Evidence for Confinement Improvement by Velocity-Shear Suppression of Edge Turbulence

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The electrostatic fluctuations are decorrelated in the region of a naturally occurring $\mathbf{E}_r \times \mathbf{B}$ velocity shear close to the outermost closed flux surface of regular Ohmic TEXT discharges. The concomitant local steepening of the density profile and suppression of the fluctuations are consistent with theoretical predictions. The high-confinement mode (H mode) found in other tokamaks shows in exaggerated form similar characteristics and could thus be related to the same mechanism leading to a locally improved confinement.

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Quantitative comparisons on the TEXT tokamak demonstrate that electrostatic fluctuations are a major cause of the anomalous particle and energy transport[1] in Ohmic discharges as suggested previously by other experiments.[2,3] In addition, a radial electric field E_r has been shown to modify the global confinement[4] as well as the edge turbulence and electrostatic-fluctuation-induced transport.[2,5] Most recently a series of experiments has been conducted on the Constant Current Tokamak (CCT) using a highly biased emissive electrode.[6] The biasing triggered a transition to a regime with the characteristics of the high-confinement mode (H-mode regime first reported on ASDEX[7]), which is one of the most successful paths to improve the plasma confinement in tokamaks. Associated with the transition on CCT was a measured increase in E_r, and thus in the rotation velocity $\mathbf{v}_E \equiv \mathbf{v}_{\mathbf{E}_r \times \mathbf{B}}$. Such changes in E_r have also been observed on DIII-D, a large tokamak, at the transition to the H mode.[8] Since the physics of H modes is not well understood, this is a motivation for further experimental studies.

The above experiments suggest that one possible mechanism for improved confinement is a change in the edge electric field, and concomitant change in the $\mathbf{E} \times \mathbf{B}$ rotation velocity v_E and the fluctuation levels. Theoretical work[9-14] shows that, if changes in radial electric field result in an angular-velocity shear, then turbulence can be reduced leading to a decreased outward transport. In this paper we examine the theoretical predictions of turbulence suppression by sheared plasma rotation. Based on results from TEXT we demonstrate a clear correlation between velocity shear, reduction of the turbulence, and local improvement of the confinement.

A velocity shear due to a peaking plasma potential close to the outermost closed flux surface has been characterized on TEXT[15] and other devices.[16,17] The mean velocity of the fluctuations perpendicular to $\mathbf{B}$ measured with a two-point correlation technique in the laboratory frame of reference,

$$v_{\text{ph}} = \sum_{k>0,\omega} [\omega/k_\theta(\omega)] S(k,\omega) \Big/ \sum_{k>0,\omega} S(k,\omega) ,$$

is dominated by $v_E = E_r/B$ effects,[18] as shown in Fig. 1(a), where v_{de} is the diamagnetic drift velocity. (The contribution to v_E from ∇p is thus small and only slowly varying with radius.) The density and floating potential fluctuations, $\tilde{n}$ and $\tilde{\varphi}$, are reduced in a region shifted to larger r/a from the shear region by roughly half the radial shear width, as shown in Fig. 1(b). The mean density is slightly steepened in the region of maximal shear, as

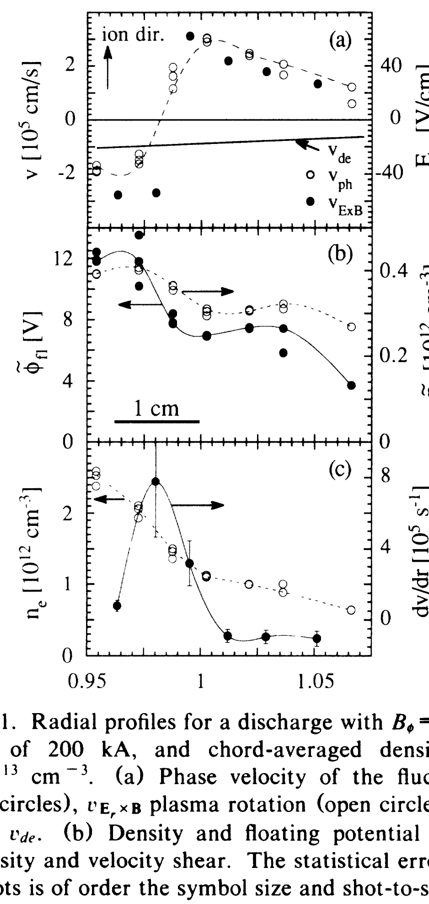

FIG. 1. Radial profiles for a discharge with $B_\phi = 2$ T, plasma current of 200 kA, and chord-averaged density of $n_{\text{chord}} = 2\times10^{13}$ cm^{-3}. (a) Phase velocity of the fluctuations v_{ph} (closed circles), $v_{\mathbf{E}_r\times\mathbf{B}}$ plasma rotation (open circles), and drift velocity v_{de}. (b) Density and floating potential fluctuations. (c) Density and velocity shear. The statistical error for individual shots is of order the symbol size and shot-to-shot reproducibility is given by the individual symbols. The systematic error in the plasma position is 0.5 cm or $r/a \simeq 0.02$.

shown in Fig. 1(c). The steepening is not pronounced, but consistently found on reproducible discharges.

