Observation of a Localized Transition from Edge to Core Density Turbulence in the TFTR Tokamak

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(Received 19 August 1993)

A localized transition zone is observed between turbulent, long-wavelength density fluctuations ($k_\perp < 2$ cm^{-1}) in the core and edge of beam-heated discharges in TFTR. The core turbulence is unimodal while the edge has two counterpropagating modes, both of which are spectrally distinct from the core fluctuations. The fluctuation amplitude in the core scales with the global energy confinement time while in the edge it does not. These observations suggest that distinct modes are responsible for turbulence in the two regions and that only the core mode is directly related to global confinement.

PACS numbers: 52.35.Ra, 52.25.Gj, 52.55.Fa

Understanding anomalous particle and energy transport in tokamak experiments remains one of the principal outstanding problems in plasma physics [1,2]. It has long been hypothesized that the observed anomalous transport is given by turbulent fluctuations. However, the effort to prove a causal connection between the observed plasma fluctuations and global plasma confinement and to identify the responsible modes is still in its early stages [1-5]. In general, the amplitude of density fluctuations in the edge (defined here as the region just *inside* the last closed flux surface) is on the order of 10%-50% and decreases rapidly to the order of 1% in the core. There is evidence that fluctuations in both the edge [6,7] and core [4,5] are responsible for the *local* anomalous transport. However, it is not clear how the fluctuations in the two regions contribute to the *global* confinement. It is also not known whether the edge and the core fluctuations are due to completely different instability modes or whether a single instability is responsible for fluctuations in both regions (in which case the change in fluctuation amplitude would be due only to changes in the local drives) [8,9]. The answer to these questions could have profound implications for the development of plasma turbulence theory and further experimental studies.

We report here the first observation of a clear demarcation zone between edge and core turbulence in tokamak plasmas. It is found that the fluctuations in the edge and core regions of the plasma are uncorrelated and spectrally distinct from each other, and are thus due to distinct modes. Only the core mode is found to be directly related to global confinement.

Beam emission spectroscopy (BES) [10] was used to measure and compare long-wavelength density fluctuations (in the range $k_\perp < 2$ cm^{-1} where the dominant fluctuation power is observed [4,5]) in the core and edge regions of beam-heated discharges (*L*-mode and supershot) in the Tokamak Fusion Test Reactor (TFTR). Clear differences between the edge and core coherency and cross-phase spectra imply a fundamental difference between the turbulence in the two regions. For example, Fig. 1 shows these spectra for a typical supershot discharge [$T_e(0) = 6.5$ keV, $T_i(0) = 9.1$ keV, $n_e(0) = 4.2 \times 10^{19}$ m^{-3}, $q_a = 5.5$, $P_{\text{beam}} = 14$ MW, balanced injection]. In the core, there is a single mode which propagates in the ion diamagnetic drift direction in the laboratory frame while in the edge two counterpropagating modes are seen: a low frequency mode which propagates in the ion drift direction (negative cross phase) and a higher frequency mode which propagates in the electron drift direction (positive cross phase).

Using this cross-phase information to determine the fluctuation amplitude of each of the counterpropagating edge modes (through appropriate frequency filtration), it is seen that the electron mode is localized to the edge region and disappears in the core [Fig. 2(a)]. The transition from the bimodal edge to the unimodal core is quite abrupt, occurring over a range of 1-2 cm (at $r/a \approx 0.9$ in this discharge).

Fluctuations propagating in the ion diamagnetic drift direction are observed in both the edge and the core.

