

TOKAMAKS: TURBULENCE AND FIRST TEST OF AN ERGODIC MAGNETIC LIMITER

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Abstract

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The characteristics of the ubiquitous low-frequency turbulence in tokamaks have been examined in an extensive set of experiments using far infra-red scattering to measure the full spectrum, $S(k_{\perp}, \omega)$, of density fluctuations throughout the plasma in the TEXT tokamak and using sets of probes to measure the structure of both density and potential fluctuations at the edge of TEXT and continuing into the interior in the smaller Caltech tokamak. Scattering experiments reveal a broad frequency spectrum of fluctuations which show clear dispersion in k_{θ} , propagating in the electron diamagnetic direction with phase velocity $\cong 2-3 v_{De}$, but no k_r dispersion. The wavelength spectrum is peaked at $k_{\perp} \rho_s < 0.5$. The fluctuations show marked spatial asymmetries. The amplitude rises toward the outside; probes show \tilde{n}/n of 20-80% at the periphery. Probes reveal complex turbulent structures with statistical properties matching those from scattering which reverse apparent propagation direction at the limiter. Density and potential fluctuations are related to drive an outward radial flux. The Ergodic Magnetic Limiter (EML) on TEXT, created with eight modular coils which impose a helical magnetic perturbation, m/n , of $7/2$ or $7/3$, is designed to explore the effects of an EML and study heat transport in an ergodic layer. Experiments have demonstrated that a small resonant perturbation with a fractional amplitude of $\sim 10^{-3}$ creates a stable ergodic magnetic layer and substantially modifies the heat flow pattern to the limiter.

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Low-frequency microturbulence driven by plasma inhomogeneities is universally observed in tokamaks and generally considered to be related to anomalous transport [1,2]. Experiments reported here provide a comprehensive description of the phenomena. On TEXT ($R=100$ cm, $a=27$ cm, $B_T=3$ T), a unique far-infrared ($\lambda=1.2$ mm) scattering system measures the complete $S(k_{\perp}, \omega)$ spectrum of density fluctuations within the plasma for a single discharge [3]. Arrays of Langmuir probes provide spectral information for both density and potential at the edge. In the Caltech tokamak ($R=45$ cm, $a=16$ cm, $B_T=0.35$ T), an 8×8 probe array provides similar information, adding pictures of the 2-D structure in the edge region. The results are complementary and consistent.

For a scattering volume located along a vertical chord through the plasma center, frequency spectra for each k_{θ} are shown in Fig. 1(a), which is a single representative shot from the plateau region of a sawtooth discharge at $\bar{n}=3.5 \times 10^{13} \text{cm}^{-3}$, $T_{e0}=900 \text{eV}$, and $T_{i0}=600 \text{eV}$. Three general features are the distinct frequency peak for each wavenumber, the shift of the peak to higher frequency and broadening at larger k_{θ} , and a significant reduction in magnitude for $k_{\theta} > 7 \text{cm}^{-1}$. The statistical dispersion relation inferred from the peaks is shown in Fig. 1(b). The dispersion is linear for $k_{\theta} < 9 \text{cm}^{-1}$ with a phase velocity $\approx 2-3 v_{De}$, the electron diamagnetic drift velocity, and rolls off at higher k_{θ} . Heterodyne measurements show the fluctuations to propagate in the electron diamagnetic direction. The poloidal wavenumber spectrum peaks broadly at $k_{\theta \rho_s} = 0.25$. In contrast, the k_r spectra have no dispersion, peaking near zero frequency and broadening as k_r increases. The integrated spectra correspond to $\bar{n}/n > 15\%$ at the plasma edge.

