Tokamak Magnetic Turbulence over the Safety-Factor Range $0.6 < q < 3$

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Magnetic turbulence ($\nu < 400$ kHz) has been measured both internal and external to a tokamak plasma as the edge q is varied from 0.6 to 3. The radial and poloidal spatial dependences of the coherence are investigated. The spatial and frequency dependences of the fluctuations are similar over the wide range of q.

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Despite the omnipresence of broad-band magnetic fluctuations in tokamaks,[1-8] both the cause and consequence of turbulence remain undetermined. Characterization of turbulence in tokamaks is hampered by the difficulty of internal measurements. The pitch of the helical magnetic field lines in a toroidal plasma is described by the safety factor, the number of field line toroidal transits per poloidal transit. The Tokapole II poloidal divertor tokamak[9] operates over a wide range of edge safety factor q_a from 3 to 0.6 (where q_a is defined as the edge safety factor of a circular plasma of the same current and cross-sectional area as that within the divertor separatrix). Behavior of disruptions and sawtooth oscillations over this q_a range in Tokapole II has been previously reported.[9,10]

We describe here observations of the internal magnetic turbulence as we vary q_a, an important geometric parameter which affects, for example, the free energy sources and magnetic resonances within the plasma. Moreover, since the amplitude of the turbulence is observed to vary with q, a controlled q_a scan also permits study of the relation of magnetic turbulence to transport and the dependence of the turbulence properties on the fluctuation amplitude. The relatively low temperature of Tokapole II plasmas (~ 100 eV) allows internal magnetic measurements, which yield new results on the spatial coherence of the turbulence, as well as the q_a dependence thereof. The results reveal a commonality to the turbulence over the wide range of q, implying that its cause, as well as a suitable theory, may not depend upon fine details of the equilibrium.

Plasma parameters for these experiments are $R \sim 0.5$ m, $a \sim 0.09$ m (distance from magnetic axis to separatrix), $T_e \sim 100$ eV, $n_e \sim 0.5 \times 10^{13}$ cm^{-3} (high q_a) to 1.0×10^{13} cm^{-3} (low q_a), and $B_T \sim 2$ kG (low q_a) to 5 kG (high q_a). Outside the four-node divertor separatrix is a scrapeoff region which extends about 0.13 m beyond the separatrix to the vacuum vessel wall. For the experiments the plasma is operated without scrapeoff plates ("magnetically limited"). Plasma density and temperature fall off beyond the separatrix with a decay length of about 0.1 m. Spatial properties of magnetic fluctuations are measured, up to 400 kHz, with probes consisting of four to eight radial field coils placed at 1-cm intervals radially, inserted within a 0.3-mm-wall stainless-steel tube encased in a cylindrical particle shield 0.6 cm in outer diameter. Isolation of one coil signal from another is measured at -60 dB or better for all frequencies below 400 kHz. Turbulence signals are digitized at 1 MHz. Power spectra are obtained from ensembles of 30 to 100 time records of duration $T = 256$ μs. The amplitude spectrum, $\tilde{b}_r(\nu)$, used in radial amplitude decay measurements, is the square root of the power spectrum, and the rms fluctuation level, $\tilde{B}_r$, is the square root of the integral of the power spectrum. Correlations and coherences between pairs of signals are obtained by use of ensembles of ≥ 100 records of at least 128-μs duration.

In that we have made internal probe measurements of the magnetic turbulence, a brief discussion of observed probe perturbation is appropriate. We have found that, for the frequencies discussed here, no significant variation of the amplitude or frequency characteristics of the signal from a probe outside the separatrix occurs when a

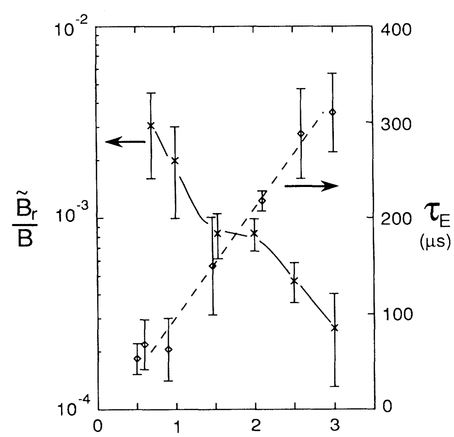

FIG. 1. Variation of normalized B_r fluctuations and energy confinement estimate with q_a. Turbulence levels are obtained from a coil at $r = 8$ cm over frequency range 10–400 kHz, and are normalized to the total field. Curves are drawn to facilitate reading the graph.

