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Experimental Investigations of Plasma Turbulence Suppression in the DIII-D Tokamak

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Abstract

Reducing turbulence has been shown to improve confinement under a variety of plasma operational modes. Turbulence measurements during the formation of internal transport barriers in plasmas with negative central magnetic shear have shown that turbulence-driven fluctuations are dramatically reduced inside the barrier while energy transport is also reduced. This is consistent with the $\boldsymbol{E} \times \boldsymbol{B}$ shearing model of turbulence suppression during formation of an internal transport barrier. A complementary path to turbulence suppression is suggested by recent experiments in which impurities are puffed into a quiescent L-mode discharge. Turbulence is dramatically reduced in response to the impurity puff, and energy confinement increases simultaneously. This behavior is consistent with gyrokinetic simulations which indicate that dilution of the working ions by impurities can reduce growth rates of ion temperature gradient driven turbulence.

Keywords:

turbulence, fluctuations, internal transport barrier, flow shear, suppression, impurity effects

1. Introduction

Anomalous cross-field transport, observed in most magnetically confined plasmas, reduces energy and particle confinement from that which would be obtained if transport were driven solely by neoclassical collisional processes. Plasma turbulence is widely believed to be responsible for this anomalous transport. Turbulence and the resulting electrostatic fluctuations induce an anomalous flux, $\Gamma = \langle \tilde{n}\tilde{v}_r \rangle$ that can be described by a diffusive transport coefficient that is often orders of magnitude above the neoclassical values. Recent advances in experimental methods and applications of new techniques have demonstrated the ability to suppress plasma turbulence and thereby reduce transport and improve confinement.

The $\boldsymbol{E} \times \boldsymbol{B}$ shearing model [1] successfully explains the suppression of turbulence in a wide variety of plasma modes. In this model, a radial electric field is formed through a core charge imbalance generated by a combination of tangential and poloidal plasma rotation as well as the plasma pressure gradient. Radial shear in the radial electric field, $\mathrm{d}E_r/\mathrm{d}r$, results in sheared poloidal flows,

$$v_\theta = \frac{\boldsymbol{E}_r \times \boldsymbol{B}_\mathrm{T}}{B^2},$$

that alter turbulence through two mechanisms: turbulent eddies are sheared apart by the poloidally varying flow

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velocity, reducing their amplitude, and density and potential fluctuations are decorrelated by a change in the phase angle between density and potential fluctuations [2]. This is formalized by writing the shearing rate,

$$\omega_{E\times B} = \frac{\left(RB_\theta\right)^2}{B}\frac{\mathrm{d}}{\mathrm{d}\psi}\left(\frac{E_r}{RB_\theta}\right)$$

[3]. It has been shown [4] that as the shearing rate becomes comparable to or greater than the growth rate of the largest unstable drift wave modes, the turbulence is suppressed or eliminated and transport is reduced.

Turbulence manifests itself as fluctuations in plasma parameters such as the density, electrostatic potential, temperature, and magnetic fields. The development of advanced plasma diagnostics has allowed for the direct measurement of fluctuations in some of these quantities and is providing a more detailed understanding of the nature and behavior of turbulence in magnetically confined plasmas. Results presented here incorporate measurements obtained with the Beam Emission Spectroscopy (BES) diagnostic on the DIII-D tokamak [5]. BES observes density fluctuations in the wavenumber range $k \leq 3$ cm^{-1} where modes that drive most of the anomalous ion transport are believed to be dominant.

The development of advanced operational regimes in tokamaks has been shown to dramatically alter the underlying plasma turbulence and thereby affect and often reduce the transport in these plasmas. Plasmas with negative central magnetic shear on DIII-D, TFTR, JT-60U, JET and other tokamaks exhibit regions of significantly reduced or completely eliminated turbulence with the resulting transport in the ion channel at or near the neoclassical level, the irreducible minimum of collisionally induced transport. Electron transport is typically still anomalously large though some discharges have been produced in JT-60U [6] and DIII-D [7] with reduced electron transport as well.

2. Transport Barrier Turbulence Dynamics

Internal transport barriers are reproducibly generated in L-mode plasmas in DIII-D using the technique of early neutral beam injection to increase the electron temperature, slowing penetration of ohmic flux. This produces an inverted safety factor, q, profile with negative central magnetic shear which facilitates production of an internal transport barrier [8,9]. The mechanism is believed to be that magnetic shear stabilizes Kelvin-Helmholtz instabilities which in turn allows for poloidal rotational shear to develop and suppress turbulence through decorrelation and eddy shearing [1]. Measurements of fluctuations in such plasmas are broadly consistent with the thesis that turbulence is suppressed by $\boldsymbol{E} \times \boldsymbol{B}$ shear. Measurements with far infrared scattering [10], which observes density fluctuations over the central region of the plasma, show a sharp reduction in fluctuations as an internal transport barrier developes, along with an increase in the average lab-frame frequency of the fluctuations, indicating an increase in the core rotation velocity of the plasma [11].