The spatial distribution of poloidal fluctuations is examined by scanning the scattering volume along a vertical chord through the plasma center as shown in Fig. 1(c) for $k_{\theta} = 9 \text{cm}^{-1}$. The center of the scattering volume is translated beyond the plasma edge to verify spatial resolution. The scattered power peaks near the edge, as expected, but surprisingly is an order of magnitude larger at the top than at the bottom. Only minor changes in the shape of the frequency spectra are observed across the plasma; a similar asymmetry is observed at $k_{\theta}=4.5, 7$ and 12cm^{-1} . Reversing the direction of plasma current inverts the spatial distribution as shown in Fig. 1(d). The plasma was well centered for these observations; deliberate movement of the center up, down, in and out had only small effects on the asymmetry.

Laser ablative impurity injection provides one means of studying the cause of the microturbulence. Sufficient impurity (here scandium) may be introduced to produce significant changes in plasma parameters and profiles. The

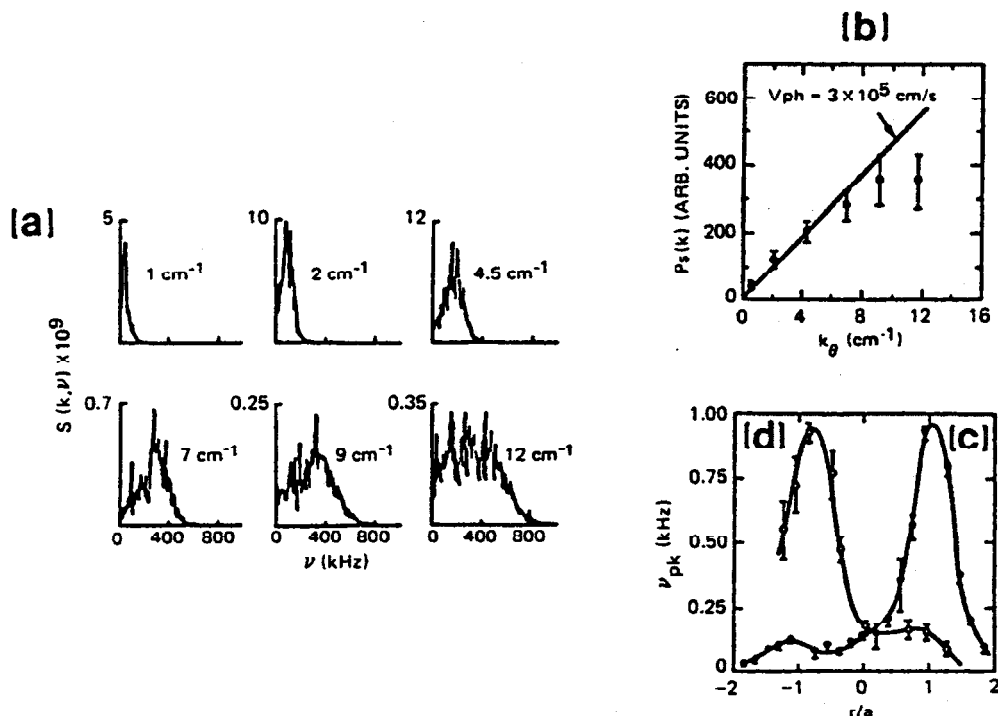


FIG.1. Density fluctuation spectra from scattering.

consequences for $S(k_\perp, \omega)$ may be continuously monitored. The effect of the injection on the frequency (at $k_\theta = 4.5 \text{ cm}^{-1}$) and wavenumber spectra are illustrated in Fig. 2. Prior to injection, typical spectra are observed. Within 1 ms after injection, both the frequency and wavenumber spectra shift to lower values, followed by a reduction in the fluctuation level, which reaches a minimum at 4 ms. The spectra recover within 10 ms. The frequency shifts are seen at all k_θ ; \bar{n} is reduced by $\sim 30\%$. The concomitant changes in the plasma include a prompt increase in edge density, giving a threefold increase in density gradient scale length, followed by a slower return to the original profile with 10% greater average density. Electron temperature, as measured by cyclotron emission, likewise decreases promptly upon injection across the plasma, lowering T_e without change in profile. The prompt changes coincide with the spectral changes at 1 ms and are qualitatively consistent with drift waves.

