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FLUCTUATION MEASUREMENTS AT c/ω_{pe} SPATIAL SCALES IN A TOKAMAK

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Abstract

Magnetic and electrostatic fluctuations have been measured at the short scale length of the collisionless skin depth (c/ω_{pe}) using small magnetic and electrostatic probes in the Tokapole II tokamak. For certain conditions and at high frequency (MHz range) the amplitude is observed to increase as wavelength is decreased toward the c/ω_{pe} scale. Wavelength dependence is inferred from measurements with probes of varying sizes. The amplitude of the turbulence at the c/ω_{pe} scale is smaller than the dominant low frequency turbulence, and is thus not relevant to transport in Tokapole II. Comparison with theoretical treatments of c/ω_{pe} turbulence is discussed.

I. INTRODUCTION

Fluctuations have long been measured in detail in tokamaks through a variety of techniques. Most measurements have explored wavelength ranges roughly equal to or larger than the ion gyroradius. However, it has been argued through a sequence of theoretical papers over the years that the collisionless skin depth is a scale length at which significant fluctuations might reside, with consequent anomalous energy transport. The collisionless skin depth, c/ω_{pe} (where $\omega_{pe} = (n_e e^2 / \epsilon_0 n_e)^{1/2}$ is the electron plasma frequency), is typically of the order of one mm and is often smaller

than the ion gyroradius. In this paper we report measurements of magnetic and electrostatic fluctuations at the spatial scale of c/ω_{pe} in the Tokapole II tokamak. Magnetic and Langmuir probes of varying size are used to infer the fluctuation amplitudes at varying spatial scale over frequencies ranging from 10 kHz to 6 MHz. Results regarding the predominance and significance of fluctuations at this scale are mixed. At high frequency ($f > 500$ kHz), fluctuations are observed to be enhanced at the c/ω_{pe} scale relative to larger scales. However, these high frequency fluctuations are much smaller in amplitude than the dominant low frequency fluctuations and thus are not significant to transport for the plasma conditions of Tokapole II.

Ohkawa¹ first identified c/ω_{pe} as a possible scale length for spontaneous fluctuations. He considered electromagnetic fluctuations generated at mode rational surfaces. The modes are evanescent in the radial direction, as are injected ordinary electromagnetic waves in a plasma at $\omega < \omega_{pe}$. Thus, the waves are localized radially to within a distance c/ω_{pe} of the rational surface. Particle flow along a magnetic field in the presence of the radial magnetic field fluctuation was postulated to cause transport. A diffusion coefficient was estimated by assuming the transport to operate with a step length of c/ω_{pe} and a correlation time of a particle transit time around the torus. This yields transport with a density dependence that is similar to that observed in tokamak experiments. Similar approaches, which also did not specify the source of the turbulence, were elaborated in later work.^{2,3}

Lee et al⁴ suggested that an electromagnetic instability driven by an electron temperature gradient could be the source of fluctuations at the c/ω_{pe} scale. They argue that such instabilities could arise with wavelengths between the electron and ion gyroradii, the same range in which c/ω_{pe} often resides. However, the collisionless skin depth does not explicitly enter the linear theory as a parameter, and the linear eigenfunctions tend to have radial widths of the order of the electron gyroradius. Through a qualitative quasilinear estimate of the thermal conductivity, it was

observed that transport would maximize for wavelengths of the order of c/ω_{pe} . The resulting transport coefficient was of a form similar to that obtained by Ohkawa, with an added multiplicative factor dependent on $\eta_e = (d \ln T_e / dr) / (d \ln n_e / dr) = L_n / L_T$. The threshold for instability onset is $\eta_e = 1$. Horton et al⁵ extended the results to toroidal geometry, but in that linear work the c/ω_{pe} scale was also not directly linked to the instability.

The link between fluctuations and the c/ω_{pe} scale was made stronger in the nonlinear hydrodynamic computation of electron temperature gradient driven turbulence by Bekki et al.⁶ In the time dependent computation, linear electrostatic instabilities arise at the electron gyroradius scale, as anticipated by earlier studies. As time progresses, fluctuations arise at the longer scale of c/ω_{pe} as the linearly unstable electrostatic instabilities couple to stable longer scale electromagnetic modes. Thus a connection to c/ω_{pe} arises but only through nonlinear effects. The authors note that the longest wavelength of the simulation grid is about c/ω_{pe} , so that final conclusions concerning the spectrum would require further computation.

