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ABSTRACT

The scaling of broad band density fluctuations in the confinement zone of TFTR measured by microwave scattering, beam emission spectroscopy (BES), and reflectometry show a relationship between these fluctuations and energy transport measured from power balance calculations. In L-mode plasmas scattering and BES indicates that the density fluctuation level, δn^2, in the confinement zone for $0.2 < k_\perp \rho_s < 1.0$ depends qualitatively on P_{aux} and I_p in a way that is consistent with variations in energy transport. Fluctuation levels measured with all systems increase strongly toward the edge in all heating regimes following increases in energy transport coefficients. Measurements using BES have shown that poloidal and radial correlation lengths in the confinement zone of L-mode and supershot plasmas fall in the range of 1 to 2 cm. with a wave structure which has $k_{max} \approx 1$ cm^{-1} ($k_\perp \rho_s \approx 0.2$) in the poloidal direction and k_{max} approaching zero in the radial direction. A simple estimate of the diffusion coefficient based on a measured radial correlation length and correlation time indicates good agreement with power balance calculations. Similar estimates using reflectometry give radial coherence lengths at 10 to 20 kHz in low density ohmic and supershot plasmas of between 1 and 2 cm.

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I. INTRODUCTION

Core density fluctuations in a number of tokamaks have been shown to scale inversely with auxiliary heating power,[1,2,3] and probe measurements of edge turbulence have shown a connection between electrostatic fluctuations at the edge and particle confinement.[4] In TFTR circumstantial evidence suggests that the magnitude of broad band density fluctuations in the range $k_\perp \rho_s = 0.1$ to 1.0 ($\rho_s = c_s/\omega_{ci}$, c_s is the ion sound speed and ω_{ci} is the ion cyclotron frequency) in the confinement zone are related to transport; however, quantitative comparisons to transport and the identification of specific instabilities or drive mechanisms is just beginning. Both microwave scattering[5] and beam emission spectroscopy[6] (BES) have shown that the density fluctuation level increases with increasing heating power in L-mode discharges. Mixing length estimates of the diffusivity from the level of these fluctuations is large enough to cause the observed transport.[7,8,9] In addition, local measurements from BES of correlation lengths in the range 1 to 2 cm and correlation times can be used to estimate diffusivity, and these estimates are also in rough agreement with diffusion coefficients based on power balance calculations.[10]

Radial correlation lengths from BES are very similar to reflectometry measurements of the radial coherence length although measurements in the same discharge conditions are sparse. Reflectometry has measured radial coherence lengths of about 2 cm. at 10 to 20 kHz in a limited number of low density ohmic plasmas at r/a = 0.5. For supershot plasmas at a similar location the coherence length is in the range 1 to 2 cm.[11]

Density fluctuation levels are also consistent with the L-mode transport dependence on toroidal plasma current. Fluctuation levels from scattering at $k_\theta \approx 3$ to 4 cm^{-1} and from BES at $k < 1.5$ cm^{-1} vary inversely with I_p for $r/a > 0.3$ in plasmas which have a 2 second equilibrium phase. During current ramp experiments.[12,13] both system measure fluctuation levels which follow spatial and temporal variations in transport.

BES measurements have shown that, while correlation lengths in L-mode plasmas are similar in the poloidal and radial direction, there are significant differences in the radial and poloidal k spectra. In the poloidal direction there is a wave structure with $k_{max} \approx 1$ cm^{-1} ($k_\perp \rho_s \approx 0.2$) while in the radial direction one has k_{max} approaching zero. Scattering results have shown that for $k_\theta > 2$ cm^{-1} ($k_\perp \rho_s \approx 0.5$) fluctuation levels decrease strongly.

Good spatial resolution in BES and reflectometry and sensitivity to low k allows the observation of MHD like features at specific frequencies with long radial and poloidal correlation lengths. On the outside major radius, where the measurements are typically made, these modes do not appear to concentrate on rational q surfaces. These modes appear to coexist with broad band, low coherence turbulence which is presumed to be the part responsible for energy and particle loss.