The scattering observations continue to the plasma edge, where they overlap consistently with Langmuir probe measurements which determine both density and potential fluctuations with finer spatial resolution. The edge parameters for both TEXT and Caltech tokamaks are $n \approx 10^{12} \text{ cm}^{-3}$ and $T_e \approx 20 \text{ eV}$. The $S(k_\theta, \omega)$ at three radial positions from

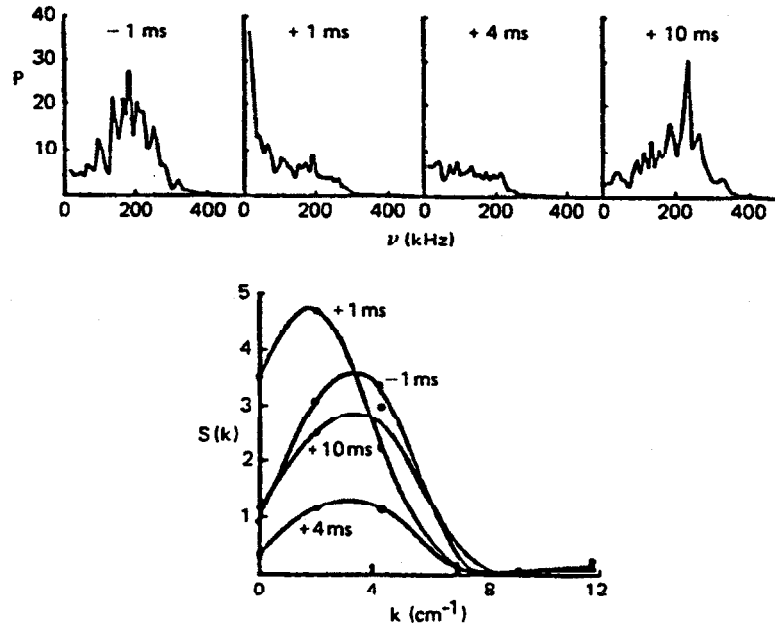


FIG. 2. Effect of impurity injection on spectra.

inside to outside the limiter ($a_L = 27\text{cm}$) in TEXT are shown in Fig. 3 as contour plots [4]. Inside, propagation is in the electron diamagnetic direction, and the characteristics of the turbulence match the scattering results in general features. Outside, the direction reverses, but this is explicable by a Doppler shift induced by the $E_r \times B_T$ poloidal drift velocity resulting from the radial electric field measured in this region. The intervening region of broadened spectra is rendered peculiarly complex by the high shear present; additional shear-driven processes may enter [5,6].

A picture of the structure of the density fluctuations is provided by an 8×8 probe array covering a region $1.8\text{cm} \times 1.8\text{cm}$ at the edge of the Caltech tokamak [7]. Variations from the mean density are represented by color (dark is dense) smoothed between probes over the 2-D array. Figure 4 shows several frames from a movie thus produced; the time interval between frames is $1.2 \mu\text{s}$. Again, propagation is in the ion direction near the wall, reversing toward the interior. The 2-D structure actually appears to consist of localized "blobs" which move irregularly through the edge region. However, these blobs do not appear to have a lifetime significantly longer than the local autocorrelation time (5 – $10 \mu\text{s}$), and they appear to have a range of shapes and sizes comparable to the average correlation lengths [8].

