Long-Wavelength Density Turbulence in the TFTR Tokamak

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Long-wavelength ($k_\perp \rho_i < 1$) density turbulence has been measured with good spatial localization in the core region of a high temperature tokamak plasma with auxiliary heating. Density fluctuations of $\tilde{n}/n > 0.5\%$ exist for $k_\perp < 2$ cm^{-1} with radial and poloidal correlation lengths typically 1–2.5 cm in the confinement region, corresponding to $k_\perp \rho_i \approx 0.1$–0.3. An anisotropic wave-number spectrum is observed, and estimates of the turbulence-driven transport are comparable to the anomalous transport observed in tokamaks.

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Small-amplitude fluctuations in the local plasma density and potential are generally thought to be the cause of the anomalously high cross-field transport of energy and particles observed in tokamak plasma confinement experiments [1,2]. While detailed measurements of such turbulence in the edge region of tokamaks have shown a quantitative correlation between the local transport and the turbulence-driven fluxes, relatively little information on the details of the plasma turbulence and its relation to the transport in the hot core region of tokamak plasmas is available [3].

Of particular interest is the long-wavelength turbulent spectrum (with $0.01 < k_\perp < 1$ cm^{-1}), which has not been systematically explored but is suspected to be of central importance to the turbulence-driven transport for the following reasons. First, microwave scattering experiments have indicated that the bulk of the fluctuation power in density turbulence in tokamak plasmas lies in this long-wavelength region, where the wavelength of the fluctuations perpendicular to the confining field is much larger than the local ion gyroradius (i.e., $k_\perp \rho_i \ll 1$) [4,5]. Second, several theories of drift-wave turbulence and magnetohydrodynamicslike turbulence suggest the importance of long-wavelength modes in determining the local turbulence-driven transport [2]. Finally, recent TFTR and JET experiments suggest that the local transport follows Bohm-like scaling, consistent with a dominant role of long-wavelength or global turbulence in local transport [6,7].

However, the limited spatial resolution of scattering measurements has prevented definitive observation of the expected peak in the turbulent spectrum $S(\mathbf{k},\omega)$ at low k. With the notable exception of heavy ion beam probe measurements in Ohmically heated plasmas in medium-sized tokamak experiments [8,9], low-k turbulence has been experimentally inaccessible in the hot core of large tokamak plasmas. The recent introduction of beam emission spectroscopy (BET) and correlation reflectometry on large tokamak experiments [10–12] was motivated to provide characterization of this crucial regime of the turbulent spectrum.

We report here the first detailed observations of the local density turbulence spectrum at long wavelengths in the hot core region of a large fusion-grade tokamak plasma. These observations have been made using the new BES technique, which measures the collisionally induced fluorescence of an injected neutral beam to deduce the plasma density fluctuation in the localized volume defined by the intersection of the beam and an observation line of sight [13].

The results discussed here were obtained in well-conditioned, neutral-beam-heated, hot-ion-mode plasmas with enhanced confinement (i.e., the supershot regime [14]). For these results, $I_p = 1.2$ MA, $B_t = 4.8$ T, $\langle n_e \rangle = (2.1\text{–}2.6)\times 10^{19}$ m^{-3}, $P_{\text{inj}} = 9$–14 MW, $a/R = (0.80$ m)/(2.45 m), $T_i(0) = 12$–14 keV, and $T_e(0) = 7$ keV. The measurements were averaged over a 0.5 sec period over which discharge parameters were held constant to reduce incoherent photon noise in the data. The discharges were tailored to exhibit no large-scale magnetohydrodynamics activity (i.e., sawteeth, Mirnov activity, etc.) which would interfere with the local broadband turbulence measurements. In general, the injected power from the neutral beams was balanced between the coinjection and counterinjection sources to minimize the influence of toroidal rotation in the observations.

The BES experiment on TFTR provides up to twenty simultaneous observations of local density fluctuations in the plasma's core region, with the observation points separated in a plasma radially or poloidally by a minimum distance of 1.5–2.0 cm. Correlation analysis of these multiple point measurements provides measures of the local correlation length, decorrelation time, and the frequency-integrated power spectra $S(\mathbf{k})$ of the local turbulence. Because of the ~1.5 cm width of the sampled volume, the BES measurements have a wave-number response function which is maximum at $k = 0$ cm^{-1} and decreases monotonically to very low values for $k > 2$ cm^{-1}. This upper limit of ~2 cm^{-1} overlaps the lower limit of the microwave scattering k range where its spa-

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tial resolution is of the order of the minor radius.