2. TOROIDAL PLASMA ROTATION

It is now well recognized that all techniques which measure density fluctuations within a tokamak plasma are strongly affected by toroidal plasma rotation. Toroidal rotation or, equivalently, radial ($v_\phi B_\theta$) electric fields, appears to be a common feature of most, even ohmic, plasma regimes and obscure fluctuation effects due to plasma gradients. In TFTR these effects are particularly severe because the heating beams are tangential. Density striations tend to be aligned along field lines so that bulk toroidal rotation causes density variations to appear as poloidally propagating wave structures in the laboratory frame. Thus, the fluctuation magnitude can be measured simply but frequency spectra, mode velocity, and coherence are affected by rotation. The calculation of rotationally invarient correlation properties requires careful analysis. A systematic study of these rotational effects and cross comparisons between the fluctuation systems has resulted in improved understanding of the basic measurements.

Rotational effects have always been one of the most obvious aspects of scattering spectra. Heterodyne instruments can distinguish the direction of poloidal mode rotation; so that in ohmic plasmas one almost always observes poloidal rotation in the electron diamagnetic direction but with a magnitude several times larger than that expected from the drift wave dispersion relation. In beam heated discharges these shifts can be much greater and can occur as propagation in the laboratory frame electron diamagnetic drift direction (counter injection) or in the laboratory ion direction (co injection). Measurements of the toroidal rotation profile can be combined with these measurements to verify that the location of the scattering coincides with the crossing of the antenna patterns and showing that the frequency spread of the power spectra is simply due to the variation of the rotation velocity across the scattering volume. In this case no information on mode damping can be inferred from the width of the spectra even for nominally balanced injection because residual rotation is always important. This situation may also be true for ohmic discharges where small (typically counter) toroidal rotations cause the anomalous drift velocity in the electron drift direction in the laboratory frame.[14]