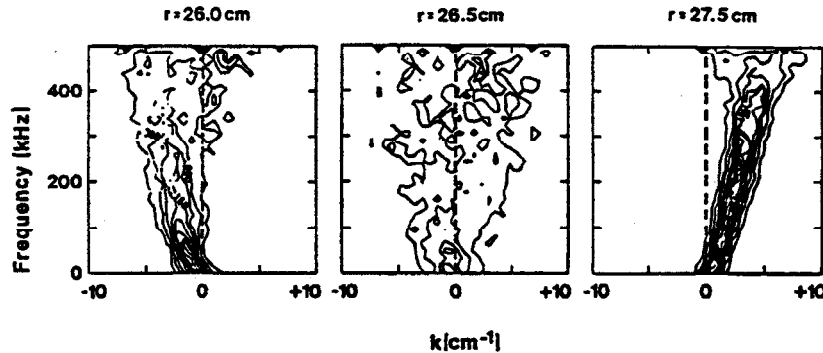


FIG.3. $S(k_\theta, \omega)$ from probes in the edge of TEXT.

Statistical analysis of the data from both machines establishes several common features. The probes as used are nonperturbing. The frequency and k spectra are broad. The wavenumber spectrum peaks at $k_\theta \rho_s \approx 0.1$ and has most of its power within $k_\theta \rho_s < 0.5$, where ρ_s is the ion gyroradius at T_e . The fluctuation amplitude is large, n/n ranging from 20% to over 80% near the wall. The spectral index for power law decay of $P(\omega)$ or $P(k)$ at large argument is in the range of 2 to 4. The density and potential fluctuations are correlated with a phase relation to drive a radially outward particle flux.

The large amplitude and broad spectra of the fluctuations must be interpreted as strongly nonlinear turbulence. Although the description of a strongly turbulent plasma is an extremely difficult problem, several nonlinear models have been presented recently which can explain semi-quantitatively many of the observed features [9]. In particular, two numerical fluid models of strong collisional drift-wave turbulence predict a 2-D structure which looks remarkably similar to that of Fig. 4 [10,11]. However, turbulence from the resistive MHD rippling mode is also a possible explanation [12]. Further work will be necessary to test the various models and explain all the features of the observations.

An Ergodic Magnetic Limiter (EML) offers promise as an effective mechanism for radiative cooling of future high power devices [13,14]. In TEXT, eight modular coils are used to generate a helical perturbation field with mode number ratio, m/n , of $7/2$ or $7/3$ [15]. A weakly ergodic structure results from the radial overlap of the fundamental island mode with the several harmonic modes produced by toroidal coupling. The radial perturbation field strength relative to B_T is typically 10^{-3} .

One of the most striking effects of the EML is the transformation seen in the annular ring of recycling light

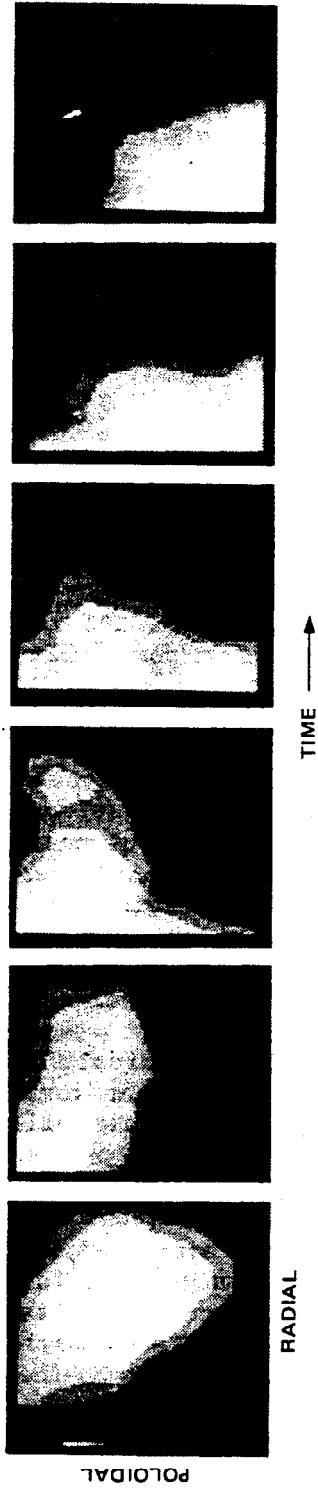


FIG.4. Patterns of relative density perturbation in the Caltech tokamak. Plasma center to right; electron diamagnetic direction up.

