Observation of Large-Amplitude, Narrow-Band Density Fluctuations in the Interior Region of an Ohmic Tokamak Plasma

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(Received 29 April 1985)

Strong spatial asymmetries in the spectrum and magnitude of low-frequency ($\omega << \omega_{ci}$) density fluctuations have recently been measured in the Texas experimental tokamak. Large-amplitude, narrow-band (as low as $\Delta\omega/\omega \simeq 0.1$) modes have been observed on the inside of the high-field torus in addition to the typical broad-band ($\Delta\omega/\omega \simeq 1$) microturbulence which is present throughout the plasma cross section. These narrow-band fluctuations are only detected at the plasma interior, being localized towards the midplane, and are not seen at the edge.

PACS numbers: 52.35.Mw, 52.35.Kt

The characterization of plasma-inhomogeneity–driven microturbulence is thought to be necessary to the understanding of transport in present day toroidal confinement devices.[1] As a result, it is essential to determine the spatial distribution and spectral properties of fluctuations throughout the plasma cross section. Recent collective-Thomson-scattering measurements[2–4] have noted substantial deviations from the standard observations of broad-band ($\Delta\omega/\omega \simeq 1$) isotropic turbulence[5] in the plane perpendicular to the toroidal magnetic field. For example, although density fluctuations are commonly found to peak at the plasma periphery, a new tokamak edge phenomenon known as the MARFE has been observed in Alcator C (Lipschultz *et al.*[2]). This condition, which exhibits a density threshold for onset, is distinguished from ordinary turbulence by greatly increased radiation, density, and density fluctuations, and decreased temperature in a small volume at the inner major-radius edge of the plasma. In addition, a quasicoherent fluctuation ($\Delta\omega/\omega \simeq 0.1$; Slusher *et al.*[3]) was recently observed during the *H*-mode regime of discharges in the neutral-beam–heated poloidal divertor tokamak PDX discharges. The narrow-band fluctuation was noted as a temporal burst over a narrow region of minor radius near the separatrix. Finally, previous measurements on the Texas experimental tokamak TEXT (Brower *et al.*[4]) thoroughly described the (k_r, k_θ) spectra of the broad-band microturbulence and identified a strong up-down asymmetry in the distribution of poloidal fluctuations. Such a spatial asymmetry was only observed in the magnitude of the density-fluctuation level. It should be noted that all the above-mentioned phenomena are associated with the poor-confinement edge region of tokamaks.

In this Letter, a new type of density fluctuation localized in the plasma interior is reported. Along with the usual broad-band microturbulence,[4,5] large magnitude, narrow-band (as low as $\Delta\omega/\omega \simeq 0.1$) fluctuations are observed throughout the plateau region of the discharge which are located toward the inside of the high-field torus. Vertical spatial scans of the scattering volume indicate that these fluctuations are localized towards the equatorial midplane of the torus and are not observed at the plasma top or bottom edge. Hence, the existence of the narrow-band fluctuations manifests itself as a spatial asymmetry between the inside and the outside of the torus in both the spectrum and the amplitude of the density fluctuations. The internal localization of the narrow-band fluctuations provides information on turbulence and transport in the central region of the tokamak plasma where global confinement is determined.

Collective Thomson scattering[6] of electromagnetic radiation provides a nonperturbing technique for measuring density fluctuations. On TEXT, a multichannel far-infrared scattering apparatus permits the complete $S(k_\perp,\omega) \propto [\tilde{n}(k_\perp,\omega)]^2$ spectrum to be monitored throughout the duration of a single tokamak discharge. Frequency-shifted scattered radiation is simultaneously collected at six discrete wave numbers ($0 < k_\perp < 15\ \mathrm{cm}^{-1}$). Detailed information on the scattering system and the calibration procedures employed is described by Park *et al.*[7] The portion of the far-infrared laser ($P_0 \simeq 8$ mW, $\lambda_0 = 2\pi/k_0 = 1222\ \mu$m) utilized as the probe beam is weakly focused along a vertical chord to a waist of $\simeq 2$ cm producing a measured wave-number resolution of $\Delta k_\perp = \pm\ \mathrm{cm}^{-1}$. The length of the scattering volume varies as a function of wave number and ranges from ± 8 cm (e^{-1} points of the scattered power) at $k_\perp = 12\ \mathrm{cm}^{-1}$ to a chord average as $k_\perp \to 0$. Horizontal and vertical translation capabilities of the scattering volume afford access to virtually the entire plasma cross section. In this paper, fluctuations from scattering-volume locations centered along the midplane of the torus at $|\pm r/a| \leq 0.6$ will be contrasted in addition to positions 20 cm above and below the midplane along a vertical chord at $R - 0.2a$, as shown in Fig. 1(a). For these locations $k_\perp$ is composed of both radial (k_r) and poloidal (k_θ) components.