In section II we describe the plasma parameters and diagnostics. The parameters (section IIA) are suitable for a search for c/ω_{pe} turbulence. The small magnetic and electrostatic probes are described in sections IIB and IIC. Comparing fluctuations measured by probes of different sizes allows us to construct coarse k spectra. Section III contains the results on both magnetic fluctuations (IIIA) and electrostatic fluctuations (IIIB). Comparison of experimental results to aspects of theories of c/ω_{pe} turbulence is discussed in section IIIC, and conclusions are included in section IV.

II. EXPERIMENTAL SETUP

A. Plasma Parameters

Tokapole-II is a poloidal divertor tokamak⁷ with major radius $R = 50$ cm, minor radius $a = (8-10)$ cm (here a is the approximate location of the separatrix), toroidal magnetic field $(3-5)$ kG, plasma current $I_p = (10-40)$ kA, $T_e \sim 100$ eV (core) and $T_e \sim 10-40$ eV (scrape-off region), $n_e \sim (0.5-3) \times 10^{13} \text{cm}^{-3}$. With these parameters, $c/f_{pe} = 6-15$ cm (where $f_{pe} = \omega_{pe}/2\pi$), and the ion gyroradius $\rho_i \sim 2$ mm. It should be recognized that c/f_{pe} is a scale length, not a precise prediction for the fluctuation wavelength. The expected frequency (the drift wave frequency at c/f_{pe} scale lengths) is in the MHz range and is within the experimentally detectable band of frequency.

Electron temperature and density profiles were measured at the edge with admittance and triple probes, and are shown in figure 1 for discharges with edge safety factors $q_a = 1.5$ and $q_a = 3.5$. Although the uncertainties of these measurements do not permit an accurate determination of η_e , a rough estimate gives $\eta_e \gtrsim 1$. Thus, the condition for instability is roughly satisfied, particularly at high q_a values.

The data were collected for discharges with edge safety factor varying from 1 to 3, which corresponds to varying beta from $\beta \sim 10m_e/m_i$ (for $q_a \sim 1$) to $\beta \sim m_e/m_i$ (for $q_a \sim 3$)

B. Magnetic Prob

Magnetic probes were used to measure the radial magnetic field fluctuations. Because probes with smaller shield diameters resolve fluctuations at smaller

wavelengths (transverse to the probe), probes of different diameters were used to detect different ranges of poloidal wavelengths.

The wavelength resolution of a shielded coil is strongly dependent on (1) the attenuation and phase shift associated with the diffusion of a magnetic field through the electrostatic shield, and (2) spatial averaging of the magnetic flux over the area and length of the coil. The first effect can easily be taken into account with a bench calibration of amplitude and phase. However, the modulation effects due to the spatial averaging cannot be as easily calibrated because short scale-length magnetic field variations are not readily produced on the bench. Expressions for the response of a model probe were derived in ref. 8. The sensitivity of the probe to probe-transverse (poloidal) wavelengths λ_θ is determined entirely by the shield outer radius and is independent of the coil radius. The response falls to 1/2 of the maximum amplitude at $\lambda_\theta \sim 2 \times$ shield diameter, which is the criterion used to determine the limit of resolution (i.e., the smallest resolvable transverse wavelength). The response to probe-axial (plasma-radial) wavelengths λ_r is complicated and depends on all probe dimensions, but if the 1/2 amplitude criterion is used, the minimum resolvable axial wavelength will be $\lambda_r \sim 2.5 \times$ coil radius, $\lambda_r \sim 3.5 \times$ shield inner radius, or $\lambda_r \sim 3.3 \times$ coil length, whichever is largest.

Four probes of different overall diameter (shield outer diameter) were used to acquire most of the data presented here: one 6.35 mm probe; two 2 mm probes, one with a long coil (2.0 mm) and the other with a short coil (0.6 mm); and one 1 mm probe. Table 1 gives for each probe the minimum resolvable wavelengths in the probe-transverse (poloidal) and probe-axial (radial) directions. The response of each probe (except the short-coil 2 mm diameter probe) to radial wavelengths is similar despite having very different coil lengths, so we interpret these three probes as measuring approximately the same range of radial wavelengths. A cylindrically symmetric probe cannot distinguish between poloidal and toroidal wavelength effects

because its response to poloidal and toroidal wavelength is identical. However, low-frequency measurements and most tokamak turbulence models (including the nonlinear η_e model) indicate that $\lambda_z \gg \lambda_\theta$. Under this assumption the response of the probes to the toroidal wavelengths lies in the long-wavelength regime and is identical for each probe used here. Hereafter we interpret probes with different diameters as measuring different ranges of *poloidal* wavelength.