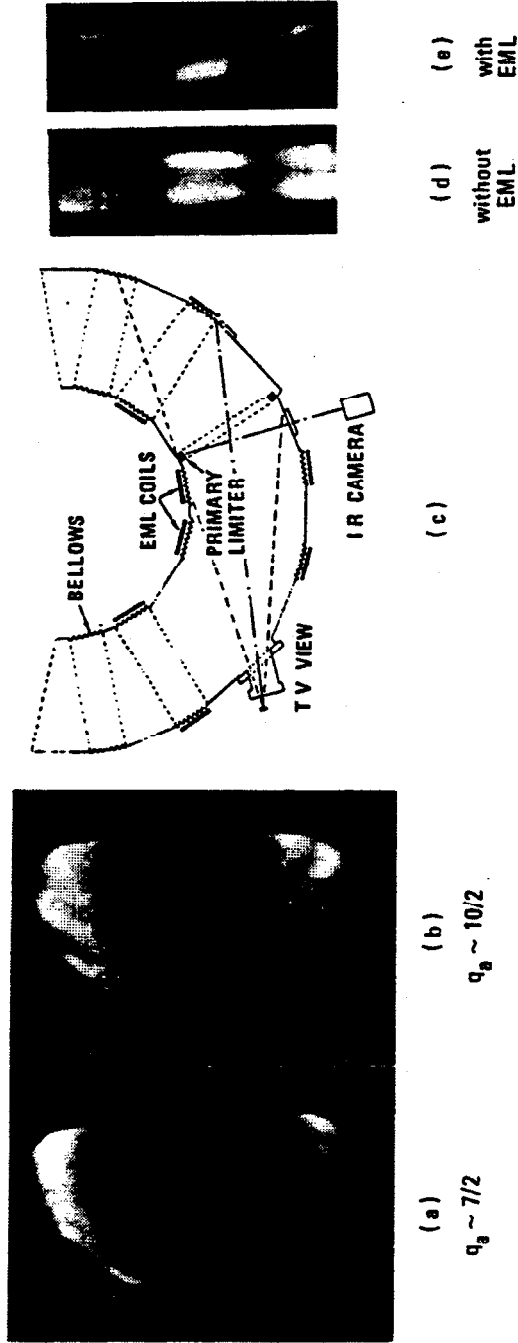


FIG.5. The Ergodic Magnetic Limiter (EML) of GA Technologies.

present in tangential view of the poloidal limiter [Fig. 5(c)]. With EML ($m/n = 7/2$), the emission manifests a poloidal pattern at $q_a \approx 7/2$ resembling that of nested magnetic "islands" [Fig. 5(a)]. With increasing q_a , this island pattern evolves into a striped structure. Fig. 5(b) shows the clear stripes present when $q_a \approx 10/2$, at which point the resonant layer lies deep inside the limiter radius. The depth in the plasma column to which structure can be seen increases strongly with plasma density. For the $m/n = 7/3$ coil configuration, however, the visible structures described above are seen only faintly.

An infrared, thermal-imaging camera measures the heat deposition profile on the inboard side of the primary hoop limiter, which is comprised of 16 Ti-coated graphite tiles. Without the EML the heat flux profile on the central three tiles is fairly uniform [Fig. 5(d)]. With EML, the heat flux pattern is localized poloidally in a pattern that repeats with an angular spacing approximately equal to the separation between island centers [Fig. 5(e)]. The bilateral asymmetry in the pattern arises because the heat fluxes parallel and antiparallel to a field line intersect the right and left sides, respectively, of the limiter. The spatial location of the poloidally concentrated heat flux depends on q_a . At high q_a the heat flux pattern with EML becomes similar to that without. Field-line calculations show that the bright areas are the locations connected to the interior of the plasma column and the dark areas are connected back to the limiter with little radially inward excursion. The excellent agreement of the measured patterns with theory demonstrates that parallel heat transport dominates over perpendicular in the EML region.