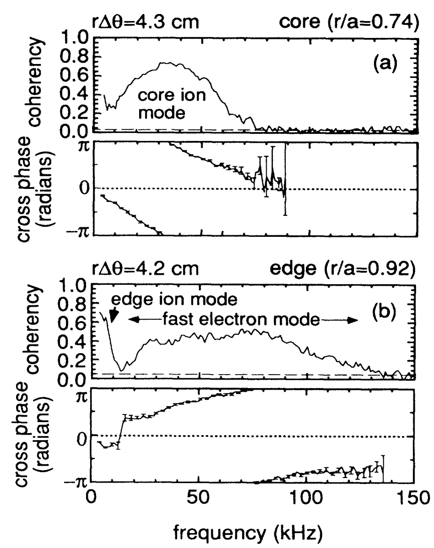

FIG. 1. Poloidal cross power and cross-phase spectra in the core (a) and edge (b) of a balanced injection TFTR supershot ($P_{\text{NB}} = 14$ MW).

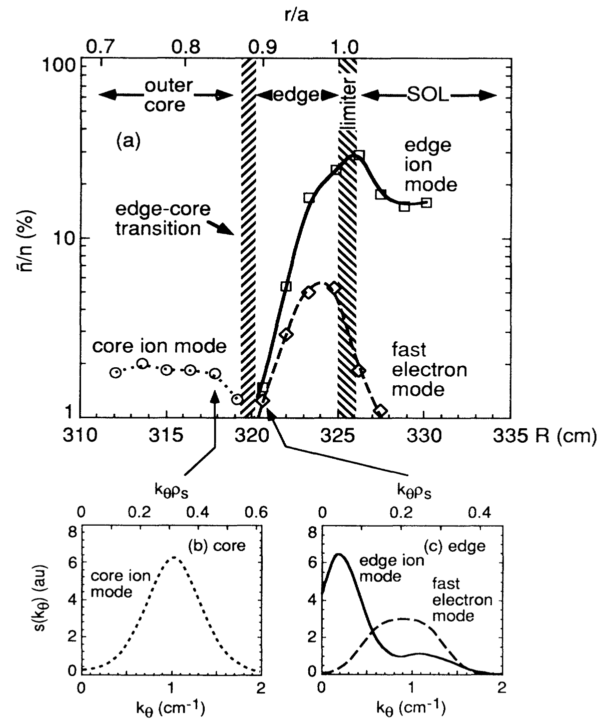

FIG. 2. (a) The amplitude of density fluctuations as a function of radius for the edge ion mode (□), edge fast electron mode (◇), and the core ion mode (○). (b) The wave-number spectrum in the core region ($R=318$ cm). (c) The wave-number spectrum in the edge region ($R=320.5$ cm).

However, wave-number spectra [4,11] imply that the edge and core ion modes are distinct. Poloidal wave-number spectra are typically obtained in two ways: via a full multipoint correlation analysis or from the autopower spectrum and the measured toroidal rotation [using the observation that the autopower spectrum is typically dominated by the rotation-induced Doppler shift, i.e., $S(\omega) \approx S(k_\theta v_\phi r/qR)$ where the toroidal rotation velocity, v_ϕ, is measured by charge exchange recombination spectroscopy [4]]. Multipoint correlation analysis can be performed only at certain radii where poloidal detector arrays are positioned while the autopower technique can be performed at radial locations between the poloidal arrays.

The wave-number spectra throughout the core are self-similar in shape. The spectra in the edge region are distinct from those in the core, but are also self-similar in shape throughout the edge. At a particular radius, which depends on the discharge conditions, the wave-number spectra of the fluctuations which propagate in the ion direction shift abruptly to higher average k in the core [Figs. 2(b) and 2(c)] as the fluctuations propagating in the electron direction disappear. The wave-number spectrum in the edge [Fig. 2(c)] was obtained by multipoint correlation analysis while the core spectrum was obtained from the autopower spectrum. The core spectrum obtained from the autopower spectrum is essentially identical to that obtained by full multipoint correlation analysis slightly deeper in the core ($R=312$ cm). The multipoint analysis unambiguously proves that there is indeed a clear difference between the edge and core wave-number spectra while the autopower technique is used only to determine the spatial localization of the transition region. The radial wave-number spectra show a similar abrupt shift to higher average k across this transition layer. The abrupt spectral change is also reflected in the radial correlation function which is highly asymmetrical near the transition layer: The edge and core fluctuations show strong correlation within their respective regions but become totally and abruptly decorrelated with each other across the 1–2 cm transition layer.