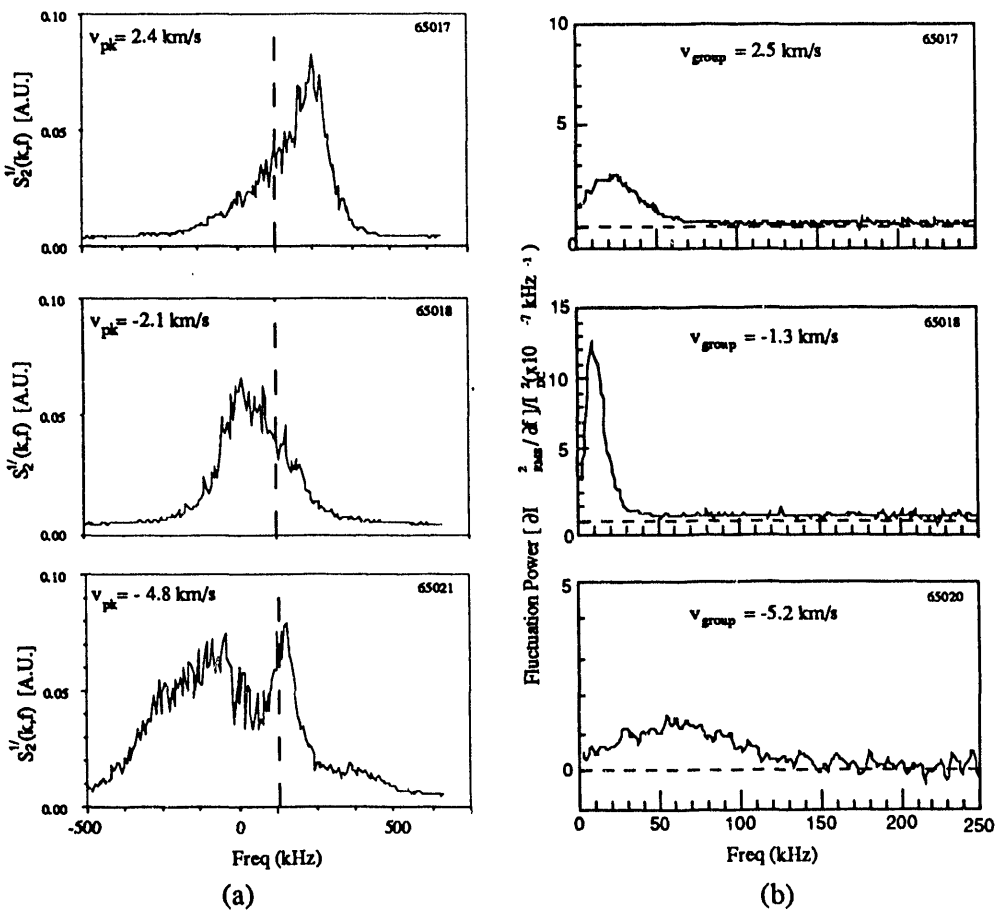

Fig. 1 Power spectra for several different rotational velocities induced by tangential neutral beam injection for (a) microwave scattering at r/a = 0.45 to 0.75 for $k_\theta = 3.0$ cm^{-1} where the spectral shift direction is determined by the sign of toroidal rotation and $2\pi f \approx k_\theta v_\phi (B_\theta / B_\phi)$; and (b) BES at r/a = 0.75 where group velocities measured from the poloidal array.

BES spectra have, in the past, also shown hints that the frequency spectra had rotational effects. Recently, improved methods of eliminating common mode effects have reduced low frequency components and revealed that the remaining spectra look very much like scattering measurements where the shift in frequency is caused by toroidal rotation at the position of the measurement.

Figure 1a and b show a comparison of the scattered and BES spectra near the same flux surface. The scattering results are averaged by the finite beam intersection volume which extends 35 cm radially (r/a = 0.45 to 0.75) while the BES results are averaged over a 2 cm element at R = 309 cm (r/a = 0.75). In scattering the estimate of the poloidal rotation comes from the Doppler shift: $2\pi f_{pk} = k_\theta v_{\theta p k}$ where k_θ = 3.0 cm is determined by the scattering beam geometry. For BES the velocity is inferred from time delay correlation in the poloidal direction. Thus, the width of the frequency spectra can be interpreted directly as a mode width and the value of k for the dominant poloidal wave number gives $k_\theta \approx 1$ cm or $k_\perp \rho_s \approx 0.2$. The two systems track together as the toroidal velocity is changed from balanced (shot # 65017) to mainly co-injection. (shots 65020 and 65021) and the magnitude of the shift agrees with the measured toroidal rotation from charge exchange recombination spectroscopy and the tilt of the magnetic field estimated from q(r).

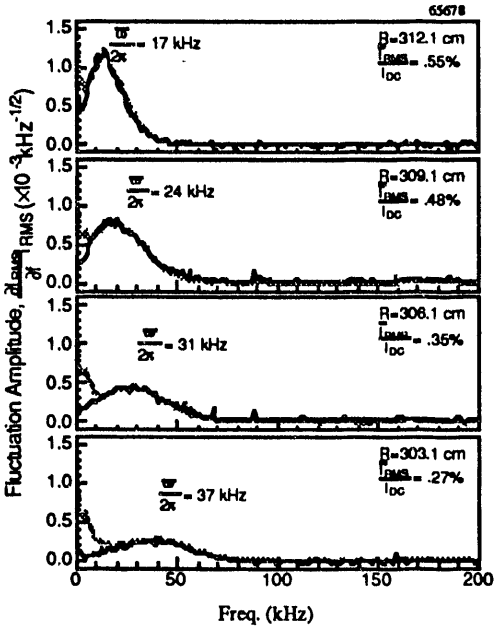

Fig. 2 BES fluctuation amplitude vs. frequency at several radial positions in a rotating supershot plasma.

In supershot plasmas the density becomes large enough that refraction distorts the scattered microwave beams and complicates the analysis. However, BES can easily see rotational features similar to those in L-mode cases. Fig. 2 shows plots of the frequency spectra at several values of r/a. Again these track the measured toroidal rotation well.