Radial magnetic fluctuations were measured over a broad range of radial positions outside, across and inside the separatrix ($0.5 \leq r/a \leq 1.4$). Two or more probes of different sizes were inserted radially into the discharge from the side of the machine. Tokapole II discharges are sufficiently cool that even the smallest, most fragile probes can usually survive extended runs anywhere in the machine. However, discharge quality and reproducibility are typically degraded if the probe is inserted too far past the separatrix.

The toroidal separation of adjacent pairs of probes was 30° for these experiments. To compare data from different toroidal locations, we assume that the turbulence is toroidally homogeneous. This assumption was confirmed by exchanging probes at different locations and checking the similarity of the measured spectra.

The frequencies of interest span nearly 3 decades from drift frequencies corresponding to large-scale modes (~ 10 kHz) to drift frequencies at c/ω_{pe} and ρ_i scales ($\lesssim 5$ MHz). The dynamic range of the raw probe signals spanned nearly six decades and was beyond the capability of any single amplifier and digitizer combination. To circumvent this problem the frequency range was divided into two experimental bands, each with its own set of amplifiers and filters. For low frequencies (10 kHz to 750 kHz) Tektronix AM502 differential amplifiers were used (with an internal high-pass filter at 10 kHz) together with an external fast-rolloff low-pass filter with a corner at 1 MHz to prevent aliasing at a 5 MHz sampling rate. For

high frequencies (0.5 - 7 MHz), a high-gain amplifier and filter system with fast-rolloff band-pass filter modules were used, and the signals were sampled at 20 or 50 MHz.

C. Electrostatic Probes

To resolve electrostatic fluctuations with small wavelengths, ion saturation current measured by a spherical Langmuir probe 0.5 mm in diameter was compared to the current measured by larger probes. Two sets of probes were built. In one set, the fluctuation power of the "small" spherical tip was compared with those of two "large" cylindrical tips each 3 mm in length and 0.4 mm in diameter, one oriented in the radial and one in the poloidal direction. This arrangement allows us to distinguish fluctuations with small spatial scales (with wavelengths $\lambda \geq 1$ mm for the spherical probe) from fluctuations with larger scales ($\lambda \geq 6$ mm for the two 3 mm probes) in the radial and poloidal directions. The second set of probes has the "small" spherical tip near a "large" cylindrical tip 3 mm in length and an even larger cylindrical tip 1 cm in length, both oriented in the radial direction. The range of spatial scales was then extended since the very large tip can only detect radial wavelengths larger than 2 cm.

The probes were inserted radially from the side of the machine, up to approximately the location of the separatrix, since probe arcing problems occur further into the plasma. All probes were biased into ion saturation at -200 volts. Low frequency fluctuations (10 kHz to ~ 300 kHz) were measured using Tektronix AM502 differential amplifiers (with an internal high pass filter at 10 kHz) and an external low-pass filter with a corner at 300 kHz. A high-frequency amplifier and filter system with band-pass filter modules (500 kHz and 300 kHz to 1.5 MHz) were used to measure the higher frequencies. Low frequencies were digitized at 1 MHz and high frequencies at 10 MHz.

III. RESULTS AND DISCUSSION

A. Magnetic fluctuation measurements

The power spectra measured inside the separatrix ($r = 6$ cm) and outside ($r = 11$ cm) in $q_a \sim 1$ discharges are shown in figures 2a and 3a. As expected the fluctuation power measured by the smaller probes is always greater or equal (within error bars) to that received by the larger probes which cannot resolve short wavelengths. In figures 2b and 3b, are plots of the ratio of the power measured by the 1 mm (at $\lambda_\theta > 2$ mm) and 2 mm ($\lambda_\theta > 4$ mm) probes to that of the 6.35 mm probe ($\lambda_\theta > 13$ mm). As a general rule, a ratio of spectra greater than two will be considered significant. We see that the power ratio exceeds two, corresponding to substantial small-scale power ($2 \text{ mm} < \lambda < 4 \text{ mm}$), at high frequency ($f \gtrsim 1$ MHz). The $q_a \sim 1$ discharges (with $\beta_e \sim 10 \text{ m}_e/m_i$) exhibited the largest small-scale fluctuations of any of the discharges examined. The ratio was largest at $r = 5$ cm and $r = 6$ cm and between ~ 3 MHz and ~ 600 kHz, although increased power levels at small scales extended down to ~ 100 kHz. At $r = 6$ cm the range of poloidal wavelengths $\lambda_\theta \gtrsim 2$ mm resolved by the 1 mm probe contained as much as 20 times more power than the range $\lambda_\theta \gtrsim 13$ mm measured by the 6.35 mm probe. The range of poloidal wavelengths $\lambda_\theta \gtrsim 4$ mm resolved by the 2 mm probe contained as much as 8 times more power than the range measured by the 6.35 mm probe. Though the small-probe power levels at the higher frequencies are much larger than for the 6.35 mm probe, they are still well below the power levels measured by all probes at the lower frequencies (as in figure 2a).