The (one-point) correlation time $\tau_c^{\rm lab}$ of the fluctuations measured in the laboratory frame of reference is obtained from the e-folding time τ of the autocorrelation function $R(\tau,\mathbf{r}) \equiv \langle x(t,\mathbf{r}) x(t+\tau,\mathbf{r})\rangle$. The fluctuation quantity $x(t,\mathbf{r})$ is the ion saturation current (proportional to density) and the angular brackets represent averaging over a temporal interval large compared to τ and ensemble averaging over several realizations. From Fig. 2 we find $\tau_c^{\rm lab} = 10 \pm 1.5$ μs behind the velocity shear ($r/a \simeq 1$), 2 ± 0.4 μs at the location of maximal shear, and 5 ± 1 μs on the bulk plasma side of the shear layer ($r/a \simeq 0.95$).

Similarly we compute the normalized cross-correlation function between two points $\mathbf{r}$ and $\mathbf{r}+\delta\mathbf{r}$,

$$\gamma(\tau,\mathbf{r},\delta\mathbf{r}) \equiv C(\tau,\mathbf{r},\delta\mathbf{r}) / [R(\tau=0,\mathbf{r}) R(\tau=0,\mathbf{r}+\delta\mathbf{r})]^{1/2},$$

where the cross-correlation function is

$$C(\tau,\mathbf{r},\delta\mathbf{r}) \equiv \langle x(t,\mathbf{r}) y(t+\tau,\mathbf{r}+\delta\mathbf{r})\rangle .$$

By varying the Langmuir-probe separation $\delta\mathbf{r}$ we obtain the correlation lengths in the radial, poloidal, and toroidal directions from the separations for which the peak values of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ decrease to $1/e$ of the values at $\delta\mathbf{r}=0$. The resulting correlation lengths on the bulk plasma side of the velocity shear ($r/a = 0.95$) are $\sigma_r \simeq 0.5$ cm, $\sigma_\theta \simeq 1$ cm, and $\sigma_\phi \simeq 100$–200 cm.[19] To study the dependence of the correlation length on the velocity shear we measured the fluctuations simultaneously with an array of four probes separated poloidally and toroidally by a fixed distance of $\delta r = 3$ mm. As shown in Fig. 3 the peak values of the normalized cross-correlation function decrease in the shear layer with respect to the values on either side for both radially and poloidally separated probes. (The decrease is not large since the probe spacing is within a correlation length.) Furthermore, the τ dependences of $\gamma(\tau,\mathbf{r},\delta\mathbf{r})$ in the poloidal and radial directions are similar in the shear layer. The turbulence is thus isotropic perpendicular to the magnetic-field direction, in contrast to the turbulence on either side of the shear layer where the decorrelation is faster in the radial direction than in the poloidal direction, consistent with the correlation-length measurements.

Relating the experimental observations to theoretical models, we can form three groups of questions: (i) What causes the peaking plasma potential leading to the strongly nonuniform electric field? (ii) Can the free energy in the velocity shear drive instabilities? (iii) Can the velocity shear suppress turbulence and thus improve the confinement? The first two questions are only briefly addressed for completeness.

On TEXT the width of the plasma potential peak which is connected with the velocity shear is typically 2 cm and thus approximately of the width of a poloidal ion Larmor radius (banana orbit width) for the hot-ion tail with $\nu^*(v) \leq 1$. The positive peak of the plasma potential causing the nonuniform radial electric field is thus possibly due to a differential orbit loss mechanism at the outermost closed flux surface.[11,20,21] Mechanisms causing a nonambipolar transport may also generate such effects.

For the strong velocity shear measured here, the Kelvin-Helmholtz (KH) instabilities[22] must be examined. The radial extent over which significant fluctuation levels are observed experimentally is much larger than the velocity-shear region. Further the fluctuation level is reduced and not enhanced in the velocity-shear region. Based on these experimental results, the KH instability is not expected to dominate the edge turbulence. A theoretical study also comes to the conclusion that the edge plasma of TEXT is KH stable because of the stabilizing role of the magnetic shear.[9]

Before the velocity shear is sufficient to destabilize KH instabilities it is already capable of reducing the ambient turbulence level due to the fissuring of fluid elements subject to a velocity shear:[12] A *nonuniform* radial electric field ($E_r' = \partial E_r/\partial r \neq 0$) causes in a slab a velocity dif-