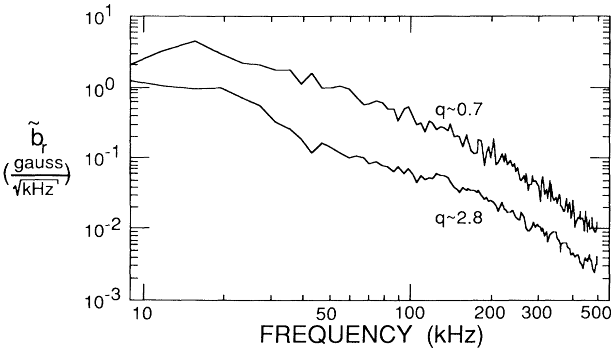

FIG. 2. $\tilde{b}_r(\nu)$ for extreme values of q_a. Data are from $r=8$ cm, about 1 cm inside the separatrix.

second probe is positioned inside. In addition, once a desired q_a is obtained with internal probes, global parameters, and their profiles to the extent that they are known, are found to be basically the same as would be obtained for that q_a without probes. The only exception to these occurs when a probe is placed at a radius of less than 6 cm in a discharge of high q_a (>1.5). Hence, no data are presented here for radii less than $r=6$ cm.

We describe here the dependence upon q_a, frequency, and radius of the amplitude, radial coherence, and poloidal coherence of the fluctuations in B_r, which is the component that may cause enhanced transport. Measurements of $\tilde{B}_p$ and $\tilde{B}_t$ yield that $\tilde{B}_p \approx 2\tilde{B}_r$ and $\tilde{B}_t \approx 0.2\tilde{B}_r$, with all components displaying similar frequency structure.

As q_a is reduced from 3 to 0.6, the normalized fluctuation level $\tilde{B}_r/B$ within the plasma, about 1 cm inside the separatrix, increases by a factor of 11 (Fig. 1). Global energy confinement time τ_E is estimated via

$$\tau_E = \tfrac{3}{2}\langle n\rangle T_e v/V_l I_p ,$$

where T_e is the electron conductivity temperature, V_l is the plasma loop voltage, I_p is plasma current, $\langle n\rangle$ is the density averaged over the interior vessel volume v, and is inferred from line-averaged density and edge profile measurements. Here the ion temperature T_i [$\approx(0.2$–$0.25)T_e$] is neglected. Confinement thus calculated is seen to decrease substantially as q_a decreases (with an increase in $\tilde{B}_r$), as per Fig. 1. Although no causal relation between $\tilde{B}_r$ and τ_E has been established in this work, if the parallel correlation length is on the order of $2\pi R$, R being the major radius, the transport due to stochastic magnetic fields[11] may be a significant factor determining τ_E at $q_a \leq 1$. For $q_a > 1$, however, the calculated stochastic transport is too small to affect τ_E.

In the remainder of this Letter we compare the turbulence properties at the extreme values of the q scan, $q_a=2.8$ and 0.6. The frequency spectra at $r=8$ cm are quite similar at the two q values (Fig. 2). However, the radial dependence of the fluctuations differs at the two q values. At $q_a=0.7$, all frequency values of $\tilde{b}_r(\nu)$ are un-

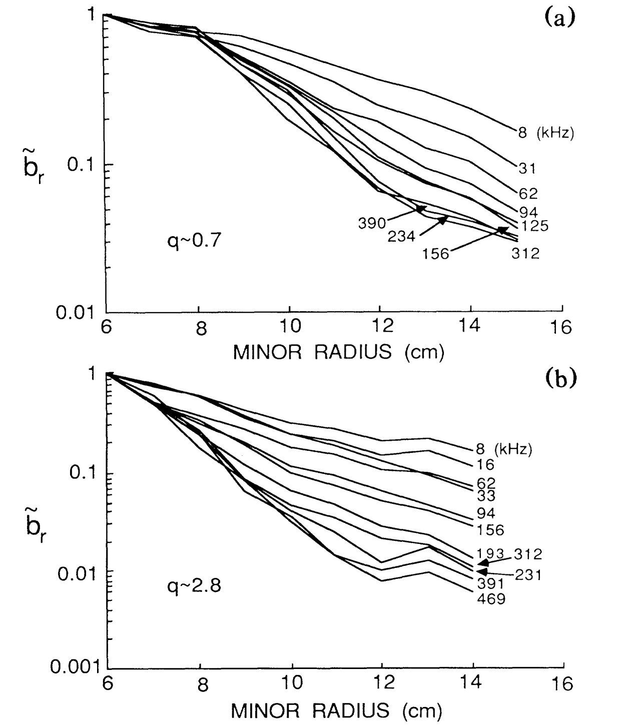

FIG. 3. Radial decay of $\tilde{b}_r(\nu)$ from $r=6$ cm (inside the separatrix), for (a) low q_a and (b) high q_a, at various frequencies. Ordinates are normalized so that for each frequency the amplitude at the smallest radius is unity.