Spatially localized measurements of density fluctuations obtained with BES, shown in Fig. 1, demonstrate that long-wavelength density fluctuations are significantly reduced deeper in the core of the plasma, while outside of a given radius, there is little change in fluctuation level. The integrated broad-band density fluctuation amplitude ($\tilde{n}/n$) is plotted here. This suggests that the transport barrier is very localized radially since the spatial region graphed covers just the radial range from ρ = 0.63–0.76. Inside of about ρ = 0.65, the fluctuations drop by a factor of two to three after formation of the internal transport barrier. The density is gradually drifting upwards over this time frame and changes by less than 30% over the time range observed, so the reduction results primarily from a drop in ñ. The emission intensity fluctuation spectrum is shown in Fig. 2 before and after barrier formation in a similar discharge. It is seen that the overall level (integrated power) of the fluctuations are significantly reduced after barrier formation. In addition, the average frequency of the fluctuations increases from 135 KHz to

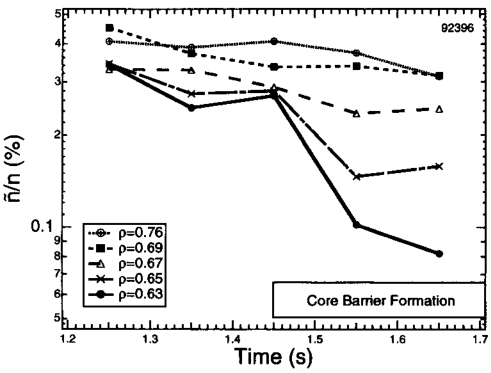

Fig. 1 Fluctuation amplitude at several spatial locations before and after the formation of a core transport barrier showing rapid drop in turbulence inside of ρ = 0.65. Outside of the region, there is little change in the fluctuation amplitude. Broadband density fluctuations are integrated over the range 80 to 350 KHz.

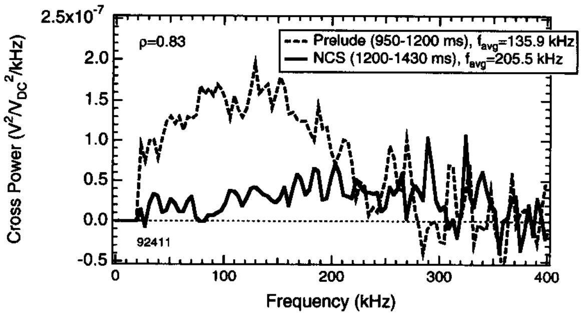

Fig. 2 Broadband density fluctuation spectrum before and after the formation of an internal transport barrier showing the reduction in amplitude due to the barrier formation and increase in the average frequency from the increasing doppler shift.

over 200 KHz owing to an increase in the plasma rotation velocity and the resulting doppler shift as the transport barrier evolves.

The fluctuation amplitude is compared in two discharges with similar prelude phases (prior to the transport barrier formation) and different neutral beam power steps. Both discharges start with two beam sources, with one stepping up to three sources, the other to four sources. Fluctuations are most dramatically suppressed in the higher power discharge, shown in Fig. 3(a), consistent with ideas of shear stabilization. The higher power discharge transiently exhibits almost complete suppression of turbulence at the observed radius of $\rho = 0.6$. Subsequently, the fluctuations increase again as the pressure gradients increase owing to the reduced transport. This can be explained by a larger $\boldsymbol{E} \times \boldsymbol{B}$ shear in the higher beam power plasma. The force balance from which the radial electric field is derived,

$$E_r = \frac{\nabla P}{n_i Z_i e} + v_{\varphi,i} B_\theta - v_{\theta,i} B_\phi \,, \tag{1}$$

is typically dominated by the tangential rotation term, $v_\varphi B_\theta$, due to the all co-injection neutral beam system on DIII-D. Thus faster rotation will generally yield a higher electric field and typically, though not necessarily, the $\omega_{E\times B}$ shearing rate is also higher. The pressure gradient, which is a primary turbulence drive mechanism, shown in Fig. 3(b), increases monotonically throughout this period of the discharge. The shearing rate, also shown in Fig. 3(b) also tends to increase. The pressure gradient itself contributes to reducing the radial electric field, but in the these discharges has a minor effect compared with the much larger tangential rotation term. These results, in combination with the fluctuation measurements indicate that at least transiently, the increasing shearing rate dominates the increasing pressure gradient to suppress turbulence.

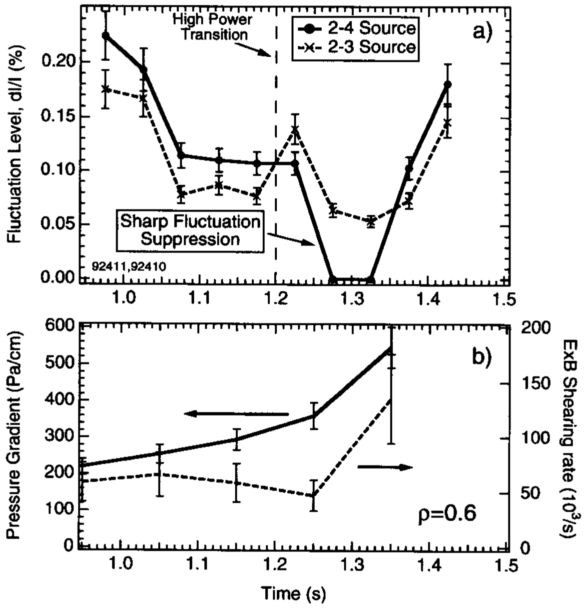

Fig. 3 (a) Comparison of the fluctuation amplitude in two discharges at ρ = 0.6 with initially similar conditions, one with a two to three source transition, and one with a two to four source transition. (b) Pressure gradient and E × B shearing rate evolution at the same minor radius.