The macroscopic plasma parameters (e.g., temperature, density, safety factor, and toroidal rotation) vary smoothly and continuously across this transition. If a single ion mode were responsible for both the edge and core fluctuations then the spectra should also vary continuously. The sudden change in the spectra thus implies that the edge and core ion modes are distinct.

The relative velocities of the counterpropagating modes in the edge are consistently found to be anomalously high in both L-mode and supershot discharges. The mode phase velocities have been obtained both from the cross-phase spectra and from time-delay correlation analysis [11]. In the case of Fig. 1 the laboratory-frame velocities in the edge ($R=320.7$ cm) are found to be $+2.5\pm0.1$ km/sec (ion drift direction) and -5.5 ± 0.2 km/sec (electron drift direction) and thus the relative velocity of the modes is $\Delta v_{e\text{-}i}^{\text{obs}}=8.0\pm0.3$ km/sec. For drift waves (the class of instabilities most commonly invoked to explain plasma turbulence) the plasma frame propagation velocities are on the order of the diamagnetic drift velocity, $v_D^{e,i}=T_{e,i}/eB_\phi L_{n_e}$, where L_{n_e} is the electron density scale length and T_e is the electron or ion temperature for the electron and ion drift velocities, respectively [12]. The maximum expected relative velocity would be for counterpropagating ion and electron drift waves: $\Delta v_{e\text{-}i}^{\text{dw}}=|v_D^i|+|v_D^e|$. For this supershot discharge the ion and electron drift velocities are found to be $+2.6$ km/sec and -1.0 km/sec, respectively, and thus $\Delta v_{e\text{-}i}^{\text{dw}}=3.6$ km/sec, which is significantly smaller than the measured relative velocity (typically, $\Delta v_{e\text{-}i}^{\text{obs}}\approx 2\text{–}3\ \Delta v_{e\text{-}i}^{\text{dw}}$). The relative velocity of a mode which propagates slowly in the plasma frame (e.g., magnetic islands [13]) and a counterpropagating electrostatic drift mode is on the order of v_D and is thus also expected to be much smaller than the observed relative velocity. This *relative* velocity of the counterpropagating modes is independent of the reference frame and thus the existence of bulk plasma rotations does not affect this conclusion.

To determine which of the edge modes propagates anomalously fast, it is necessary to transform the measured phase velocities from the laboratory frame to the plasma frame for comparison to theory. "Plasma frame" here conventionally refers to that frame of reference for which the radial electric field is zero (i.e., drift effects on the mode propagation due to finite density and temperature gradients are assumed to be accounted for explicitly in the theory). Thus, the plasma frame phase velocity, $v_{\rm ph}^{\rm pl}$, is given by

$$v_{\rm ph}^{\rm pl} = v_{\rm ph}^{\rm lab} - \frac{E_r}{B_\varphi}.$$

The radial electric field is not measured on TFTR. However, if the impurity toroidal rotation is neoclassical then the measured impurity (carbon) toroidal rotation, v_ϕ^I, can be related directly to E_r [14]. For the case where the impurity strength parameter, $\alpha = n_I Z_I / n_i Z_i$, is of order 1 and the impurity ions are in the banana or banana-plateau regimes (which is typically the case for carbon near the edge-core transition layer in TFTR), the plasma ($E_r = 0$) frame phase velocity is given by [14]

$$v_{\rm ph}^{\rm pl} = v_{\rm ph}^{\rm lab} - \frac{B_\theta}{B_\varphi} v_\varphi^I.$$

For the case shown in Fig. 1, $(B_\theta/B_\phi)v_\phi^I \approx 0.1$ km/sec and so $v_{\rm ph}^{{\rm pl},i} = +2.6 \pm 0.2$ km/sec and $v_{\rm ph}^{{\rm pl},e} = -5.4 \pm 0.3$ km/sec. Thus $v_{\rm ph}^{{\rm pl},i} \approx v_D^i$ and $v_{\rm ph}^{{\rm pl},e} \approx 5v_D^e$; that is, in the $E_r = 0$ frame the edge ion mode propagates at or near the ion diamagnetic drift velocity (as does the core ion mode [4]), while the electron mode propagates at about 5 times the electron diamagnetic drift velocity.