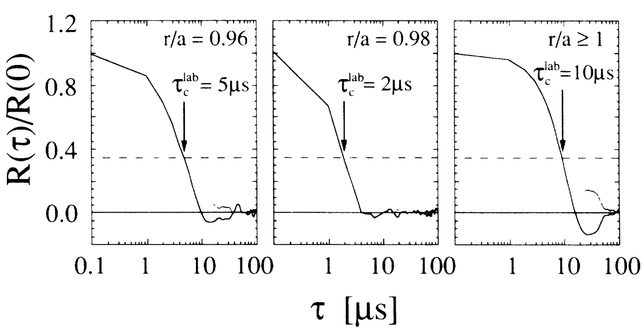

FIG. 2. Normalized one-point correlation function for two positions on either side of the shear layer and in the velocity shear. Dotted curve is the absolute value. Arrow indicates e-folding time $\tau_c^{\rm lab}$.

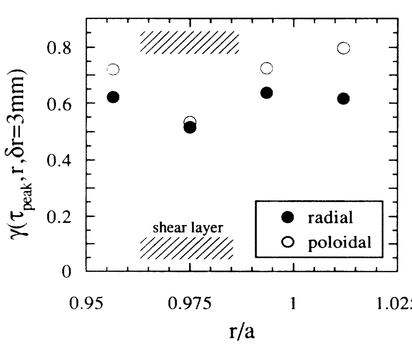

FIG. 3. Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r = 3$ mm.

ference Δv_E over a radially correlated structure of correlation length σ_r of $\Delta v_E = (\partial v_E/\partial r)\sigma_r$. In a cylindrical plasma the relevant quantity is the angular velocity v_E/r, causing a correction to the velocity shear

$$\Delta v_E = r\frac{d(v_E/r)}{dr}\sigma_r = \left(\frac{\partial v_E}{\partial r} - \frac{v_E}{r}\right)\sigma_r .$$

A shear decorrelation time $\tau_{\rm sh}$ can now be defined as the time in which the correlation volume is stretched apart by a correlation length $\sigma_\perp \simeq \sigma_\theta$,[18]

$$\tau_{\rm sh} = \frac{\sigma_\perp}{|\Delta v_E|} = \frac{\sigma_\perp}{\sigma_r}\left(\left|\frac{\partial v_E}{\partial r} - \frac{v_E}{r}\right|\right)^{-1} . \qquad (1)$$

As a special case of Eq. (1), a *constant* radial electric field E_r can also suppress the turbulence in cylindrical or toroidal plasmas due to the non-rigid-body rotation. The resulting decorrelation time is $\tau_E \simeq (\sigma_\perp/\sigma_r)(|v_E/r|)^{-1}$. The distinction between τ_E and $\tau_{\rm sh}$ is useful on TEXT, where E_r' effects dominate the edge while E_r is roughly constant in the interior.

To test if the constant electric field and/or the electric-field shear have an influence on the overall correlation time of the turbulence, we compare the predictions for τ_E and $\tau_{\rm sh}$ using Eq. (1) outside of the velocity-shear region and in the shear region with the measured correlation times at these locations. The shear decorrelation time τ_E is computed from the measured velocity v_E, and $\tau_{\rm sh}$ is obtained from $\partial v_{\rm ph}/\partial r \simeq \partial v_E/\partial r$ and v_E, which are given in Figs. 1(a) and 1(c). For the correlation length of the turbulence without shear we use the measured values from a location in the bulk plasma past the shear layer ($\sigma_r \simeq 0.5$ cm, $\sigma_\perp \simeq \sigma_\theta \simeq 1$ cm at $r/a = 0.95$). We thus assume that the ambient turbulence has the same characteristics in the region of high velocity shear as on either side (i.e., no KH instability effects, but the fluctuation level is weakened by shear flow stabilization). The results are presented in Fig. 4.

The correlation times $\tau_c^{\rm lab}(r)$ from Fig. 2 are shown in Fig. 4 as cross-hatched rectangles. For a comparison with the predicted decorrelation times due to electric-field effects, however, the correlation time τ_c in the frame of reference of the bulk rotation must be computed. The transformation into the moving frame can be neglected where $v_E \simeq 0$ in the region of maximal shear ($\tau_c \simeq \tau_c^{\rm lab}$). Outside of the velocity-shear region the bulk rotation dominates the poloidal propagation, as $v_{\rm ph} \simeq v_E$ [see Fig. 1(a)]. The fluctuations outside of the shear show the behavior of a frozen flow for which the decorrelation time is dominated by the correlation length $\sigma_\perp$ of the structures which are swept by the probes, and not by the temporal decay of the structure, i.e., $\tau_c^{\rm lab} \simeq \sigma_\perp / v_E < \tau_c$. The correlation time in the moving frame, τ_c, is thus further increased with respect to $\tau_c^{\rm lab}$. Thus the reduction of τ_c in the shear layer is more pronounced than the reduction of $\tau_c^{\rm lab}$. The correlation time of the turbulence in the absence of the shear flow can also be estimated from the diffusive decorrelation time τ_D, where $\tau_c = \tau_D \simeq \sigma_r^2/D = \sigma_r^2 \nabla n/\Gamma \simeq 5$–$10$ μs and the diffusion coefficient D is determined from the locally measured particle flux Γ and the density gradient.

