Scaling of Turbulence Suppression with velocity Shear

J. A. Boedo[1], D. S. Gray[1], P. W. Terry[2], S. Jachmich[3], G. Tynan[1], R. W. Conn[1], and the TEXTOR-94[4] Team.
[1]University of California, San Diego, La Jolla, California, United States of America
[2]University of Wisconsin-Madison, Madison, Wisconsin, United States of America.
[3]ERM/KMS, Brussels, Belgium.
[4]IPP, FZ-Juelich, Juelich, Germany.
[*]e-mail contact of main author: jboedo@ucsd.edu

Abstract. The scaling of turbulence, turbulent particle flux and cross-phase with shear is measured and compared with various analytical theories. It is found that the scaling can be expressed as a second-order polynomial and that the cross-phase plays a key role in the suppression of the particle flux. The variable rate of shear, kept below the value required to produce a Low-to-High particle confinement transition, was obtained by changing, in a shot to shot basis, the voltage applied to an electrode introduced 4 cm into the plasma.

1. Introduction

Tokamak plasmas can undergo transitions from a low energy confinement state (L-mode) to a higher energy confinement state[1] (H-mode) spontaneously. The transition is accompanied by a negative radial electric field inside the last closed flux surface (LCFS) and is characterized by a steepening of the edge profiles or formation of a transport barrier and a fast reduction of the H_α signal, corresponding to increased particle confinement. Similar behavior to the spontaneous L-H transition was obtained in the CCT[2] and TEXTOR[3,4] tokamaks by applying an external radial electric field to the edge plasma[5] with a biased electrode and thus, those experiments suggested that the radial electric field and induced poloidal rotation played a crucial role in the L-H transition. The increase in confinement in the spontaneous H-mode was accompanied by a reduction in turbulence levels in DIII-D[6] and PBX-M[7], and in the electrode generated one in TEXTOR. Thus stabilization of turbulence by $\vec{E} \times \vec{B}$ shear, a general mechanism, was proposed[8] as the underlying cause for overall confinement, hypothesis supported by early work at the TEXT[9] tokamak. Clear correlation between externally applied electric fields and a reduction in turbulence levels, without the gradient influence to cloud the issue, was first shown by our early work[10]. A variety of theories consider the stabilization of turbulence by $\vec{E} \times \vec{B}$ shear by linear stabilization of modes[11,12] or decorrelation of turbulence[13,14] and scalings of the turbulence suppression with velocity shear, $|dv_E/dr|$ were derived for either the strong or weak shear regimes. In the work by Biglari and Diamond[8] above the ensemble of fluid fluctuations normalized to its equilibrium value in a sheared fluid divided by the ensemble in a shear-free fluid, $\Theta \equiv \left\langle \left|\delta\xi\right|^2 \right\rangle / \left\langle \left|\delta\xi\right|^2 \right\rangle_0$, is related to the shearing rate, ω_s, and the turbulent decorrelation time, $\Delta\omega_t$, by:

$$\frac{\left\langle \left|\delta\xi\right|^2 \right\rangle}{\left\langle \left|\delta\xi\right|^2 \right\rangle_0} \approx \left(\Delta\omega_t/\omega_s\right)^{2/3} < 1 \qquad \textit{Eq. 1}$$

which is an expression valid for the strong shear regime and results in a $|dv_E/dr|^{-2/3}$ dependence while Shaing[15] finds a $|dv_E/dr|^2$ dependence in the weak shear regime. Further work by Zhang and Mahajan[16] aimed to unify and extend the theory, resulting in the relations:

$$\left\langle \hat{k}_\perp^2 \right\rangle \hat{\Theta} = 1 - \frac{4}{3}\left(\frac{|dv_E/dr|t_{c0}}{\alpha\left\langle \hat{k}_\perp^2 \right\rangle^{1-\gamma}}\right)^2 \quad \textit{weak shear}\ \text{limit},\ \textit{scales as Shaing} \qquad Eq.2$$

$$\left\langle \hat{k}_\perp^2 \right\rangle \hat{\Theta} = \left(\frac{\sqrt{3}\,|dv_E/dr|t_{c0}}{\alpha\left\langle \hat{k}_\perp^2 \right\rangle^{1-\gamma}}\right)^{-2/(3-2\gamma)} \quad \textit{strong shear}\ \text{limit}\ \textit{scales as} \begin{Bmatrix} \textit{Biglari for}\ \gamma = 0 \\ V_0^{\prime -2}\ \textit{for}\ \gamma = 1 \end{Bmatrix} \qquad Eq.3$$