Conversion of the observed intensity fluctuations to local density fluctuations is obtained through multistep beam excitation calculations to estimate the population of the $n=3$ state which gives rise to the observed D_α radiation [15]. This derived fluctuation level is further corrected upwards (typically by factors of 2–3) after accounting for the reduced sensitivity at higher wave numbers. A multipair correlation analysis approach is used to subtract all common mode noise arising from edge-turbulence-induced beam density fluctuations, and prevent false measurements of long radial correlations along the direction of the neutral beam [16].

The autopower spectrum, $S(\omega)$, of the observed density fluctuations is concentrated at low frequencies for these low-k fluctuations [17,18], and is shown in Fig. 1 for various values of plasma rotation. This is generally consistent with the scattering measurements at lower wave numbers and with a linear dispersion characteristic for these modes.

As suggested in Fig. 1, the spectrum is found to be strongly dependent on the local plasma rotation speed, indicating that it is dominated by Doppler shifts of the plasma-frame spectrum (i.e., $\Delta_\omega = \mathbf{k}\cdot\mathbf{V}_{\rm rot}$ where $\mathbf{V}_{\rm rot}$ is the local plasma rotation velocity). Indeed the spectrum becomes increasingly narrow and centered at low frequencies as the rotation speed is reduced. The local diamagnetic drift frequency is typically ~ 5 kHz or less, much less than the spread or shift in observed frequencies. The laboratory-frame group velocity in the poloidal direction changes sign as the toroidal rotation of the plasma is reversed, confirming the Doppler interpretation and consistent with the scattering results.

The minimal group velocity and narrowest spectrum is usually found at slightly counter plasma rotation, suggesting a net poloidal propagation in the ion diamagnetic flow direction. However, the possibility of neoclassical

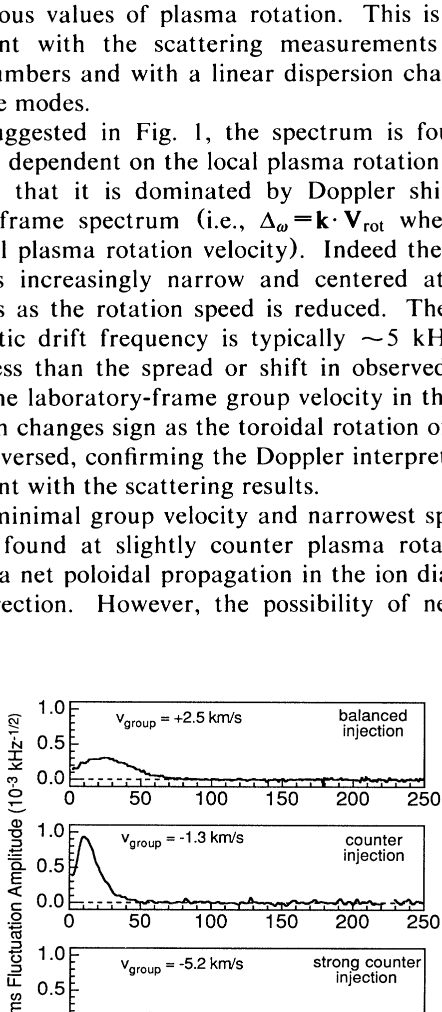

FIG. 1. Autopower spectra of relative density fluctuations in the interior of TFTR supershots for three values of the local plasma rotation. The laboratory-frame poloidal group velocity of the fluctuations is noted. $P_{\rm inj}=9$ MW.

poloidal flows of order v_* (the local diamagnetic flow speed) plus the lack of direct measurements of poloidal rotation in these plasmas preclude an accurate determination of the turbulence propagation velocity in the plasma frame. So far, we can conclude that the fluctuations may be propagating poloidally in the ion diamagnetic flow direction at speeds up to $\sim 3v_*$, or they could in fact be nearly stationary in the plasma frame. They definitely do not propagate in the electron direction with speeds of order v_*. This long-wavelength turbulence thus appears, to zero order, as large semistationary structures in the plasma frame aligned along the tilted field lines. They appear as higher frequency turbulence in the observations only due to the presence of plasma rotation.

The wave-number spectra in the radial and poloidal directions, $S(k_r)$ and $S(k_\theta)$, respectively, are given by a spatial frequency analysis of the measured spatials and cross-correlation function for displacements in the respective directions. However, for a volume-sampling turbulence measurement such as BES, the resulting $S(\mathbf{k})$ and all other derived turbulence characteristics can be quite dependent on the spatial sampling function in both directions. The effective instrumental transfer function in $\mathbf{k}$ space is modeled here from detailed ray tracing of both the BES optical system and the neutral beam power distribution in the plasma. The spatial frequency spectrum of the turbulence is then obtained by constructing a model $S(k)$ with maximum entropy in k space while providing a minimum χ^2 fit to the measured cross-correlation function after including the spatial transfer function. Uncertainties in $S(k)$ from possible aliasing of power from higher wave numbers are minimized by also requiring a monotonically decreasing $S(k)$ spectrum for $k \geq 2$ cm^{-1}, as indicated by the microwave scattering measurements [4]. An overall error range for $S(k)$ is estimated by assigning a 10% uncertainty to the spatial transfer function.