The propagation of both the core and edge ion modes is consistent with a number of theories including ion drift waves (driven, for example, by the ion temperature gradient) and also, possibly, some kinds of MHD turbulence [13]. The electron mode propagates anomalously fast and is not consistent with either conventional drift wave or MHD turbulence theories.

This fast electron mode may be similar to an anomalously fast, long-wavelength electron mode observed in the *core* of the medium-sized tokamak TEXT by a heavy ion beam probe [15]. In both cases the mode propagation was at least several times that of the electron diamagnetic drift velocity. The similarity of these observations might imply that, at least in some respects, the fluctuations in the *core* of a smaller, TEXT-class machine are similar to those at the *edge* of TFTR. Support for this idea comes from the observation that, as the central temperature is lowered in TFTR, the observed position of the edge-core transition moves monotonically deeper into the plasma. For example, in a high power supershot the edge-core transition occurs near the limiter (e.g., at $r/a \approx 0.9$ in Fig. 1). As the central temperature is decreased the position of the edge-core transition is found to move deeper into the plasma so that in a relatively cold L-mode discharge [$T_e(0) = 2.5$ keV, $T_i(0) = 1.7$ keV, $n_e(0) = 3.1 \times 10^{19}$ m^{-3}, $q_a = 7.4$] the edge-core transition is observed at $r/a \approx 0.6$ (an inward shift of about 30 cm).

It is possible, if one extrapolates this trend, that in relatively low temperature discharges on TEXT the bulk of the core plasma may never make the transition to fully "corelike" behavior as seen in TFTR. This is a point which requires further study since many important fluctuation studies have been, and continue to be, performed on smaller machines. Thus the extent to which fluctuations in these experiments are representative of those in a reactor-relevant plasma is an extremely important consideration.

Though the data presented above are from a supershot discharge, a localized edge-core transition layer is observed consistently in *all* the operating regimes which have been studied with BES in TFTR to date (which includes a wide range of L-mode and supershot discharges but no Ohmic discharges).

It is of great interest to clarify the relationship of the various modes to the overall plasma confinement properties. Figure 3 shows the relative density fluctuation amplitude in the core [8] and edge for a series of L-mode discharges where the input neutral beam power was varied to change the global energy confinement time, τ_E (following the usual L-mode power scaling, $\tau_E \propto P^{-1/2}$). The fluctuation amplitude in the core clearly scales inversely with τ_E while the edge fluctuation amplitude is unrelated to the global confinement. This implies that only the core mode is directly related to global confinement in TFTR (though fluctuations are thought to account for the *local* anomalous transport in both the edge and core [4–7]).

If the edge-core transition layer indeed represents the interface between distinct modes then there may be, by analogy with phase transitions in thermodynamic systems, some dimensionless parameter which determines where the transition boundary occurs. A detailed study of the transition scaling has not been performed but some preliminary observations are available. Several parame-

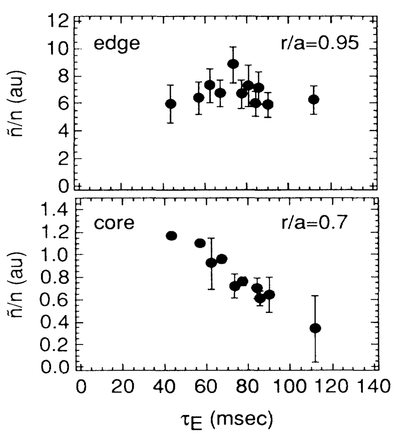

FIG. 3. The density fluctuation amplitude (from beam emission spectroscopy) as a function of τ_E (from a diamagnetic loop) in the edge and core for a beam power scan in L mode (1 MA, $P_{\rm BEAM} = 2$–16 MW).