$$\left(\left\langle \hat{k}_\perp^2 \right\rangle \hat{\Theta}\right)^{-1} = 1 + 2\left(\frac{|dv_E/dr|t_{c0}}{\alpha}\right)^2 \quad \textit{arbitrary shear}\ (\gamma = 1) \qquad Eq.4$$

where $\left\langle \hat{k}_\perp^2 \right\rangle$ is the ratio of the averaged square of the perpendicular wave number with shear flow to that without shear flow, α measures the anisotropy of the k spectrum and $t_{c0} \equiv \sqrt{2}\left(\left\langle k_\perp^2 \right\rangle D\right)_0$ is the decorrelation time without shear flow that depends on the diffusion coefficient, D, and γ is a parameter between 0 and 1 determining the strength of the turbulent regime (i.e. γ=1 for weak turbulence or γ=0.5 for strong turbulence). Later work by Ware and Terry[17] developed expressions for the response of resistive pressure gradient driven turbulence (RPGDT) to velocity shear in the weak shear limit. This work related the turbulence-driven particle flux, Γ, and density-potential cross-phase, δ, to the velocity shear as follows:

$$\frac{\Gamma\left(|dv_E/dr|\right)}{\Gamma\left(|dv_E/dr| = 0\right)} \approx 1 - 2.1\frac{\left(k_y|dv_E/dr|W_0\right)^2}{\gamma_0^2} \qquad Eq.5$$

$$\cos\delta_k^n \approx 1 - 1.2\frac{\left(k_y|dv_E/dr|W_0\right)^2}{\gamma_0^2} \qquad Eq.6$$

where γ_0 is the dominant mode linear growth rate and W_0 is the unsheared radial mode width. A frequently unnoticed milestone of the Ware-Terry work is that there is a prediction for the cross-phase that, since then, has proven to be a crucial parameter to understand turbulent particle and heat fluxes. It is important to notice that the dependencies on $|dv_E/dr|$ are mostly quadratic or offset quadratic.

In the work presented here, the thin, (δr=1.5 cm) rotating $\vec{E}\times\vec{B}$ shear layer induced by the electrode is characterized with high-spatial resolution and correlated to the profiles of absolute and normalized turbulent quantities, including the turbulence-driven radial particle flux. It is found that the amplitude of the fluctuations is reduced in the sheared layer and that fact, coupled to changes in the cross-phase results in reduced turbulent transport and improved confinement. It is also found that relatively low shearing rates are sufficient to affect the fluctuations and a scaling with shear is produced that is compared to existing analytical theories.

2. Description of Experiments

These experiments were performed in ohmic (OH) plasmas with toroidal magnetic field B_t=2.25 T, plasma current Ip=200 kA and chord-averaged density $\bar{n}_{e0}$=1.0E13 cm-3. The discharge was tailored to reduce the heat flux to the electrode. The electrode is mushroom-shaped and built of graphite composites 1.5 cm thick and 10 cm in diameter, which is introduced to a radius of 41 cm as described in previous work[7]. The ALT-II toroidal belt limiter[18] is nominally located at 46cm. The data were obtained using two fast reciprocating probe arrays[19] featuring five 1.2 mm long tips. The main reciprocating probe is located at the outer midplane of the tokamak and the second probe is at the top. TEXTOR edge plasmas are toroidally symmetric due to the ALT-II belt limiter[20]. The data for the turbulent measurements is digitized at 1 MHz with a 10 bit digitizer and filtered by low pass 500 kHz anti-aliasing filters. We find that the power spectrum decays very quickly with frequency and is significant only to up to 250 kHz, thus a bandwidth of at least 500 kHz is desirable for turbulence measurements.

The electrode voltage is applied to the electrode as a 100 ms linear ramp starting at 1s and then held constant for 1.5 s, as shown in Fig. 1-e, and was varied in 50 or 100 V steps in a shot to shot basis as shown in Fig 1-g. The electrode current increases linearly and then remains constant (Fig. 1-e) while the density stays constant or shows weak signs of an increase (Fig. 1-d) at higher voltages. The discharge is in stationary state as shown in Figs. 1-c and 1-d. The probe enters the plasma at t=1.6 s (Fig.1-a), sampling the shear layer, as evidenced by the increase in the floating potential (Fig. 1-b). The radial electric field increases with voltage featuring a narrow profile that is determined by the radial conductivity[5] and eventually bifurcates reaching a maximum value of ~500 V/cm and producing a L-H transition, as discussed in detail in our previous work[10,5,21].