A drop of $\approx 20\%$ in the boundary temperature due to EML has also been observed by an electron cyclotron emission radiometer. Such a drop is most evident at densities below $4 \times 10^{13} \text{ cm}^{-3}$ and high helical field. The conditions for the temperature drop and the magnitude of the drop are consistent with the theoretically estimated electron thermal conductivity. Corroborative evidence for a depression of the temperature across the EML layer is the observed broadening of the radial profiles of doubly and triply ionized carbon. A factor two reduction in the Ti-XI and Ti-XXI signals is likewise suggestive of a reduced temperature for the plasma in contact with the TiC-coated limiter.

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REFERENCES

- [1] WALTZ, R.E., PFEIFFER, W., DOMINGUEZ, R.R., Nucl. Fusion 20 (1980) 43.
- [2] HORTON, W., "Drift wave turbulence and anomalous transport", Handbook of Plasma Physics, Vol.2, North-Holland, Amsterdam (1984) 383.

- [3] BROWER, D.L., PhD Dissertation, University of California at Los Angeles (1984).
- [4] LEVINSON, S.J., BEALL, J.M., POWERS, E.J., BENGTON, R.D., Nucl. Fusion 24 (1984) 527; BEALL, J.M., KIM, Y.C., POWERS, E.J., J. Appl. Phys. 43 (1982) 3993.
- [5] HORTON, C.W., Jr., LIU, J., University of Texas at Austin Rep. IFSR-111 (1984).
- [6] TERRY, P., DIAMOND, P.H., University of Texas at Austin Rep. IFSR-143 (1984).
- [7] ZWEBEN, S.J., GOULD, R.W., Nucl. Fusion 23 (1983) 1625.
- [8] ZWEBEN, S.J., GOULD, R.W., "Structure of edge-plasma turbulence in the Caltech tokamak" (to be published).
- [9] LIEWER, P.C., "Measurements of microscopic fluctuations in tokamaks and comparisons with theories of turbulence and anomalous transport" (submitted for publication).
- [10] WALTZ, R.E., "Numerical Simulation of Electromagnetic Turbulence in Tokamaks", General Atomic Report GA-A17521 (1984).
- [11] WAKATANI, M., HASEGAWA, A., Phys. Fluids 27 (1984) 611.
- [12] GARCIA, L., DIAMOND, P.H., CARRERAS, B.A., CALLEN, J.D., "Theory of Resistivity Gradient Driven Turbulence", University of Texas Rep. IFSR 146 (1984).
- [13] OHYABU, N., Nucl. Fusion 21 (1981) 519.
- [14] FENEBERG, W., WOLF, G.H., Nucl. Fusion 21 (1981) 669.
- [15] OHYABU, N., DEGRASSIE, J.S., BROOKS, N.H., TAYLOR, T.S., IKEZI, H., J. Nucl. Mater. 121 (1984) 363.

DISCUSSION

R.N. SUDAN: What fraction of the width of the measured frequency spectrum is attributable to the intrinsic effect of turbulence?

K.W. GENTLE: The width of the spectrum cannot be attributed chiefly to plasma variation within the volume observed. Especially for k_r and the higher values of k_θ , which have the broadest spectrum, the plasma is fairly uniform within this volume.

R.N. SUDAN: How does this width vary with wavenumber k ?

K.W. GENTLE: The width is greater at higher k .

S.M. HAMBERGER: Although the existence of turbulent drift-like waves has been convincingly demonstrated, is there any real experimental evidence relating such waves to the transport inside the plasma?

K.W. GENTLE: Probe analyses of turbulence indicate particle transport rates at the periphery consistent with particle confinement times. Within the plasma it has not yet been possible for fluctuations to be linked quantitatively with transport.