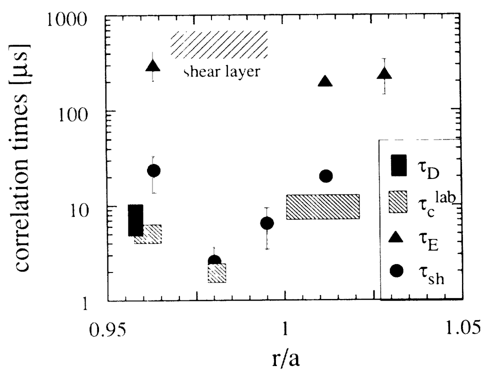

FIG. 4. Turbulent decorrelation times due to a constant radial electric field, τ_E, and due to the nonuniform electric field, $\tau_{\rm sh}$, compared with the autocorrelation time of the fluctuations, $\tau_c^{\rm lab}$ (dashed area indicates confidence limit). Also shown is the diffusive correlation time $\tau_D \simeq \tau_c$.

From Fig. 4 we find that the shear decorrelation time $\tau_{\rm sh}$ dominates the decorrelation time due to a constant radial electric field, τ_E, in the velocity shear layer. The value predicted for the shear decorrelation $\tau_{\rm sh}$ is comparable to the measured decorrelation time τ_c in the shear region. Further, the measured decorrelation in the shear region, shown in Fig 3, is consistent with the theoretical prediction,[12] $\sigma_r^{\rm sh}/\sigma_r^{\rm amb} \simeq (\tau_{\rm sh}/\tau_D)^{1/3} \simeq 0.8$, as well as is the more isotropic characteristics of the turbulence in this region.

In conclusion, we find evidence that the fluctuations and consequently the turbulent transport mechanisms are locally reduced due to the naturally occurring $\mathbf{E}_r \times \mathbf{B}$ velocity shear in the edge of the TEXT tokamak. This is manifested by a reduced radial and poloidal correlation time, a diminished fluctuation level, and a steeper density gradient than on either side of the shear layer. The casual relationship between E_r, velocity shear, gradient steepening, and fluctuation reduction is verified by applying a stochastic magnetic field[23] to the edge region. This results in a modified edge plasma potential profile and thus a reduced or entirely suppressed velocity-shear layer close to the outermost closed flux surface depending on the level of the perturbation (while a new maximum in the potential forms further into the interior). For larger stochastic fields no dip in the fluctuations is seen.[24] The reduction of the turbulence by shear decorrelation and the isotropic behavior of the turbulence perpendicular to the magnetic field are consistent with theoretical models.[12] A reduction of the fluctuation level in the interior of the plasma by a constant radial electric field[11,12] may be possible, but is not investigated here.

The effects of the turbulent decorrelation on the fluctuation level cannot be very strong in a steady-state situation: Since particle and energy balance must hold, the particle and energy fluxes must remain approximately unchanged through the narrow shear layer. For fluxes dominated by fluctuations, the profiles readjust (by a local increase of the density and thus of the gradient in the shear layer). Substantial local dips in the fluctuation levels can thus be present only during transients until a new steady-state condition is reached.

The velocity-shear region close to the outermost closed flux surface of normal Ohmic discharges on TEXT shows many signatures also found in H modes. The H-mode regime is characterized by a substantial steepening of the edge density and temperature profiles near the outermost closed magnetic flux surface. Recent results from DIII-D show a dramatic increase in the poloidal plasma mass rotation at the transition to the H regime in a layer just inside of the separatrix.[8] This velocity increase cannot be explained by a change of the pressure gradient (v_{de}) alone and thus implies a substantial increase in the radial electric field. In addition, the fluctuation levels are substantially decreased in a narrow layer of a few centimeters width in the vicinity of the separatrix.[17] We can thus speculate that H modes may be an exaggerated representation of the same physical mechanism observed on TEXT, but caused by a much larger poloidal rotation velocity and velocity shear than in Ohmic discharges.

Several other experimental methods have been reported to actively modify the plasma potential, the rotation velocity, and/or the confinement in the edge plasma, such as biased limiters and divertor plates,[2,25] internal electrodes,[4-6] field-line perturbations,[23] neutral beams,[26] and electromagnetic waves.[27] A detailed investigation of such experiments may provide additional means to study the role of plasma rotation on the confinement.

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