The measurements were performed on TEXT, a medium scale Ohmic tokamak of major radius $R = 1$ m and limiter radius $a = 0.27$ m. The tokamak parame-

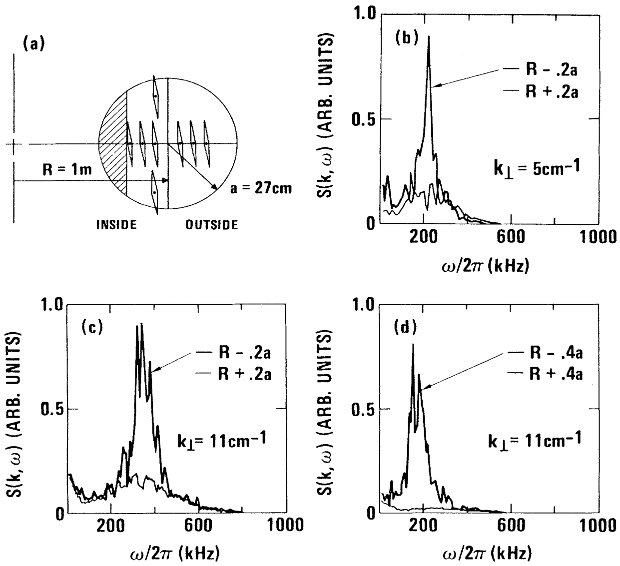

FIG. 1. Frequency-spectra comparison. (a) Scattering-volume geometry for midplane positions $R \pm 0.2a$, $R \pm 0.4a$, $R \pm 0.6a$, and vertical locations ± 20 cm above and below the midplane at $R-0.2a$ for $k_\perp = 11\ \mathrm{cm}^{-1}$; shaded region, inaccessible. (b) $k_\perp = 5\ \mathrm{cm}^{-1}$, $R \pm 0.2a$; (c) $k_\perp = 11\ \mathrm{cm}^{-1}$, $R \pm 0.2a$; and (d) $k_\perp = 11\ \mathrm{cm}^{-1}$, $R \pm 0.4a$.

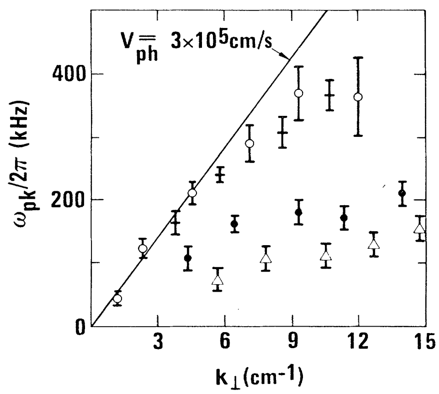

FIG. 2. Density-fluctuation dispersion at R, $R-0.2a$, $R-0.4a$, and $R-0.6a$ corresponding to open circles, crosses, solid circles, and triangles, respectively. Only the narrow-band fluctuation dispersion is plotted for positions on the inside of the torus.

ters for results to be presented herein are $I_p = 300$ kA, $\bar{n}_e = 3.5\times 10^{13}\ \mathrm{cm}^{-3}$, $B_T = 28$ kG, $T_{e0} = 950$ eV, $T_{i0} = 600$ eV, $Z_{\mathrm{eff}} \simeq 1.8$, and $\tau_E \simeq 12$ ms. Data are taken during the plateau region (I_p, B_T, n_e) of sawtooth discharges where $r_{q=1} \simeq 0.25a$.