Near the separatrix ($r \sim 8$ cm) the difference between the small- and large-probe spectra is smaller than inside the separatrix, but still significant. The 1 mm probe measured as much as 10 times more power than the 6.35 mm probe, and the 2 mm

probe measured 5 times more power than the 6.35 mm probe in the same range of frequencies.

Outside the separatrix (figure 3, $r=11$ cm) no significant increase of the small-scale fluctuations was observed. Below ~ 1 MHz all three probes measured spectra that were similar to within the factor of ~ 2 total uncertainty. Above ~ 1 MHz the spectra at $r = 11$ cm are dominated by electronic noise.

The ratios of the small-probe to the 6.35 mm probe amplitude profiles in the low-frequency ($f > 20$ kHz) and high-frequency ($f > 0.5$ MHz) ranges are plotted in figures 4(a) and 4(b) respectively for $q_a \sim 1$ discharges. The error bars in each plot indicate the statistical scatter in the underlying data. At the higher frequencies (plot (b)) the 1 mm ($\lambda_\theta \geq 2$ mm) and 2 mm ($\lambda_\theta \geq 4$ mm) probes measure ~ 4 and ~ 2 times the fluctuation amplitude of the reference probe ($\lambda_\theta \geq 13$ mm). At the lower frequencies (plot (a)) the small probes measure slightly more power than the reference probe. The profiles of $\tilde{B}_r/B$ measured by each probe at low and high frequencies are shown in plots (c) and (d) (vertical scales are given in units of the common value at the edge). The edge values of the fluctuation levels are $\sim 10^{-4}$ and $\sim 10^{-6}$ in the low- and high-frequency ranges, respectively, and are indicated by the dashed lines. The maximum enhanced fluctuation level for the $q_a \sim 1$ discharges is $\sim 3 \times 10^{-5}$ and occurs at $r = 5$ cm for $f > 0.5$ MHz.

The power measured in the different ranges of λ_θ can be converted into a simple histogram that shows the approximate distribution of power in k_θ . The k_θ distribution measured in $q_a \sim 1$ discharges at $r = 6$ cm and $r = 11$ cm for selected frequencies is shown in figure 5. For comparison, the range of k_θ corresponding to $k_\theta = \omega_{pe}/c$ for Tokapole II parameters is indicated. The area in the first bin ($k_\theta \leq 0.5$ rad/mm = $2\pi/2$ (6.35 mm)) represents the power measured by the 6.35 mm probe. The heights of all bins at each frequency are normalized to the height of the first bin. Note the change of vertical scales at the different frequencies. The total area in the

first and second bins ($k_\theta \leq 1.57 \text{ rad/mm} = 2\pi/2 \text{ (1 mm)}$) represents the power measured by the 2 mm probe. The total area in all three bins ($k_\theta \leq 3.14 \text{ rad/mm} = 2\pi/2 \text{ (1 mm)}$) represents the power measured by the 1 mm probe. The strong spectral enhancement that is evident for $r = 6 \text{ cm}$ near $f = 2 \text{ MHz}$ in figure 2 appears in figure 5 for $f = 1.91 \text{ MHz}$ as a sharply increasing k_θ distribution. The experimental distribution increases as k_θ increases toward the c/ω_{pe} scales from smaller k_θ . The computation of nonlinear toroidal η_e modes⁶ predicts that the k_θ spectrum increases as k_θ decreases toward the c/ω_{pe} scales from larger k_θ . However, the experimental and computational results presently lack resolution ($k_\theta > \omega_{pe}/c$ in experiment and $k_\theta < \omega_{pe}/c$ in computation) to demonstrate a definite peak in the k_θ spectrum near c/ω_{pe} scales. Below the frequencies of enhancement ($f \leq 0.6 \text{ MHz}$) the distribution decreases monotonically with k_θ , and contains little power at the c/ω_{pe} scale.

