Evidence for Poloidal Asymmetry of Core Electron Temperature Fluctuations in the Texas Experimental Tokamak

Christopher Watts and R. F. Gandy
Department of Physics, Auburn University, Auburn, Alabama 36849

G. Cima
Fusion Research Center, University of Texas at Austin, Austin, Texas 78712
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Electron temperature fluctuations are measured in the core of a tokamak plasma across the poloidal cross section. There is a strong poloidal asymmetry; the fluctuation amplitude peaks off the equatorial plane in four "lobes" symmetric about the equatorial plane on both the high- and low-field sides. At the plasma top the fluctuation amplitude decreases by over 2 orders of magnitude from its peak value. On the high-field-side equatorial plane the fluctuations also show a sharp reduction in amplitude.

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Turbulent electrostatic fluctuations are considered by many as one likely mechanism to explain the anomalously poor electron confinement of toroidal magnetic confinement schemes [1–5]. The confinement is termed "anomalous" because random-walk theories of confinement based on Coulomb interactions that include toroidal effects (neoclassical theories) underestimate electron transport by over an order of magnitude. The electrostatic-fluctuation-induced transport consists of two components, a particle flux Γ_e and a heat flux Q_e, given by

$$\Gamma_e = \langle \tilde{n}_e \tilde{v}_e \rangle = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B \,, \tag{1}$$

$$Q_e = \tfrac{3}{2} \langle \tilde{p}_e \tilde{v}_e \rangle = \tfrac{3}{2} n_e \langle \tilde{T}_e \tilde{E}_\theta \rangle / B + \tfrac{3}{2} T_e \Gamma_e \,. \tag{2}$$

Here, $\tilde{n}_e$, $\tilde{T}_e$, and $\tilde{p}_e$ represent the fluctuations in electron density, temperature, and pressure, and $\tilde{v}_e \approx \tilde{E}_\theta / B = -\nabla_\theta \tilde{\varphi} / B$ is the radial component of the fluctuating $\mathbf{E} \times \mathbf{B}$ velocity. Thus the particle flux component results from the correlated fluctuations of plasma electric field and electron density, while the conducted heat flux is due to correlated fluctuations of the electric field and electron temperature.

Measurements of fluctuating temperature, density, and potential with probes indicate that the observed electron transport in the plasma edge of tokamaks can be accounted for by these electrostatic fluctuations [6,7]. To verify this hypothesis in the plasma core, several diagnostics have been developed to monitor the turbulent fluctuations in the plasma interior. Far infrared (FIR) scattering [8] and the heavy ion beam probe (HIBP) [9] both measure density fluctuations, while the HIBP can also measure potential fluctuations. Recently, electron temperature fluctuations, $\tilde{T}_{e,\mathrm{rms}}/T_e$, have been measured in interiors of both stellarator [10] and tokamak [11–13] plasmas using a technique correlating the plasma electron cyclotron emission (ECE). Aside from the obvious difference that the diagnostic measures electron temperature rather than density fluctuations, the diagnostic has the advantage of excellent spatial resolution (in contrast to FIR scattering), and does not suffer from path effects (as does the HIBP).

In this Letter we report on results of studies of the temperature fluctuations over the poloidal cross section of the Texas Experimental Tokamak-Upgrade (TEXT-U) [14]. With the highly localized sample volume of the ECE system, a detailed map of the fluctuations reveals that they are strongly asymmetric. The mode peaks in a region about 20° either side of the equatorial plane, increasing with minor radius, and is symmetric about the equatorial plane and the high- and low-field sides.

On TEXT-U, correlation radiometry of ECE (CRECE) correlates the emission of two largely overlapping sample volumes in two disjoint frequency bands [11–13]. The technique reduces the random, uncorrelated inherent wave noise of the ECE signal while retaining the common temperature fluctuation amplitude. Detailed power spectra of these temperature fluctuations have been obtained over the low-field side of the plasma in the equatorial plane [11]. The method has the advantage that the radiometer need not be absolutely calibrated. However, in order to reduce the wave noise to an acceptable level requires long time averaging, on the order of 1 sec, and any temporal information of the turbulent fluctuations is lost. For all data presented below, the quoted uncertainty in the temperature fluctuation amplitude is derived based on the statistical nature of the analysis procedure of Gaussian random data [15]. Thus, the error $\varepsilon(\tilde{T}^2_{e,\mathrm{rms}}) \propto 1/\sqrt{N}$, where N is the number of independent samples. This statistical uncertainty dominates all systematic sources of error investigated (e.g., density fluctuation contamination) [11,16], which are small for the results reported here. Significantly, however, we note that the results presented below are very reproducible. Both the temperature fluctuation amplitudes and the associated power spectra have been duplicated in several experimental sessions.