The density-fluctuation frequency spectra at $k_\perp = 5$ and 11 cm^1, for the scattering volume centered at midplane positions $R+0.2a$ (the outside of the torus), and $R-0.2a$ (the inside of the torus), are illustrated in Figs. 1(b) and (c), respectively. In each case, it is readily apparent that the fluctuations on the inside are much larger in magnitude and more confined in bandwidth than the fluctuations on the outside. For instance, at $k_\perp = 5\ \mathrm{cm}^{-1}$ on the inside, the peak frequency of the scattered spectra[8] is $\omega_{\mathrm{pk}}/2\pi \simeq 200$ kHz with $\Delta\omega/\omega_{\mathrm{pk}} \simeq 0.1$ (FWHM), whereas on the outside, $\omega_{\mathrm{pk}}/2\pi \simeq 200$ kHz but $\Delta\omega/\omega_{\mathrm{pk}} \simeq 1$. In addition, the magnitude of the fluctuations near ω_{pk} are significantly larger on the inside. A similar observation may be arrived at for $k_\perp = 11\ \mathrm{cm}^{-1}$ where $\Delta\omega/\omega_{\mathrm{pk}} \simeq 0.2$ on the inside and $\Delta\omega/\omega_{\mathrm{pk}} \simeq 1$ on the outside with the magnitude of the fluctuations again being much larger on the inside of the torus. Further comparison of the frequency spectra for $R \pm 0.2a$ indicates that although $\Delta\omega$ is much smaller on the inside, the peak frequency ω_{pk} is roughly equivalent implying that the phase velocity (dispersion) for the fluctuations are similar. The magnitude of the fluctuations at the torus-inside and -outside positions are seen to be essentially the same for $\omega << \omega_{\mathrm{pk}}$ and $\omega >> \omega_{\mathrm{pk}}$. These observations establish the existence of a large-magnitude, narrow-band fluctuation on the torus inside which appears in addition to the broad-band microturbulence and is observed throughout the plateau region of the discharge where Mirnov oscillations are quiescent.

Moving the scattering volume further from the plasma center serves to magnify the disparity between fluctuations at the torus inside and outside. For scattering-volume positions located at $R \pm 0.4a$, the frequency spectra for $k_\perp = 11\ \mathrm{cm}^{-1}$ are shown in Fig. 1(d). Once again the fluctuations on the inside exhibit a large-magnitude, narrow-band peak in contrast to the behavior at the outside position for wave numbers up to 14 cm^{-1}. The spectral linewidth $\Delta\omega$ for $k_\perp = 11\ \mathrm{cm}^{-1}$ is unchanged from $R-0.2a$ to $R-0.4a$. However, the peak frequency of the scattered spectra is now significantly lower on the inside ($\omega_{\mathrm{pk}}/2\pi \simeq 200$ kHz) as compared to the outside ($\omega_{\mathrm{pk}}/2\pi \simeq 380$ kHz) making the narrow-band nature of the fluctuation less prominent ($\Delta\omega/\omega_{\mathrm{pk}} \simeq 0.5$).

As shown in Fig. 2, the measured dispersion relationships at scattering-volume positions R[4,9] and $R-0.2a$ are roughly comparable with $v_{\mathrm{ph}} \simeq 3\times 10^5$ cm/s. As the scattering volume is translated further towards the torus inside, an abrupt decrease in the slope of the measured dispersion occurs with $v_{\mathrm{ph}} \simeq 1\times 10^5$ cm/s at $R-0.6a$. At this location, the measured v_{ph} is approximately equivalent to v_{De}, the electron diamagnetic drift velocity. The fluctuations were observed to be propagating in the electron diamagnetic drift direction, if stationary ions are assumed.[4] Langmuir-probe measurements[10] at the plasma edge, taken under reduced current and field conditions, indicate the presence of a radial electric field of sufficient magnitude to produce an $\mathbf{E}_r \times \mathbf{B}$ Doppler shift of order of v_{De}. Projection of this potential to the plasma interior would suggest that the narrow-band fluctuations may possess a rotation-corrected phase velocity $v_{\mathrm{ph}} \leqslant v_{De}$. Some in-out asymmetry in v_{ph} is expected as a result of the $1/R$ dependence of the fields; however, this cannot account for the factor of 3 difference measured between $R \pm 0.6a$ or the narrow-band nature of the spectra.