Rotation is also important in interpreting the results of the reflectometry phase measurement. A vertical misalignment of the reflectometer with respect to the normal to the reflecting surface causes the phase to runaway. Co-rotation causes a rapid increase in the phase and a shift of the spectrum while counter injection causes a rapid decrease in the phase and a shift of the spectrum in the opposite direction. When the alignment is normal to the surface the spectrum is symmetric. Phase runaway and large amplitude fluctuations in the reflected signals during beam injection have limited the interpretation of coherence measurements from reflectometry.

A common understanding of rotation gives some confidence that the three measurements are looking at the same phenomenon. In the future a careful analysis of local BES spectra along with rotation and q measurements may allow the magnitude and sign of poloidal rotation in the plasma frame to be determined unambiguously. These measurements will be valuable in identifying changes in the poloidal drift direction theoretically predicted for electrostatic drift waves to be a function of η_i (= L_{n_i}/L_{T_i}).

3. SCALING OF FLUCTUATION LEVELS WITH TRANSPORT

Parametric dependencies of δn^2 suggest a direct relationship with observed energy transport in L-mode plasmas. However, assuming that the important fluctuations are electrostatic and lacking a simultaneous estimate of potential fluctuations, these results cannot yield a direct estimate of energy transport. The relative level of δn^2 measured with scattering for $k_\perp \rho_s > 1.0$ and BES for $k_\perp \rho_s = 0.1$ to 1.0 in the confinement zone depends qualitatively on P_{aux} and I_p in a way that is consistent with variations in energy confinement.

The radial dependence of density fluctuations measured with all systems is also consistent with some aspects of local transport. Fluctuation levels increase strongly toward the edge in all heating regimes as does the transport.

In L-mode current ramp experiments fluctuations change near the edge

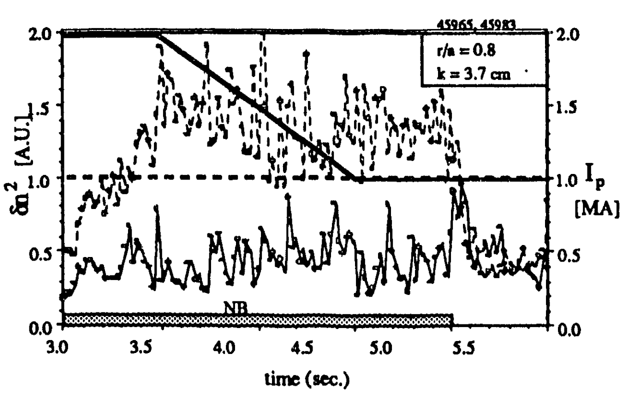

Fig. 3 Density fluctuations from microwave scattering at k = 3.7 cm^{-1} during an L-mode current ramp from 2 to 1 MA (solid lines) compared with a constant current of 1 MA (dashed lines).

more rapidly than in the core consistent with current penetration and concomitant changes in the transport. Fig. 3 shows scattering measurements during an L-mode current ramp from 2 to 1 MA and a comparison plasma at 1 MA. In steady state the fluctuation level in the edge at r/a ≈ 0.6 to 0.9 and at r/a = 0.2 to 0.4 at $k_\theta = 3.7\ cm^{-1}$ is high when the current is low and low when the current is high. During and after the ramp, fluctuation levels are unchanged and the transport is also unchanged for the duration of the beams.

Measurements from BES have shown that poloidal and radial correlation lengths, L_c, in the confinement zone of L-mode plasmas fall in the range 1 to 2 cm and correlation times, τ_c, in the range 10 to 100 µs. A simple estimate of the diffusion based on $D \approx L_c^2/\tau_c$ shows good agreement with power balance measurements. Estimates of the Kubo number, $K \equiv v_{E\times B}\tau_c/L_c \approx (cT_e/eB_\phi)(\delta n/n)/(L_c^2/\tau_c)$, are of order 0.1 to 0.3 which implies that the decorrelation time is smaller than the eddy turn over time. In this regime one theoretically[15] expects the diffusivity to be $K^2(L_c^2/\tau_c)$, but this is inconsistent with power balance measurements.