Measurements reported here have been made as outlined in [11] for Ohmically heated circular plasmas ($R = 105$ cm, $a = 23$ cm) with $B_\phi = \sim 2$ T,

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$I_p = 150$ kA, and $\bar{n}_e = 1.7 \times 10^{13}$ cm^{-3}. For these conditions the plasma is in a regime where the energy confinement time τ_E is linearly proportional to the plasma density $\bar{n}_e$. Two horizontally viewing ECE antennas were used, one located on the machine equatorial plane and a second 15 cm off the equatorial plane. The sample volume is a disk approximately 1.6 cm in diameter and 0.8 cm thick. For all measurements the sample volume is oriented such that the smaller dimension is aligned horizontally. This allows detection of wave numbers $k_v \lesssim 3.5$ cm^{-1} and $k_h \lesssim 7$ cm^{-1}, where h and v are the horizontal and vertical directions. This fixed sample volume orientation means that the diagnostic is sensitive to radial and poloidal wave vectors to different degrees, depending on sample volume location. The CRECE system is most sensitive to radial wave vectors in the equatorial plane and poloidal wave vectors on the vertical plane through the plasma center.

The survey of temperature fluctuations over the plasma was achieved through a combination of shifting the plasma horizontally and vertically and changing the toroidal magnetic field. The particular combination of parameters was chosen to provide the best achievable spatial resolution for a given sample volume location. Figure 1 shows a poloidal cross section of the plasma where each symbol indicates a measurement location included in this survey. Also depicted is a sketch of the two antenna positions. The data represent measurements ranging in minor radius from $r/a = 0.3$ to 0.9 (inside $r/a = 0.3$ there are no measurable high-frequency temperature fluctuations above the instrument noise level), and in poloidal angle over $\theta = -45°$ to $200°$, where $\theta = 0°$ corresponds to the low-field-side equatorial plane.

The solid circles of Fig. 1 indicate six measurement locations at $r/a \sim 0.7$. In Fig. 2 the power spectra of the temperature fluctuations, $\tilde{T}_{e,\mathrm{rms}}/T_e$, are plotted at each of these locations. The dashed horizontal line represents the limit of statistical significance; points above this level are significant with regards to the correlation technique used to extract the temperature fluctuation from the inherently noisy ECE signal (see [11]). At small poloidal angles the spectra epitomize results reported earlier [11]. There is broad-band turbulence extending to 250 kHz with a feature in the spectra at about 100 kHz. We interpret this feature in the turbulence as a Doppler shifted drift wave, rotating with a phase velocity $v_{\mathrm{ph}} \approx v_{\mathbf{E}\times\mathbf{B}} + v_e^*$ where $v_{\mathbf{E}\times\mathbf{B}}$ is the plasma rotation velocity and v_e^* is the electron diamagnetic drift velocity, $v_e^* = T_e/eBL_n$, where L_n is the density gradient scale length [17]. Density fluctuation diagnostics identify a similar feature in their spectra and find that this mode propagates in the electron diamagnetic drift direction [5,18]. The peak of the drift wave feature moves to lower frequency while the amplitude increases as one moves radially outward [11].

As one progresses poloidally around the plasma (Fig. 2), the power in the temperature fluctuations of the drift wave feature initially increases by about a factor of 2 over most of the spectrum. At larger poloidal angles, the power again diminishes, and then falls rapidly in the drift wave feature region by about 2 orders of magnitude. At the plasma top the only remaining feature in the fluctuation spectra is the low-frequency fluctuations due to sawtooth and magnetohydrodynamic (MHD) oscillations (below ~30 kHz) [19]. Measurements at negative poloidal angles (below the plasma equatorial plane) indicate that this behavior is symmetric with respect to the equatorial plane. We believe the observed changes in the power spectra, including the enhancement off the equatorial plane, to be genuine for two reasons: The fluctuations are well above the statistical noise limit, and these spectra have been reproduced in many experimental sessions.