3. Impurity Effects on Turbulence

Recent experiments have suggested that impurities may aid achieving improved confinement in tokamak plasmas. In particular, TEXTOR-94 [12], TFTR [13] and DIII-D [14] have demonstrated improved energy confinement in plasmas seeded with small quantities of impurities, e.g., neon, argon, krypton or xenon. The physical mechanism is not well understood but, based on observations from recent experiments and turbulent transport simulations, may be related to the suppression of turbulence as a result of the injected impurity. Probe measurements in TEXTOR-94 have shown reduced turbulent driven transport in the edge region of a neon-seeded discharge [15].

Initial experiments on DIII-D to examine this Radiative-Improved (RI) mode have been performed and fluctuations have been measured with BES. The effect of neon on integrated density fluctuations is shown in Fig. 4(a). A pair of discharges are compared with nearly identical control parameters (beam power, plasma current, density), while neon was injected at 800 ms in one discharge and not in the reference discharge. The time evolution of the fluctuation amplitude shows that there is a sharp reduction in turbulence starting about 100 ms after the neon injection. Prior to neon injection, the fluctuations levels are nearly the same, as would be expected since the discharges are very similar at this point. At 1.0 s, an additional neutral beam is injected, reducing the fluctuation levels, likely for reasons discussed in Section 2. The reduction in turbulence after neon injection is correlated with an increase in the energy confinement time as well as central electron pressure and neutron rate [16]. The stored energy for the two discharges is shown in Fig. 4(b). The discharge with neon injection exhibits a rapid increase in radiated power (not shown), to nearly double the radiated power in the no neon reference discharge, while the total stored energy also increases, indicating that heat transport is reduced.

Gyrokinetic simulations have been performed to help interpret these observations by predicting linear growth rates of the dominant turbulent drift wave modes. Initial results for the pair of shots discussed above suggest that indeed the presence of neon reduces the mode growth rate in a similar region of k-space to the observed fluctuation reduction, namely $0.5 \leq k \leq 3$ cm^{-1} that is dominated by ion temperature gradient and trapped electron modes [17]. It appears that the impurity density gradient acts to reduce the drive of the main ion modes through the η_{imp} parameter, the ratio of the impurity density scale length to the temperature scale length.

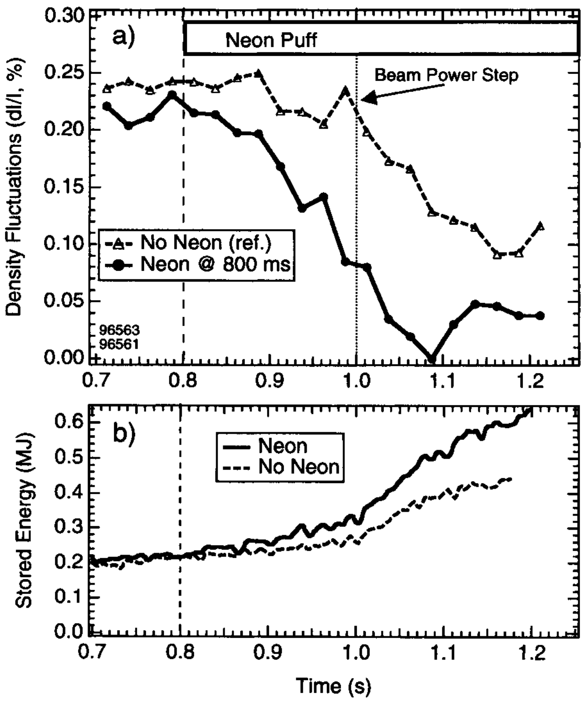

Fig. 4 (a) Density fluctuation amplitude (dI/I) in two discharges, one with neon injection at 0.8 sec, one without neon, demonstrating the suppression of turbulence resulting from the neon puff. At 1.0 sec, the beam power is increased from two to three sources in both discharges, likely accounting for the observed reduction in fluctuations at that time. (b) Comparison of the stored energy in the two discharges discussed, one with neon, one without. The stored energy increases in the neon discharge, indicating a reduction of transport.

The tools and experimental techniques discussed here have allowed for a greater understanding of plasma turbulence and in the process provided methods for influencing and perhaps controlling levels of turbulence in experimental confinement devices and ultimately in reactors. In general, reducing turbulence is desired to reduce cross field anomalous particle and energy transport while improving confinement. Confinement directly impacts reactor economics as a critical parameter in determining the size of a device. Thus, methods to control turbulence levels are crucial to the optimization of reactor scenarios.

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