Fig. 4 shows a similar estimate of the radial coherence length from reflectometry which gives about 2 cm for low density ohmic plasma. In moderately heated L-mode and supershot plasmas the coherence at even the smallest separations is strongly reduced except at occasional well defined frequencies where modes can have coherence lengths of several tens of centimeters. The cause of this reduction is currently under investigation. In supershot plasmas the coherence at 2 mm separation is about 0.5 under optimal conditions in the range 10 to 20 kHz. At r/a ≈ 0.5 the coherence falls off to 0.25 in about 1.5 cm. If there is a source of incoherent noise added to the system reducing the maximum coherence at all scale lengths uniformly, then one may infer that the coherence length in this case is approximately 1.5 cm. BES measurements in a similar supershot plasma at r/a = 0.55 gives a correlation length of 1.7±0.2 cm. However, the calculation of correlation times and the

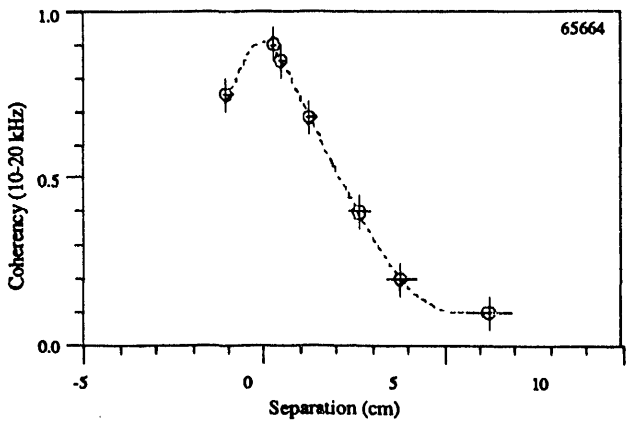

Fig. 4 Coherence versus separation at r/a = 0.5 for 10-20 kHz measured by reflectometry

transformation of coherence to correlation lengths are sensitive to plasma rotation and are not yet complete.

Calculations of the growth rate of linear trapped ion and ion-temperature-gradient drift modes with comprehensive toroidal codes[16,17] indicate that the most unstable values of k for comparable L-mode discharge have $k_\theta \rho_i \approx 0.3$ to 0.5 and ballooning structures extending smoothly across many rational surfaces. These trends are consistent with the present measurements.

Values of $\delta n/n$ measured by scattering, BES, and reflectometry in L-mode discharges for $r/a \approx 0.5$ and 5 to 15 MW is in the range 0.2 to 1.0% which is typically at or below the mixing length estimate of $1/\langle k_\perp \rangle L_n$. Scattering estimates assume 2D isotropic turbulence cut off at $k_\perp = 3\ cm^{-1}$ with spatial resolution of about 40 cm at the lowest k while BES and reflectometry measurements are sensitive to the range $k < 1.5\ cm^{-1}$ with a spatial resolution of about 2 cm at the highest values of k. Reflectometry estimates of $\delta n/n$ in the ohmic regime are typically 0.1% or less while scattering gives $\delta n/n \approx 0.2$ to 0.5% in similar plasmas. The origin of this discrepancy is still not understood.

4. CONCLUSION

Broad band density fluctuations in the confinement zone of TFTR suggest a relationship between these fluctuations and energy transport from power balance measurements. In L-mode plasmas scattering and BES show that the relative level of δn^2 in the confinement zone for $k_\perp \rho_s \approx 0.2$ to 1.0 depends qualitatively on P_{aux} and I_p in a way that is consistent with variations in energy transport. Fluctuation levels measured with all systems increase strongly toward the edge in all heating regimes as does the transport. Measurements from BES have shown that poloidal and radial correlation lengths in the confinement zone of L-mode plasmas fall in the range 1 to 2 cm. There is a wave structure in the poloidal direction with $k_{max} \approx 1\ cm^{-1}$ ($k_\perp \rho_s \approx 0.2$) while in the radial direction one has k_{max} approaching zero. Simple estimates of the diffusion based on measured radial correlation lengths and times show good agreement with power balance transport calculations in L-mode plasmas. Reflectometry estimates give radial coherence lengths for low density ohmic and supershot plasmas which are approximately 1 to 2 cm.

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