On the high-field side of the plasma the distribution and amplitude of the fluctuations in the neighborhood of the equatorial plane are similar to those of the low-field side. However, directly on the high-field-side equatorial plane the fluctuation level is 1–2 orders of magnitude below those of the low-field side. As with the plasma

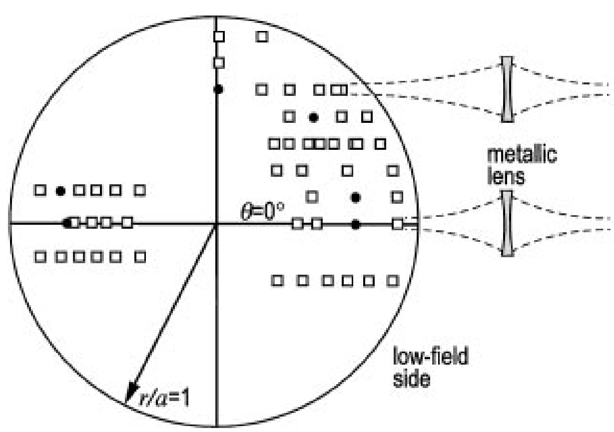

FIG. 1. Poloidal cross section of the plasma showing sample volume locations for $\tilde{T}_e$ measurement. Solid circles are locations of spectra in Fig. 2. Antenna configuration is shown schematically.

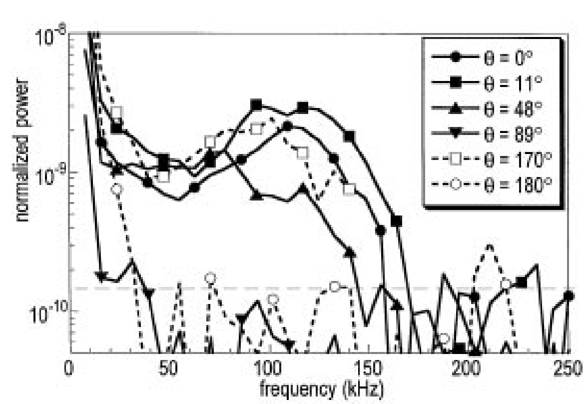

FIG. 2. Power spectra of $\tilde{T}_e$ at locations indicated by solid circles in Fig. 1

top, the only remaining feature of the spectra is the low-frequency fluctuations due to sawteeth and MHD. Although we find it surprising that such a strong gradient exists in the temperature fluctuations on the high-field side, especially in regions of low optical thickness, the existence of this gradient has again been confirmed during several experimental sessions. Measurements on the high-field side near the plasma top have yet to be performed.

Measurements on the high-field side are hampered by the fact that the vertical sample volume size is larger by about 50%, decreasing the sensitivity to short wavelengths. Extensive experimental study of the low-field side with various sample volume sizes enables us to correct for this problem [17]. There is also some concern that the measurements may reflect the change in sample volume orientation with respect to the plasma at different locations. Again, analytical models indicate that this cannot be the case [17]. Moreover, we know from studies varying the horizontal sample volume extent that the fluctuations on the low-field-side equatorial plane are comprised of significant poloidal components of high wave number [11]. Yet, at the plasma top, where our measurements are the most sensitive to poloidal wave vectors, no fluctuations are detectable. We therefore conclude that the effect of sample volume orientation is a negligible part of the observed poloidal asymmetry.

The spectra at each location shown in Fig. 1 were integrated from 25 to 250 kHz to obtain the turbulent temperature fluctuation amplitude, $\tilde{T}_{e,\mathrm{rms}}/T_e$, independent of the contribution from low-frequency MHD and sawtooth oscillations. The data were then plotted in the gray-scale contour plot shown in Fig. 3, where the smoothing was accomplished using a polar interpolation routine. White areas represent regions where no data have been taken. Although largely a qualitative picture, the plot clearly shows the asymmetric character of the date, where the largest amplitude fluctuations are located off the equatorial plane near the plasma edge. The temperature fluctuations peak in four lobes at about 20° either side of the equatorial plane on both the high- and low-field sides. Figure 4 quantifies the poloidal variation in the temperature fluctuation amplitude at three minor radii. Symbols indicate the measured fluctuation amplitude, whereas the solid lines are from the interpolation. The horizontal error bars represent the spatial extent of the sample volumes (~1°-3° poloidally), while the vertical error bars are derived from statistical considerations, as discussed above. These error bars are all but obscured by the symbols, except at low fluctuation amplitude and small minor radius.

Measurements using Langmuir probes in the plasma edge are consistent with the core temperature fluctuation data. Data from TEXT taken at $\theta = 90°$ show edge temperature fluctuation power spectra evincing a similar drift wave feature peaking near 100 kHz [20], while the amplitude is larger, commensurate with the increase in minor radius. In the CCT tokamak, both equilibrium quantities—electron temperature, density, and floating potential—and fluctuating quantities—ion saturation current, electric field, and particle flux fluctuations—show a strong poloidal asymmetry in the plasma edge which peak off the equatorial midplane [21,22]. The poloidal angle at which the fluctuations peak appears to be dependent on plasma conditions, such as the magnetic field profile or the limiter location.