varying with radius from $r=6$ to 8 cm [Fig. 3(a)]. The amplitude begins to decay near the separatrix at $r=8$ cm. This behavior resembles radial profiles of density and electron temperature, which are relatively flat with gradients localized to the separatrix and scrapeoff regions. The $q_a=2.8$ case [Fig. 3(b)] contains a radially decreasing fluctuation profile, beginning at $r=6$ cm (the innermost data point), resembling its more peaked equilibrium profiles. These results suggest that the turbulence may not result from instabilities depending on

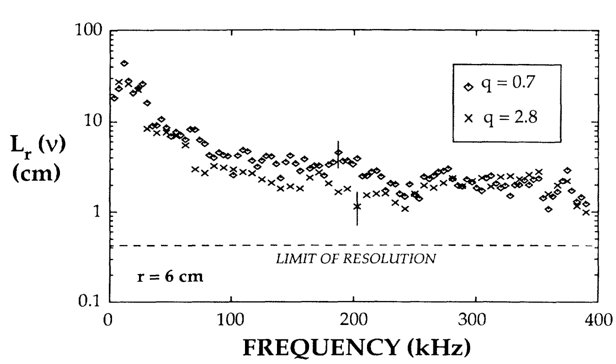

FIG. 4. Radial coherence lengths $L_r(\nu)$ of radial magnetic coil signals inside the separatrix, at minor radius $r=6$ cm.

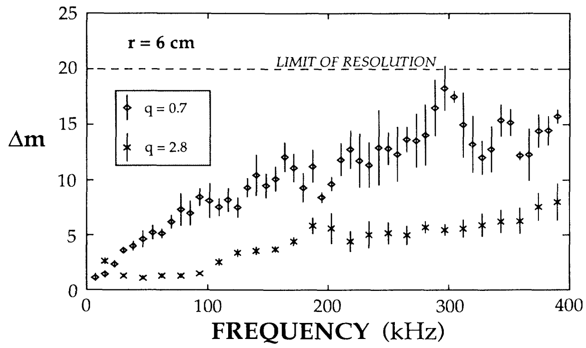

FIG. 5. Spread in poloidal mode number vs frequency from poloidal coherence lengths $L_p(\nu)$ of radial magnetic coil signals at $r=6$ cm. Error bars are from scatter in L_p.

the density gradient or temperature gradient alone.

The measured radial correlation within the plasma is essentially independent of q_a. The radial coherence lengths (the e-folding distance of the coherence) are evidently similar for the extreme values of q_a, as shown in Fig. 4. At both q values the coherence length decreases with frequency from tens of centimeters to about one centimeter.

Poloidal correlations were measured by probes separated poloidally on a magnetic surface at $r=6$ cm. The measurement is imperfect in that alignment along a magnetic surface is imprecise. From this data, one can infer the spread in poloidal mode numbers, Δm, which results in the poloidal decay of the coherence, via the estimate $\Delta m = \pi r/L_p$, where L_p is the poloidal coherence length. The results (Fig. 5) indicate that Δm at low q, which lies between 2 and 15, exceeds Δm at high q, which lies between 1 and 5. In both cases Δm tends to increase with frequency, except at very low frequency. Measurements at radii beyond $r=6$ cm yield $L_p(\nu > 160$ kHz) similar to that reported above, indicating that the poloidal scale length is independent of minor radius for the less coherent high-frequency fluctuations [Fig. 6(a)]. Hence Δm does depend on minor radius, at all q, for $\nu > 160$ kHz as shown in Fig. 6(b). (For $\nu < 150$ kHz, however, Δm is independent of r.)

An additional rough measure of the m numbers is obtained by one fitting the radial decay of $b_r(\nu)$ in the scrapeoff region by the cylindrical r^{-m-1} vacuum solution for low-n modes. The solution is inaccurate in that the equilibrium is cylindrically asymmetric due to the four divertor rings, and the scrapeoff region is not completely free of sources of fluctuation (i.e., the radial coherence lengths are finite, varying from 100 cm at low q and low frequency to 5 cm at high q and high frequency). Nonetheless, as a qualitative indicator the resultant "m" spectra (Fig. 7) indicate that "m" at low q exceeds that at high q, similar to the results obtained above for Δm. (It is interesting to note that $\Delta m/m$ is also higher for low q than for high q, by about a factor of 2.)