Table 2 summarizes the main features of the short poloidal wavelength power comparison experiments. As q_a increased from ~ 1 to ~ 3 , the value of β decreased from $\beta \sim (10 m_e/m_i)$ to $\beta \sim (m_e/m_i)$, and the degree of enhancement decreased sharply from a factor of ~ 10 to 20 to less than a factor of 4 . As q_a was increased, the radial location of the highest ratio of small-probe power to 6.35 mm-probe power moved from inside the separatrix to near the separatrix. This is consistent with the prediction that the magnetic component of the microturbulence becomes less important as β falls toward m_e/m_i .

The results presented above were obtained with probes that had a similar overall radial wavelength response. A power comparison experiment was performed to investigate the effects of *coil length* on the difference in the measured spectra. The effect of coil length was studied using the two 2 mm diameter probes listed in Table 1. The short-coil probe and long-coil probe had coil lengths of 0.6 mm and 2.0 mm, respectively. The shield parameters and, thus, the response of the probes to probe-transverse wavelengths were identical. The minimum resolvable probe-axial (plasma-

radial) wavelength for the 2 mm probes is $\lambda_r^{\min} = 2.0$ mm for the short-coil probe and $\lambda_r^{\min} = 6.6$ mm for the long-coil probe. Assuming no toroidal asymmetries, any differences in the power measured by the two probes can be attributed to the different axial response functions resulting from different coil lengths.

Figure 6 shows the power spectra measured by the two 2 mm probes at $r = 6$ cm in $q_a \sim 1$ discharges. In the range of plasma-radial wavelengths $\lambda_r \geq 2$ mm the short-coil probe measured ~ 3 times more power than in the range $\lambda_r \geq 6.6$ mm measured by the long-coil probe. Thus, there appears to be $< c/\omega_{pe}$ scale radial fluctuations in the high-frequency magnetic turbulence in Tokapole II plasmas. The range of frequencies in which the radially short scale fluctuations occur is $100 \text{ kHz} \leq f \leq 500 \text{ kHz}$, which is somewhat lower than the frequency range of the poloidally short scale fluctuations. Outside the separatrix (at $r=11$ cm) there was no difference between the spectra measured by the two 2 mm probes. The spectra were similar in all respects to those in figure 2 ($q_a \sim 1$, $r = 6$ cm case).

The short radial wavelength fluctuations is summarized in figure 7. The power measured in the different ranges of λ_r at $r = 6$ cm for a few representative frequencies was converted into a k_r histogram. The area in the first bin ($k_r \leq 0.95$ rad/mm) represents the power measured by the long-coil 2 mm probe in the radial wavelength range $k_r \geq \lambda_r^{\min} = 6.6$ mm. The total area in the first and second bins ($k_r \leq 3.1$ rad/mm) represents the power measured by the short-coil 2 mm probe ($k_r \geq \lambda_r^{\min} = 2$ mm). Even near the frequencies with strongest short scale fluctuations ($100 \text{ kHz} < f < 600 \text{ kHz}$), the enhancement at high k_r is weaker than occurs poloidally (figure 5). The numerical simulation of the toroidal η_e modes predicted that the magnetic fluctuation spectra are isotropic in the poloidal and radial directions. The experimental results do not strictly support this prediction.

B. Electrostatic fluctuation measurements

Figures 8 and 9 show the amplitude spectra measured by the first set of probes (a "small" spherical probe and two cylindrical 3 mm probes oriented in the radial and poloidal directions) for "low" and "high" frequency ranges, at different radii in a $q = 3.5$ discharge. No short scale power (ratio >1) is seen at low frequencies at any position. At high frequencies, the "small" probe measures significantly more power than the "large" ones outside but not in the separatrix region. The largest enhancement is of a factor of 4 in amplitude seen at $r = 12$ cm. In the cases shown here there is no difference in the amplitude measured by the large probes oriented in the radial and poloidal directions, indicating that the turbulence is isotropic. However there were cases in which the fluctuations in the radial direction were larger than in the poloidal direction by up to a factor of two in amplitude, in the higher frequencies. The frequency integrated fluctuation levels are very small at high frequencies (in the 10^{-4} range), and should not contribute much to transport. They are also much smaller than mixing level estimates which give $\tilde{p}/p = 1/(kL_p) \geq 3\%$ (where L_p is the plasma pressure gradient scale length) for the 3 mm probe (assuming that the pressure gradient scale length is $L_p \sim 3$ cm, and $k \leq 2\pi/0.6\text{cm}^{-1}$). Error bars indicate the statistical scatter in the data.

