through plasma center. Curve *a* I_p, B_T parallel; curve *b* I_p, B_T antiparallel. Note the large asymmetry which inverts with current reversal.

bottom. Similar observations were made at $k_\theta = 7$ and 12 cm^{-1} where the spatial resolution was adequate to differentiate between the various regions of the plasma. Reversal of the plasma current direction (I_p, B_T antiparallel) has the dramatic effect of also reversing the up-down spatial asymmetry as illustrated in curve *b* of Fig. 2. The plasma was well centered during these data runs as monitored by diagnostic loops and a video camera viewing H_α emission. Deliberately moving the plasma to extreme top-bottom or in-out positions with respect to the limiter had only small effects on the observed asymmetry. Associated asymmetries have not been measured in the basic tokamak parameters such as T_e, n_e, or the plasma radiation. The source of the asymmetry remains under active study but is clearly not instrumental in origin. The strong current dependence of the observed asymmetry may possibly be connected to recent theoretical work[13] on saturated rippling-mode turbulence where the density fluctuation level is found to be proportional to the plasma current. A nonuniform current profile would then produce an asymmetric fluctuation distribution.

In contrast to the k_θ spectra, the k_r spectra (measured along a vertical chord through the outside plasma edge) displayed few dispersive characteristics. The frequency spectra peaked close to zero frequency for all wave numbers. Figure 3 illustrates the k_θ, k_r frequency spectra for a wave number of $\simeq 9$ cm^{-1}. The k_θ spectrum in this case is localized near the top plasma edge. These log-log plots display another striking difference between fluctuations with radial and poloidal components; their spectral decays ($\propto \omega^{-\alpha}$) are seen to possess very different exponents for similar wave numbers. The exponent for radial fluctuations is roughly constant ($\alpha \simeq 5 \pm 1$) over the range of wave number studied. In contrast, the exponent for poloidal fluctuations is found to be strongly dependent on wave number. A rapid increase in the exponent is observed from $\alpha \simeq 4$ at $k_\theta \simeq 2$ cm^{-1} up to a maximum of $\alpha \simeq 9$ at $k_\theta \simeq 7$ cm^{-1} after which there follows a gradual decrease.

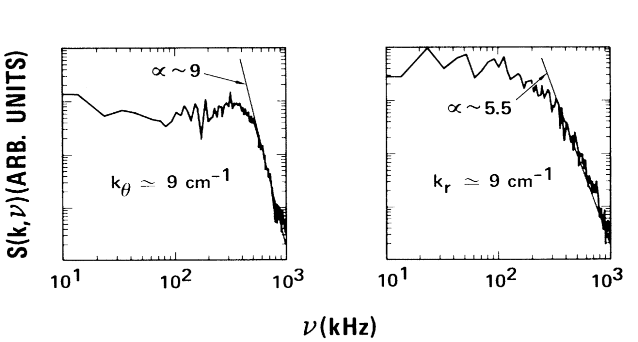

FIG. 3. The frequency spectra for poloidal and radial wave-number components are compared for $k_\perp = 9$ cm^{-1}. The log-log plots serve to clearly illustrate the differences in their spectral decay ($\alpha \simeq 9$ for k_θ; $\alpha \simeq 5.5$ for k_r).

It is clear from the above that the frequency spectra of poloidal and radial fluctuation components possess very different characteristics. The wave-number spectra are also found to differ but not in so radical a manner. The power-law falloff in $S(k_\perp)$ is similar for both radial and poloidal components varying from k^{-3} to k^{-6} on a shot-to-shot basis. However, the poloidal fluctuations are consistently found to possess a peak in their $S(k_\theta)$ distribution at 2 $cm^{-1} \leqslant k_\theta = 4.5$ cm^{-1} whereas radial fluctuations always tend to be monotonically decreasing with increasing wave number. The peak in the $S(k_\theta)$ distribution occurs at $k_\theta \rho_s \simeq 0.25$. Calculation of the density-fluctuation level resulting from radial components at the plasma edge indicates $\tilde{n}/n_e \simeq 15\%$. This is determined by the assumption of a one-dimensional distribution of fluctuations and represents a lower bound although still serving to indicate that nonlinear coupling should be important for this case of strong turbulence.

Observations of an $S(k_\perp)$ maximum at $k_\perp \rho_s < 1$ and large fluctuation levels at the plasma edge are consistent with previous experiments.[10,11,14] Prior comparison of the poloidal and radial components by Surko and Slusher[11,14] determined $S(k_r)$ (measured at the plasma edge) and $S(k_\theta)$ (measured along a vertical chord through plasma center) to be nearly identical indicating that the turbulence is isotropic in the plane perpendicular to B_T. The present experimental results on TEXT contradict this type of isotropy argument because of spatial asymmetries. In addition, the frequency and wave-number spectra for k_r and k_θ are dissimilar. Spectral isotropy can only be ascertained if the k_r, k_θ spectra are determined at the same spatial location, a measurement no scattering system is presently capable of performing.

In summary, a multichannel far-infrared laser scattering system has generated a number of interesting new observations regarding the spectra and spatial distribution of low-frequency microturbulence in a tokamak plasma. The observations of a statistical dispersion relation and spatial asymmetry for poloidal fluctuations combined with a detailed comparison between poloidal and radial components serve to distinguish the present results from previous scattering measurements. In particular, the up-down asymmetry dependence on toroidal current direction is a unique observation with strong implications for transport in tokamak confinement devices.

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