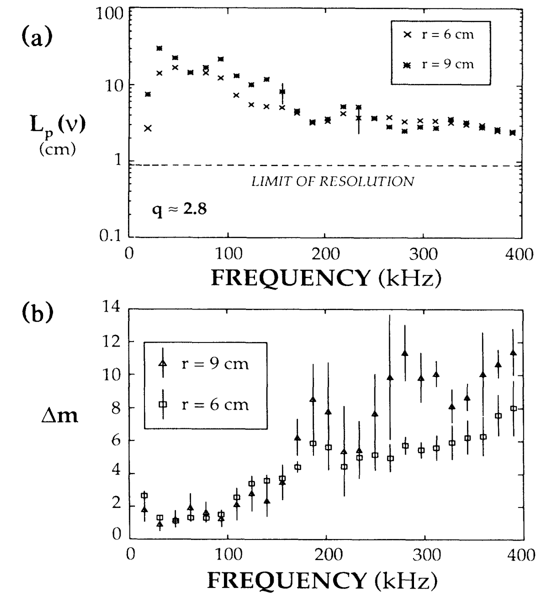

FIG. 6. (a) Poloidal coherence lengths at radii $r=6$ and 9 cm for high q (≈ 2.8), showing no variation with minor radius for $\nu > 150$ kHz. (b) Δm from the L_p data in (a), which indicates that Δm does vary with radius above 150 kHz. Similar results are obtained for $q \approx 0.7$.

In summary, the following conclusions emerge: (1) Magnetic fluctuations generally increase as q_a decreases from 3 to 0.6, although the amplitude does not change for $1.5 \le q_a \le 2$. (2) The frequency dependence and radial coherence properties of the turbulence are similar for high and low q_a. The radial coherence lengths are generally greater than 1 cm. (3) At all q_a values, higher-frequency modes are more localized radially, as might be expected if these modes correspond to higher m values. (4) At high and low q_a, the radial dependence of the fluctuation amplitude qualitatively resembles the equilibrium density and temperature profiles; this sug-

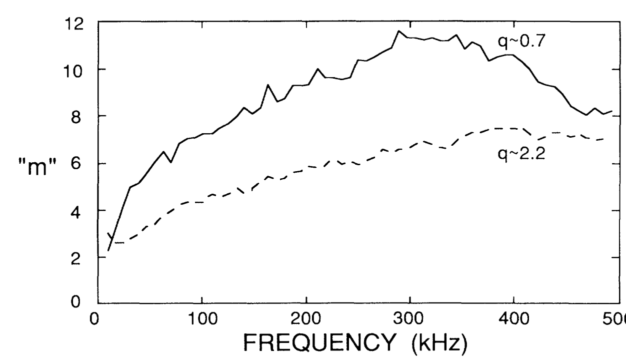

FIG. 7. Estimate of poloidal mode number "m" from radial amplitude decay at each frequency point of $\tilde{b}_r(\nu)$ outside the separatrix.

gests that the turbulence may not be a result of instabilities depending on the density gradient or temperature gradient alone. (5) The poloidal coherence length is similar in magnitude to that measured in the edge plasma of larger tokamaks,[2,12] and does not vary with radius for high frequencies in Tokapole II; i.e., the values of Δm *do* vary with radius or machine size. The independence of L_p from minor radius suggests that the high-ν modes may be tied to an intensive parameter such as gyroradius of resistive layer width. (6) The above five points imply that the turbulence over the range $0.6 < q_a < 3$ might be due to a single underlying cause or set of instabilities, with the differences in the observed fluctuations due to geometric effects; qualitative changes in the turbulence at $q_a < 1$ (as might be expected from resistive interchange or kink modes) are *not* observed. The fluctuation level and confinement time at $q_a \approx 0.6$ are similar to those of reversed field pinch experiments. Thus, one might speculate that the commonality of the magnetic turbulence might extend to the very low-q range of the reversed field pinch. (7) The reason for the higher poloidal mode numbers (inferred from poloidal coherence and "vacuum" radial falloff measurements) at low q_a is unclear; however, the larger number of poloidal modes at low q_a might account for the enhanced fluctuation level. (8) The global confinement degrades significantly as q_a decreases and fluctuations increase. Precise comparison of measured transport with that expected due to magnetic field stochasticity awaits improved measurement of transport parameters in Tokapole II, as well as measurement of the parallel correlation length of the fluctuations (now under way).

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