Representative radial and poloidal correlation functions and their resultant spectra are given in Fig. 2. The $S(k_r)$ and $S(k_\theta)$ spectra have similar widths, in agreement with the general observation of similar correlation lengths in the radial and poloidal directions, but are seen to be highly anisotropic with respect to the peak in the $S(k)$ spectrum. The radial spectrum $S(k_r)$ is peaked at $k_r=0$, while the poloidal spectrum $S(k_\theta)$ shows a strong peak typically in the range of $k_\theta \approx 0.5$–1.5 cm^{-1}. The turbulence thus exhibits a wavelike structure in the poloidal direction, while no wavelike structure appears in the radial direction. Systematic uncertainties in the spatial transfer function result in ambiguity in the nature of $S(k)$ at $k > 1.5$ cm^{-1} and uncertainties of roughly ± 0.5 cm^{-1} in the exact location of the peak of the $S(k_\theta)$ spectra, but do not alter the fundamental observations of a peak in $S(k_\theta)$ at nonzero k_θ and of a strong asymmetry in the behavior of $S(k_r)$ and $S(k_\theta)$ at low k.

The peak in the $S(k_\theta)$ spectrum at $k_\theta > 0$ is also supported by the shape of the frequency spectra in Fig. 1.

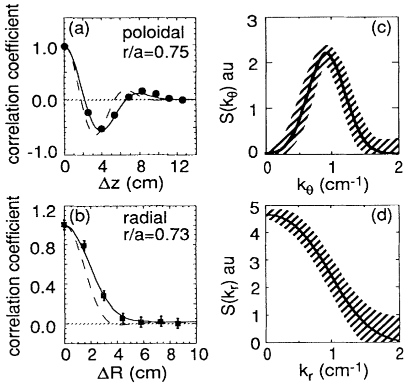

FIG. 2. (a),(b) Spatial correlation function $\rho(\Delta)$ for displacement Δ in the poloidal (a) and radial (b) directions. Solid line and markers, measured $\rho(\Delta)$; dashed line, $\rho(\Delta)$ with spatial response removed. (c),(d) Spatial wave-number spectrum obtained from the measured correlation functions in (a) and (b), respectively. Shaded region, 10% confidence level in the spatial transfer function. $P_{inj}=14$ MW.

The shapes of $S(\omega)$ spectra are found to be almost identical to the independently determined $S(k_\theta)$ spectrum, as expected for frequency spectra which are dominated by rotation-induced Doppler shifts. Since there is no net plasma flow in the radial direction, the $S(\omega)$ spectrum reflects only the poloidal k spectrum.

This asymmetry between the $S(k_r)$ and $S(k_\theta)$ spectra does not agree with the typical lowest-order picture of fully developed isotropic turbulence, which is often invoked in discussions of plasma turbulence in tokamaks and sometimes found in earlier experiments [19]. These spectra appear more akin to those found in quasilinear drift turbulence pictures, small-island magnetic turbulence models, and some nonlinear gyrokinetic turbulence models [20].

The total rms density fluctuation amplitude, $\tilde{n}/n$, is found to decrease rapidly as one moves inward through the outermost 5 cm of the plasma cross section, then decreases only gradually as r/a decreases into the plasma center region. The values of $\tilde{n}/n$ plotted in Fig. 3 are derived from the intensity fluctuations in the observed signal, including corrections (of factor ~ 2) for the k sensitivity of the BES channels derived from $S(k)$ measurements at several radii. Uncertainties in the beam excitation model and the k-sensitivity corrections result in uncertainties of roughly $\pm 50\%$ of the plotted values of $\tilde{n}/n$ in the core region. The large fluctuation level in the edge plasma region (typically $\tilde{n}/n \approx 0.3$), followed by a drop as one traverses into the hot core region, is similar to results from smaller Ohmically heated tokamaks, but the drop is usually more abrupt than seen in the smaller devices.

The radial and poloidal correlation lengths, L_c, are defined here as the $1/e$ decay distance of the local correlation function after correction for the effects of the spatial sampling function. For these discharges, the values of L_c range from 1 to 2.4 cm in the range $0.45 < r/a < 0.95$, with uncertainties of roughly ± 0.5 cm. The large uncertainty reflects the fact that the values of L_c are comparable to the spatial resolution of the measurements.