As in the magnetic case, the distribution of power in k_r can be represented in a histogram, which is shown in figure 10 for the largest enhancement which occurred at $r = 12$ cm at high frequencies. Wavelengths corresponding to ω_{pe}/c are indicated in the figure for the plasma parameters at $r = 12$ cm. The fluctuation power increases at the larger k -band, which includes c/ω_{pe} scales.

The second set of probes (a "small" spherical probe, and two cylindrical 3 mm and 1 cm probes) was used in a $q_a = 1.5$ discharge, and the results are shown in figures 11 and 12 for low and high frequency ranges at various positions. Again at low frequencies, no differences are seen at any position. At high frequencies, the smaller probe measures a larger amplitude at $r = 12$ cm and $r = 16$ cm. For $r = 12$ cm (highest enhancement), the distribution of fluctuation power with k is shown in figure 13. With three different probe sizes, the power is distributed in 3 k-bands. At lower frequencies (400kHz) there is no extra power at the largest k-band (which contains c/ω_{pe} wavelengths), but some power exists in the second band. The differences increase at higher frequencies, at 800 kHz there is power in the largest k-band and even more power at the second band. The peak in power at the second band increases at 1.2 MHz. The frequency integrated fluctuation level is again very small at high frequencies compared to mixing level estimates and should not contribute to transport.

C. Relation to theory

The experimental parameters overlap quite well with the assumptions of the theory of η_e microturbulence. Many of the experimental scale lengths are comfortably separated and are suitable for a search for η_e mode activity. For the magnetic fluctuation measurements:

$$\rho_{ei} < \lambda_{1 \text{ mm prb}}^{\min} \leq \rho_i \sim \lambda_{2 \text{ mm prb}}^{\min} \sim c/\omega_{pe} < \lambda_{6.35 \text{ mm prb}}^{\min} < \lambda_{\eta_i \text{ modes}}^{\min}$$

where $\lambda_{1 \text{ mm prb}}^{\min}$ denotes the minimum resolvable wavelength for the 1 mm probe, ρ_i and ρ_{ei} are the ion gyroradius and the electron gyroradius calculated with the ion temperature, respectively. The c/f_{pe} wavelength lies roughly between the minimum

resolvable poloidal wavelengths for the 2 mm and the 6.35 mm probes, all of which lie between the ion gyroradius and the wavelengths at which η_i modes are predicted to be active. For the electrostatic fluctuation measurements:

$$\rho_{ei} \ll \lambda_{0.5 \text{ mm prb}}^{\min} \leq \rho_i \sim \lambda_{3 \text{ mm prb}}^{\min} < c/f_{pe} < \lambda_{1 \text{ cm prb}}^{\min}$$

The minimum resolvable wavelength for the 0.5 mm spherical tip is 1 mm and is smaller than ρ_i and c/ω_{pe} , which are both detected by the 3 mm probe. The assumption of an adiabatic ion response ($\lambda_{\perp} < \rho_i$) in the nonlinear computations, though not required, is marginally satisfied for the wavelengths of the strong enhancement ($\lambda_{1 \text{ mm prb}}^{\min} \leq 0.8\rho_i$). The assumption of non-adiabatic electrons ($\omega/k/v_e > 1$), which is required, is satisfied over most of the range of enhancement: $\omega/k/v_e \gtrsim 1$ for $f \geq 0.5$ MHz if $k_{\parallel} = 1/qR$. The high-density limit ($\omega_{pe}/\omega_{ce} \gg 1$) assumed by the reduced nonlinear η_e model equations is also marginally satisfied ($\omega_{pe}/\omega_{ce} \sim 2 - 4$).

The frequency range of the enhanced short wavelength fluctuations (0.4 MHz $\leq f \leq 4$ MHz) is consistent with range of real frequencies in which η_e modes are predicted to be linearly unstable ($\omega < 0.3 \omega_{ne}^*$, or $f < 1$ MHz).