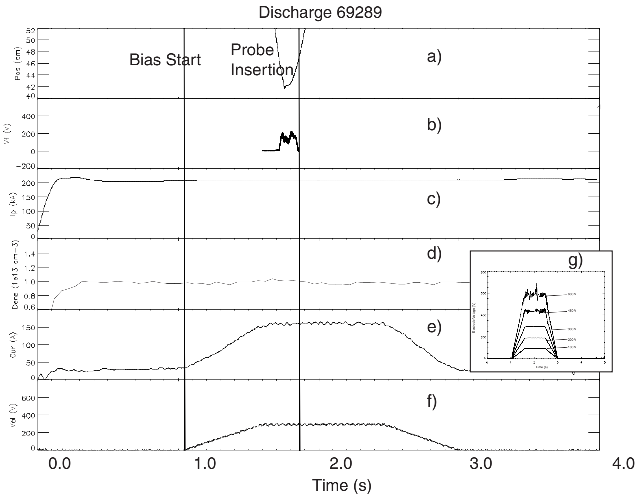

Figure 1: *Time evolution of a TEXTOR discharge showing the electrode bias pulse and the stable plasma conditions.*

3. Results and Discussion

The density profiles, labeled by the voltage applied to the electrode, plotted in Fig. 2-b show the effect of the shear as a slight modification, but no bifurcation behavior, such a dramatic steepening are seen under these conditions. Thus it can be argued that the experimental conditions are almost ideal since the profile changes do not play a major role. The poloidal velocity profiles are directly inferred from the E_r profile as it was proven in previous work[21] that the plasma velocity and the ExB velocity are equal. The velocity is shown in Fig. 2-b and the velocity peaks are marked for reference. The velocity profiles show negative and positive shear and an average shear is calculated over each region.

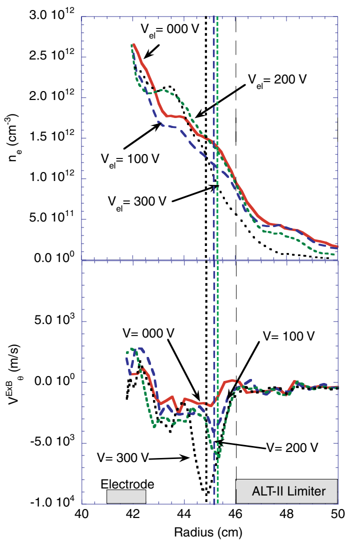

Figure 2: *Radial profiles of a) the ExB velocity and b) density. Although the profiles are perturbed due to the weak shear no L-H transition has yet occurred and the profiles are very similar.*

The turbulent plasma parameter profiles obtained by the probe are averaged in the positive and negative velocity shear regions to obtain a point per each applied voltage. The turbulence data is then plotted against the average velocity shear over the aforementioned regions. The normalized particle flux (Figs. 3 a,d), Cross-phase (Figs. 3 b,e) and normalized density (Figs. 3 c,f) are plotted against shearing rate for positive (Figs. 3 a-c) and negative (Figs.3 d-f) shear. Notice that the density is normalized *ala* Biglari-Diamond whereas the particle flux and angle are normalized *ala* Ware-Terry.