ters which have been examined but do not correlate well with the available data include the bounce-frequency normalized ion collision frequency ν_i^*, plasma pressure β, the magnetic safety factor q, and the fueling neutral penetration depth. Two parameters have been found which can reproduce the position of the edge-core transition layer within experimental errors: the position of the $\nu_e^*=1$ surface and the surface at which the strongly radiating halo of carbon burns out [viz., where $P_{\text{rad}}(r)/P_{\text{rad}}^{\text{peak}} \approx 1/e$]. Both these parameters scale similarly in the TFTR discharges studied to date and both could plausibly be linked to a mode transition, and thus further studies are required to distinguish between the two.

In summary, observations of a highly localized change in fluctuation spectra at an edge-core transition layer imply that the fluctuations in the two regions are likely due to distinct modes. Only the core mode is directly related to global confinement in TFTR.

Useful discussions with J. D. Callen, C. Hegna, E. Mazzucato, R. Nazikian, D. Ross, R. Waltz, and M. Zarnstorff and the support of the TFTR operations team are gratefully acknowledged. This work was supported by U.S. Department of Energy Grant No. DE-FG02-89ER53296 and Contract No. DE-AC02-76-CHO-3073.

[1] A. J. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, W. A. Peebles, Ch.P. Ritz, P. W. Terry, and S. J. Zweben, Phys. Fluids B **2**, 2879 (1990).
[2] J. D. Callen, Phys. Fluids B **4**, 2142 (1992).
[3] R. V. Brevenec *et al.*, Phys. Fluids B **4**, 2127 (1992).
[4] R. J. Fonck, G. C. Cosby, R. S. Durst, S. F. Paul, N. Bretz, S. D. Scott, B. Grek, H. Park, A. Ramsey, E. Synakowski, and G. Taylor, Phys. Rev. Lett. **70**, 3736 (1993).
[5] R. J. Fonck, N. Bretz, G. Cosby, R. Durst, E. Mazzucato, R. Nazikian, S. Paul, S. Scott, W. Tang, and M. Zarnstorff, Phys. Controlled Fusion **30**, 1993 (1993).
[6] W. L. Rowan, C. C. Klepper, Ch. P. Ritz, R. D. Bengston, K. W. Gentle, P. E. Phillips, T. L. Rhoses, B. Richards, and A. J. Wootton, Nucl. Fusion **27**, 1105 (1987).
[7] Ch. P. Ritz *et al.*, Phys. Rev. Lett. **62**, 1844 (1989).
[8] S. F. Paul, N. Bretz, R. Durst, R. J. Fonck, E. Mazzucato, and R. Nazikian, Phys. Fluids B **4**, 2922 (1992).
[9] D. R. Thayer and P. H. Diamond, Phys. Fluids **30**, 3724 (1987).
[10] R. J. Fonck, P. A. Dupperex, and S. F. Paul, Rev. Sci. Instrum. **61**, 3487 (1990).
[11] R. D. Durst, R. J. Fonck, G. Cosby, H. Evensen, and S. F. Paul, Rev. Sci. Instrum. **63**, 4907 (1992).
[12] N. Mattor and P. W. Terry, Phys. Fluids B **4**, 1126 (1992).
[13] C. C. Hegna and J. D. Callen, Phys. Fluids B **4**, 1855 (1992).
[14] Y. B. Kim, P. H. Diamond, and R. J. Groebner, Phys. Fluids B **3**, 2050 (1991).
[15] T. P. Crowley, P. M. Schoch, J. W. Heard, R. L. Hickock, and X. Yang, Nucl. Fusion **32**, 1295 (1992).