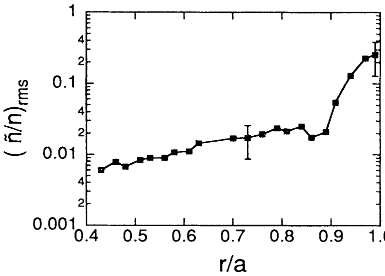

FIG. 3. Total rms density fluctuations amplitude as a function of position in the plasma for a 9 MW supershot.

Several observations suggest that this long-wavelength turbulence has a direct correlation, and *possibly* a causal relationship, to the anomalous plasma transport. In our preliminary studies, the total fluctuation amplitude, $\tilde{n}/n$, in the plasma core region at $r/a=0.7$ scaled inversely with the global energy confinement time, τ_E, in a power scan under L-mode confinement conditions [17,18].

In the present supershot plasmas, we compare the effective local thermal diffusivities derived from a power-balance kinetic analysis of the plasma transport to estimates of the local diffusivity derived from our measurements of the local turbulence characteristics. In addition to the individual ion and electron thermal diffusivities, χ_i and χ_e, we include for completeness χ_{fluid}, the thermal diffusivity obtained for the plasma treated as a single conducting fluid. Figure 4 shows a radial plot of these local

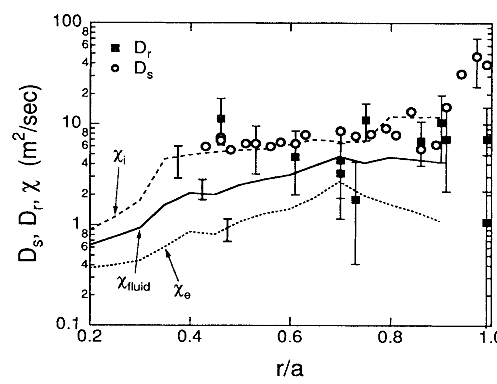

FIG. 4. Comparison of the effective thermal diffusivities from power balance transport analysis and estimates of the local turbulence-driven diffusivities D_s and D_r from the BES measurements. χ_i is the ion thermal diffusivity (dashed), χ_e is the electron thermal diffusivity (dots), and χ_{fluid} is the single fluid thermal diffusivity (solid). $P_{inj}=9-11$ MW.

power-balance thermal diffusivities, a strong-turbulence diffusivity D_s, and a random-walk estimate of the turbulent diffusivity D_r. Here, the strong turbulence estimate of the local diffusivity is given by [21] $D_s = (\tilde{n}/n) \times kT_e/eB$. The random-walk estimate is given by $D_r = L_c^2/\tau_c$ where τ_c is the local turbulence $1/e$ correlation decay time obtained from a time-delayed correlation analysis of the BES measurements in the poloidal direction. These values of τ_c are measured to be 30 and 45 μsec at $r/a = 0.45$ and 0.75, respectively, and values at other radii in the core are obtained by linear interpolation. Estimates of the uncertainties in the diffusivities are indicated by the error bars at $r/a \approx 0.4$. These represent the range of the respective χ values obtained when the input plasma parameters were varied within their error bars.

The agreement among the values of the power-balance χ's and the turbulence-related D's in the core is quite remarkable, and suggests a direct relation between the local transport and these long-wavelength modes. In the core confinement region, both D_s and D_r have approximately the same magnitude as the local thermal transport coefficients. Of course, this comparison is only qualitative since we have no information on local temperature fluctuations, the turbulent velocity, or the phase between the perturbed quantities which contribute to the turbulence-driven heat flux. We have also implicity assumed that the time for particles or heat to traverse a turbulent structure of length L_c is comparable to the measured lifetime of the structure τ_c.

The differences between D_s and D_r in the edge region ($r/a > 0.9$) are outside the uncertainties and reflect a more complex turbulence picture there. An additional edge-localized mode is observed in this region, and the presence of two distinct modes can give rise to phase mixing and interference, complicating the determination of the appropriate L_c and τ_c for comparison to the D_s values. Also, uncertainties in the edge plasma parameters preclude the determination of reliable thermal diffusivities in this edge region. More detailed studies of this complex edge region will be presented in a separate report.

While considerably more investigations are required to confirm the connection between this turbulence and the local transport, as well as to identify the underlying mechanisms or modes driving this turbulence, the present results indicate that the observed long-wavelength turbulence is a strong candidate for the driving agent of the anomalous transport in hot tokamak plasmas.

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