Core electron density fluctuation measurements reported by FIR scattering are consistent with the measurements of temperature fluctuations. The measurements indicate broad-band spectra for density fluctuations with a drift wave feature on both the high- and low-field sides [23]. However, the diagnostic has poor spatial resolution for low wave number modes [23]; at wave numbers $k \lesssim 5\ \mathrm{cm}^{-1}$ the sample volume becomes a chord through

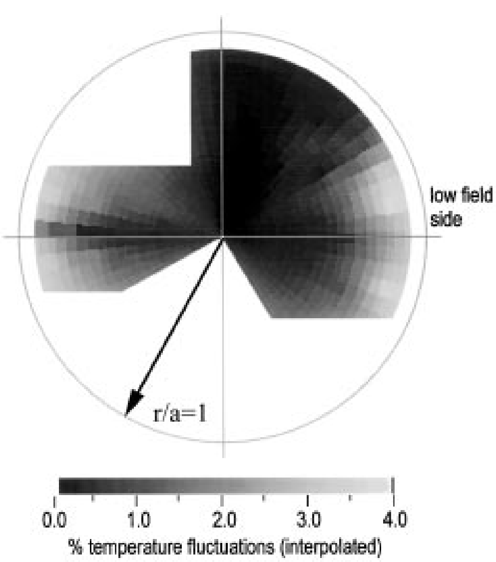

FIG. 3. Spatial distribution of temperature fluctuations. The mode occupies four lobes either side of the equatorial plane on the high- and low-field sides.

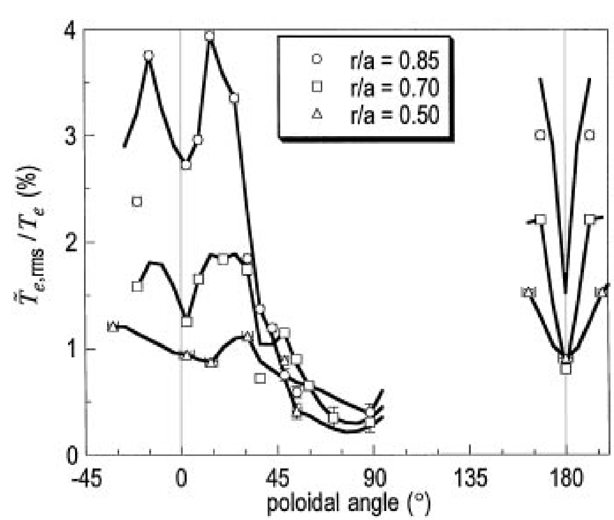

FIG. 4. $\tilde{T}_e$ vs poloidal angle. Symbols are measured amplitude, while lines are from the interpolated fit of Fig. 3.

the plasma. This poor spatial resolution does not allow the diagnostic to resolve whether the density fluctuations peak off the equatorial plane as seen in the temperature fluctuations. FIR scattering does report evidence of an up-down asymmetry which depends on the plasma current direction relative to the toroidal magnetic field. The asymmetry is reported only for high k modes which are beyond the CRECE resolution capabilities and are low in overall power (a factor of 50 less than the low k modes reported here). They also find evidence of a narrow-band "quasimode" localized to the high-field side at high wave numbers [8]. In some discharge conditions the temperature fluctuations also indicate the presence of this mode, though it is not consistently present.

HIBP measurements on the high- and low-field sides also indicate a poloidal asymmetry to the fluctuations. However, the HIBP measures the broad-band drift wave component of the fluctuations localized only to the low-field side [18]. Diagnostic restrictions do not allow the HIBP system access to the outer equatorial plane, so that peaking of the fluctuations off the equatorial plane cannot be confirmed.

In previous work we estimated the conducted heat transport due to the measured turbulent temperature fluctuations [11]. Those estimates relied on the supposition that the fluctuations measured in the equatorial plane were poloidally symmetric about the plasma. In light of the measurements over the poloidal cross section presented here, this assumption is no longer valid. However, the combined effects of the fluctuations peaking off the equatorial plane and the absence of fluctuations at the plasma top yields an average fluctuation amplitude not very different from that value on the equatorial plane. The temperature fluctuations, averaged over poloidal angle, are reduced only by about (10–20)% due to the asymmetry.

We have measured the turbulent temperature fluctuations over the poloidal cross section of a tokamak plasma with high spatial resolution. The measurements reveal that the fluctuations are spatially distributed with a strong poloidal asymmetry, localized in four lobes on either side of the equatorial plane on both the high- and low-field sides. This distribution of the turbulence is consistent with density fluctuation measurements from FIR scattering for the broad-band region of the spectrum, and with probe measurements of fluctuations in the plasma edge. The measured asymmetry results in only a modest reduction in the estimated heat flux, compared with our earlier assumption of a uniform distribution of fluctuations.

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