In Tokapole II, β_e falls from $\sim 10 m_e/m_i$ in $q_a \sim 1$ discharges to $\sim m_e/m_i$ in $q_a \sim 3$ discharges. The fact that the levels of magnetic fluctuation enhancement fall with increasing q_a while the opposite is seen in the electrostatic fluctuation enhancements is consistent with the prediction that the magnetic component of the microturbulence becomes weaker as β falls toward m_e/m_i .

Disagreement exists between the measured short scale fluctuation levels and the mixing length estimates of the fluctuation levels (which reportedly agree with the nonlinear computational results). The fluctuation levels at the c/ω_{pe} scale is $\tilde{B}/B \sim 5 \times 10^{-5}$ and $\tilde{J}/J \sim 10^{-4}$ (where J is the ion saturation current measured by the electrostatic probes). However, the mixing length estimate⁶ gives $\tilde{B}_r/B \sim k_{\parallel} c/w_{pe} \sim$

10^{-3} if $k_{||} = 1/qR$, and $\tilde{p}/p \sim 3\%$ (interpreting the ion saturation current as representative of the plasma pressure). In the magnetic case, the disagreement may arise from the fairly low β values of Tokapole II plasmas. However, the experimental β for $q_a \sim 1$ discharges is about half that used in the nonlinear simulations. The use of plasma parameters and diffusion coefficients in the nonlinear simulations that are not consistent with Tokapole's parameters may be related to the large values of $\tilde{B}_r/B$. Finally, the experimental turbulence at c/ω_{pe} scales is anisotropic in the radial and poloidal directions, in distinction to the nonlinear computations.

The simulations run to date show that the k_{θ} spectra of magnetic fluctuation power increases as k_{θ} decreases toward the c/ω_{pe} scales. However, the simulations cannot accommodate wavelengths longer than c/ω_{pe} because of the assumption of adiabatic ion response. As the size of the simulation grid is made larger to permit smaller k_{θ} , the "peak" in the spectra moves to the largest scale of the box. If the restriction on the ion response can be removed, perhaps the simulations can resolve the actual location of the peak.

The simulations that have been run to date leave other questions unanswered as well, like the frequency spectra of the saturated magnetic fluctuations. Because the simulations generate primarily k spectra and the experiments generate primarily frequency spectra, direct comparison between experiment and simulation is limited.

IV. CONCLUSIONS

Electrostatic and magnetic fluctuations have been measured at the scale length of c/ω_{pe} . The plasma conditions are mostly conducive to the onset of such turbulence, as guided by past theoretical work. The electron temperature gradient is sufficiently large at various regions in the plasma, and the high frequency anticipated

at these small scales is within the band of measurement. However, the plasma beta is lower than considered in theory.

It is indeed observed that, at high frequency (in the MHz range), fluctuations exist at the short c/ω_{pe} scale. That is, the fluctuation power increases as wavelength decreases from longer wavelengths toward c/ω_{pe} . However, the amplitude of the fluctuations at the short scale is small, less than the mixing length estimates suggested by theory and observed in nonlinear computation. Thus, in Tokapole II such turbulence is not significant for transport. Its amplitude is far smaller than the dominant low frequency turbulence. The small value of beta ($1-10 m_e/m_i$) in Tokapole II might account for the small amplitude at c/ω_{pe} . Another point of distinction with the nonlinear computation is that in experiment the turbulence is anisotropic in the radial and poloidal directions, whereas the computation evolves from an initially anisotropic state to one with isotropic vortices.

There are three extensions to this work that would make the comparison with theoretical expectation more definitive. First, more complete experimental and computational spectra are required. Under certain conditions, experimental k spectra show an amplitude which increases from low k toward c/ω_{pe} . Computational spectra show an amplitude which increases from high k toward c/ω_{pe} . Both spectra need to be extended (experiment to higher k , and computational to lower k) to more clearly resolve whether there is a peak in the vicinity of c/ω_{pe} . Second, it is not known whether the turbulence observed at the c/ω_{pe} scale is coupled to fluctuations at the electron gyroradius scale (as predicted by computation), is independently generated, or is simply generated by coupling to the large longer scale fluctuations. The dominant coupling can be discerned through bi-spectral analysis in the frequency domain. Third, experiments at higher values of beta are necessary, since the fluctuation amplitude might increase with beta. The reversed field pinch, which

possesses high values of beta even at modest temperature, is an additional suitable vehicle to study c/ω_{pe} turbulence.