Variations in the magnitude of the fluctuations between torus-inside and -outside positions are most clearly identified by comparison of the wave-number spectra as shown in Figs. 3(a) and 3(b), for positions $R \pm 0.2a$ and $R \pm 0.6a$, respectively. As the scattering volume is translated towards the torus inside, the wave-number spectra become broader with significant power in the high-$k_\perp$ modes. The wave-number spectra on the outside are generally monotonically decreasing functions of $k_\perp$. For $k_\perp \geqslant 5$ cm^{-1}, the narrow-band mode can possess an $S(k_\perp)$ more than an order of magnitude larger than that for the broad-band microturbulence found on the outside. For all positions, the power falloff of the wave-number spectra is essentially constant with $P \propto k_\perp^{-\beta}$, where $\beta = 4 \pm 1$.

The narrow-band fluctuations on the torus inside are observed in addition to the broad-band microturbulence as seen earlier from the frequency spectra. By subtraction of the wide-band fluctuation level, the wave-number dependence of the narrow-band turbulence may also be estimated. This is achieved by means of a plot of the difference in the spectral density functions, $\Delta S(k_\perp) = S_{\mathrm{in}}(k_\perp) - S_{\mathrm{out}}(k_\perp)$, as shown in Figs. 3(c) and 3(d) for spatial positions $R - 0.2a$ and

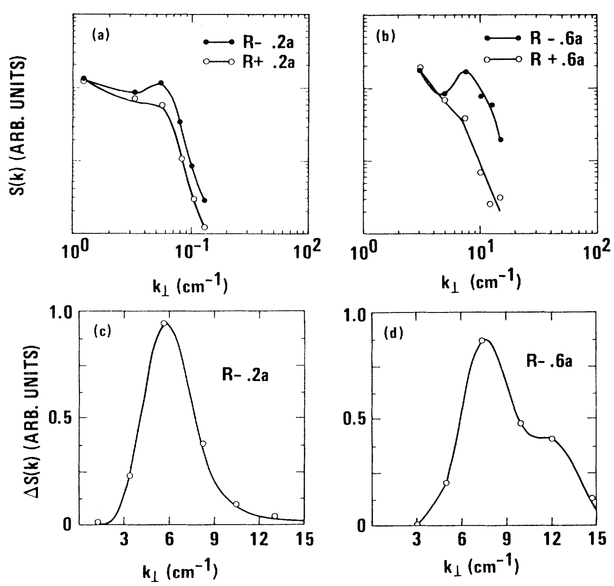

FIG. 3. Wave-number–spectra comparison at spatial positions (a) $R \pm 0.2a$ and (b) $R \pm 0.6a$ with open circles, solid circles denoting outside and inside of the torus, respectively. Wave-number spectra for the narrow-band fluctuation, $\Delta S(k_\perp) = S_{\mathrm{in}}(k_\perp) - S_{\mathrm{out}}(k_\perp)$, at positions (c) $R - 0.2a$, and (d) $R - 0.6a$.

$R - 0.6a$, respectively. Here it is observed that the narrow-band fluctuation exists over a more limited range of $k_\perp$ (i.e., $\Delta k/k_\perp \simeq 0.35$) than the broad-band turbulence (i.e., $\Delta k/k_\perp \simeq 1$) with a spectra width greater than twice the measured wave-number resolution of $\Delta k_\perp = \pm$ cm^{-1} (corrections to the measured spectrum are less than 10% when the stated instrument resolution is deconvolved). The peak in the narrow-band fluctuation wave-number spectra shifts to higher $k_\perp$ as the scattering volume is positioned further towards the torus inside, changing from 5.5 cm^{-1} at $R - 0.2a$ to 7.5 cm^{-1} at $R - 0.6a$ with the width also increasing asymmetrically at larger values of $k_\perp$.