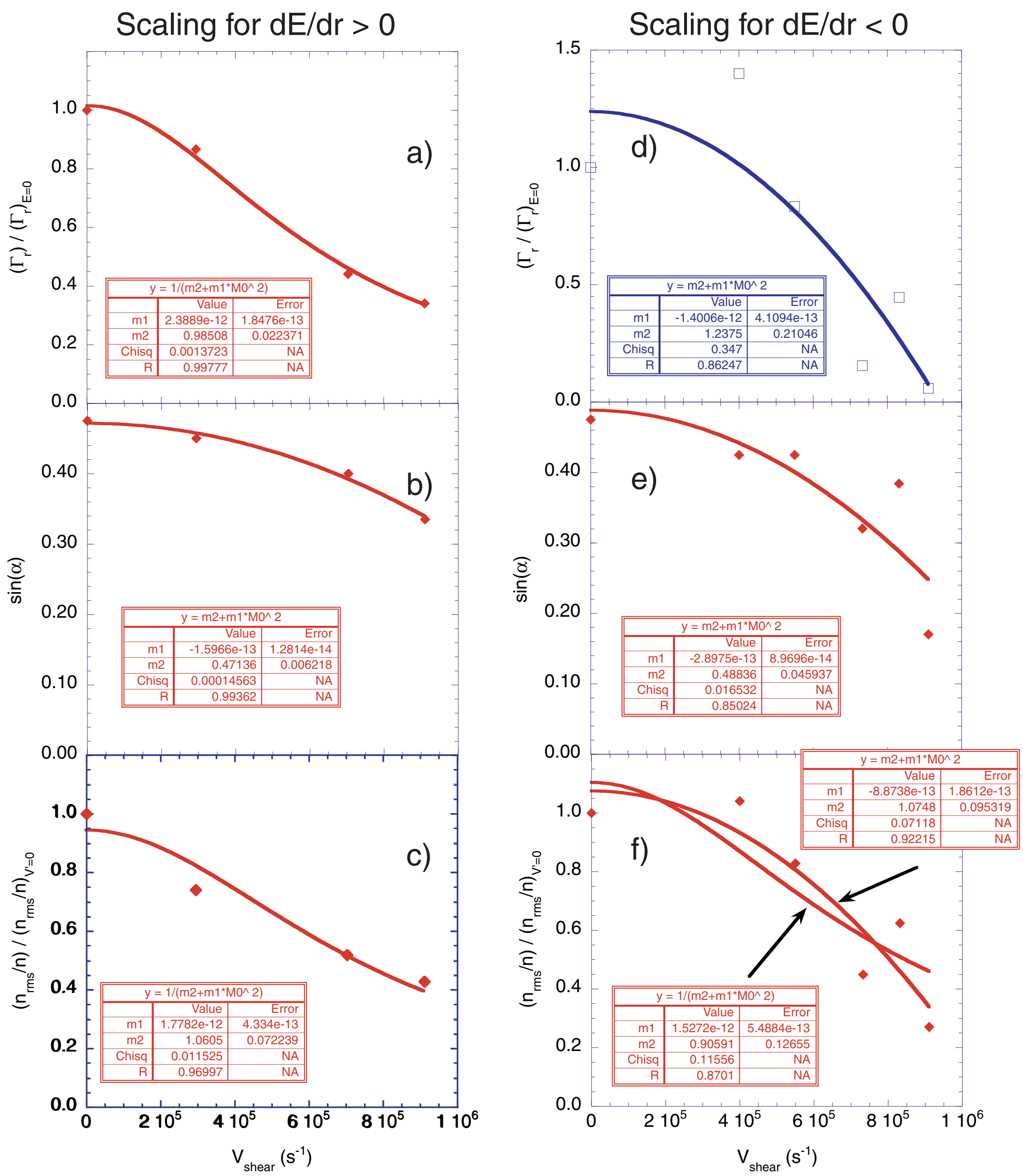

Figure 3: *Scalingss of a),d) turbulent particle flux, b),e) cross-phase and c),f) normalized density fluctuations vs shear rate. The best functional fittings and their quality are shown.*

We have performed polynomial fits to the normalized turbulent particle flux, the amplitude of the density and electric field fluctuations and the cross-phase between them. It is found that the best fits have a strong quadratic component as predicted by most of the theories considered here. A clear difference was found in the scaling of the data according to the sign of the velocity shear. A functional dependence of the form $f = c1 - c2 * V_{Shear}^2$ fits best the results from the region where dE/dr<0 (Figs. 3d-f) and consequently agrees with the forms proposed by Ware-Terry (Eqs. 5 and 6) and the Zhang-Mahajan expression for weak shear in Eq. 2 (which also agrees with Shaing's proposal). In the region where dE/dr>0 (Figs. 3a-c), a functional dependence of the form $f = 1/(c1 + c2 * V_{Shear}^2)$ fits best the flux and normalized density fluctuations data in agreement with the form proposed by Zhang-Mahajan (Eq. 4) for arbitrary shear and weak turbulence. The cross-phase is best fitted by $f = c1 - c2 * V_{Shear}^2$ in agreement with Ware-Terry and the weak shear limit of Zhang-Mahajan. Two additional results should be noted: Firstly, that there is a difference in the magnitude and scalings of the turbulence, flux and cross-phase between the positive and negative shear regions, an effect not included in the theories, which are phase-sign blind. Secondly, that the phase shows a strong variation with shearing rate, in agreement with previous findings[21] that the cross-phase becomes a dominant element in the flux at high shear.

In general, the theories proposing a scaling that makes the amplitudes drop roughly as $|dv_E/dr|^2$ seem to reproduce the data. It can be argued that a functional form that forces a fast drop to zero is preferable but the dominance of the cross-phase can make that requirement unnecessary. The observed dependence on the sign of the shear could be a curvature effect.

4. **Conclusions**

In general, good agreement is found with the Shaing, Ware-Terry and Zhang-Mahajan theories based on their quadratic prediction. A function of the form $f = c1 - c2 * V_{Shear}^2$ fits best the results obtained for the dE/dr <0 region, as predicted by Ware-Terry, whereas a function of the form $f = 1/(c1 + c2 * V_{Shear}^2)$, as given by Zhang-Mahajan, produces the best results for the dE/dr >0 region ***except*** for the cross-phase. The cross-phase shows a strong dependence on shear and therefore it should be considered intently by theoriticians. The existing theories are blind to the sign of the shear and it is not clear if curvature effects could play a role.

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6. **References**

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