ACKNOWLEDGMENTS

We are very grateful to Dr. R. Dexter for critical diagnostic advice, to Dr. W. Horton for useful discussions and encouragement, and to Dr. D. Lindberg for use of his linear stability code. I.H.T. is grateful to Dr. Z. Ning for his help with data acquisition. The work has been supported by the U.S. Department of Energy and the National Science Foundation.

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	6.35 mm Probe	2 mm Probe (long coil)	2 mm Probe (short coil)	1 mm Probe
probe outer radius	2.67	1.0	1.0	0.5
$\lambda_r^{\min}$	8.9	6.6	2.0	7.9
$\lambda_{\theta z}^{\min}$	10.7	4.0	4.0	2.0

Table 1. Estimates for minimum resolvable wavelengths in the probe transverse (θ, z) and axial (r) directions. Units are millimeters.

q_a	Range of Largest ratio of small-to-large probe power		Magnitude of ratio of Small-Probe Power Relative to 6.35 mm Probe Power	
	r (cm)	f (MHz)	1 mm Probe	2 mm Probe
1	6	0.6 – 3	~ 20	~ 8
2	~ 8	0.6 – 4	~ 5	~ 4
3	~ 10	0.3 – 3	~ 4	≤ 2

Table 2. Summary of main results of the power comparison experiments.

Figure Captions

Fig. 1 (a) Electron temperature and density profiles for $\langle q_a \rangle = 3.5$ $\eta_e \sim 2$. (b) Electron temperature and density profiles at $t = 1.5$ ms for $\langle q_a \rangle = 1.4$.

Fig. 2.(a) Magnetic power spectra measured by each probe. Error bars indicate factor of ~ 2 overall uncertainty. (b) The ratios of small probe power to large probe power for the two smaller probes show the enhancement of fluctuations at small spatial scales. $q_a \approx 1$, $r = 6$ cm.

Fig. 3 (a) Magnetic power spectra measured by each probe. Frequencies where the noise dominates. (b) The ratios of small probe power to large probe power for the two smaller probes show no significant enhancement outside the separatrix. $q_a \approx 1$, $r = 11$ cm.

Fig. 4 Magnetic fluctuation profiles in the low- and high-frequency ranges. Ratios of small-probe profiles to the 6.35 mm probe profiles, (a) and (b), show the enhancement as a function of r . The profiled $\tilde{B}_r / B$ are shown in plots (c) and (d) normalized to the edge value. $q_a \approx 1$.

Fig. 5 Approximate k_θ distribution of magnetic fluctuation power inferred from three ranges of λ_θ resolved by the probes. $q_a \approx 1$, $r = 6$ and 11 cm. Bin heights are normalized to height of the first bin. Note change of vertical scales. the c / ω_{pe} and ρ_i scales are indicated.

Fig. 6 Power spectra measured by two 2 mm probes with different coil lengths. $q_a \approx 1$, $r = 6$ cm. The short-coil 2 mm probe ($\lambda_r \geq 2.0$ mm) measures about 3 times more power at higher frequencies than the long-coil 2 mm probe ($\lambda_r \geq 6.6$ mm) indicating the presence of short-scale fluctuations in the radial component of the magnetic field.

Fig. 7. Approximate k_r distribution of fluctuations power inferred from two ranges of λ_r resolved by the probes. $q_a \approx 1$, $r = 6$ cm. Bin heights are normalized to height of the first bin. The k_r distribution is not similar to the k_θ distribution (Fig. 5) at the same location in the same discharges. Thus the fluctuations do not appear to be isotropic in r and θ .

- Fig. 8** Ion saturation current fluctuation amplitude spectra for the small (1.5 mm), big poloidal and big radial (3 mm) tips at various positions at low frequencies, $\langle a_a \rangle = 3.5$.
- Fig. 9** Fluctuation level amplitude spectra for various positions $\langle q_a \rangle = 3.5$, high frequency range, for: small (0.5 mm), big radial (3 mm) and big poloidal (3 mm) tips).
- Fig. 10** Normalized fluctuation power as a function of radial wavenumber for $\langle q_a \rangle = 3.5$, $r = 12$ cm, (a) for the integrated power from 500 kHz to 1.5 MHz, (b) for $f = 900$ kHz, and (c) for $f = 1.2$ MHz.

Fig. 1 (a)

Fig. 1 (b)

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

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