The estimated fractional fluctuation level $\tilde{n}/n_e$, obtained by performance of the appropriate integration over frequency and wave number, is more than twice as large on the inside of the high-field torus with a lower limit of $\simeq 1\%$ at $R - 0.6a$. Similar features for the narrow-band fluctuations are observed in discharges with different plasma currents and toroidal fields. No density threshold or associated perturbations to plasma parameters $(n_e, T_e, P_{\mathrm{rad}})$ have been observed. However, it is conceivable that the narrow-band fluctuations coupled with the previously reported up-down asymmetry for poloidal fluctuations[4] may be some type of precursor to the MARFE[2] condition.

By a scan of the scattering volume vertically from the torus midplane positions, the up-down spatial localization of the narrow-band fluctuations may be ascertained. Along a vertical chord at $R - 0.2a$ for $k_\perp = 11$ cm^{-1}, the narrow-band fluctuation is not observed when the scattering-volume center is situated either 20 cm above or below the midplane as shown in Fig. 1(a). Translation of the scattering volume to either the plasma top or bottom serves to eliminate observation of the narrow-band feature which is distinctly seen at the midplane for the same wave vector in Fig. 1(c). Performing a vertical scan at $R - 0.4a$ produces a similar effect except that one must move the scattering volume further away from the midplane (i.e., towards the edge) before the narrow-band fluctuation is no longer observed. These results clearly indicate that the narrow-band modes are internal fluctuations and are not observed at the plasma edge. A change in the (k_r, k_θ) composition of $k_\perp$ as a consequence of the vertical scan may potentially account for this observation since on the midplane, $k_\perp$ is made up largely of k_r while at the edge, $k_\perp$ is comprised more of k_θ. However, the narrow-band fluctuation is observed over a sufficient region of the plasma along the vertical chord to make this argument unlikely.

The spatially varying toroidal field ($B_T \propto 1/R$) is a potential source for the observed asymmetry between fluctuations on the torus inside and outside. Theories which address these particular regions of the plasma include the toroidicity-induced drift wave[11,12] and

MHD-ballooning models. The observation of a monotonically decreasing $S(k_\perp)$ at the outside is consistent with the theories of the toroidicity-induced and MHD-ballooning modes. However, the magnetohydrodynamic-ballooning instability, which is pressure driven and peaked at $\theta = 0$, does not appear to be a suitable candidate as the large-amplitude, narrow-band fluctuations are observed on the torus inside $(\theta \simeq \pi)$ at large wave vectors during periods of quiescent MHD activity in a low-β tokamak. Calculations of the nonlinear interactions of the toroidicity-induced modes[12] (resulting from ∇B_T and curvature drifts) show that the instability peaks away from $\theta = 0$ at $\theta = \pm \pi/2$. The narrow-band fluctuations also peak away from $\theta = 0$ but appear localized at $\theta \simeq \pi$, the torus inside, where Similon and Diamond[12] state that toroidicity-induced drift modes are not as strongly excited. Present toroidicity-induced drift-mode theories do not definitively address toroidal effects on the fluctuation spectral linewidth. Hence, it appears that neither of the above-mentioned theories satisfactorily describes the experimental observations.

In summary, large-magnitude, narrow-bandwidth fluctuations are observed in the plasma interior on the inside of the high-field torus. These fluctuations are narrow band in both their frequency and wave-number spectra when compared to the typical broad-band microturbulence. Correlation between experimental observations and theory is inconclusive indicating the need for additional effort in order to provide an accurate identification.

The authors wish to thank P. H. Diamond, D. W. Ross, P. W. Terry, and A. A. Ware for useful discussions. The diagnostic and technical support of R. L. Savage, Jr., and the TEXT staff is also appreciated. Machine time and operation were generously provided by the Fusion Research Center, University of Texas, Austin. This work was supported by the U. S. Department of Energy, Office of Fusion Energy under Contract No. DE-AC05-78ET53043 through Subcontract No. UT-1-24120-52019.

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