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TURBULENT FLUCTUATIONS IN THE MAIN CORE OF TFTR PLASMAS WITH NEGATIVE MAGNETIC SHEAR

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Abstract

TURBULENT FLUCTUATIONS IN THE MAIN CORE OF TFTR PLASMAS WITH NEGATIVE MAGNETIC SHEAR.

Turbulent fluctuations in plasmas with reversed magnetic shear have been investigated in TFTR. Under intense auxiliary heating, these plasmas are observed to bifurcate into two states with different transport properties. In the state with better confinement, it has been found that the level of fluctuations is very small throughout most of the region with negative shear. By contrast, the state with lower confinement is characterized by large bursts of fluctuations which suggest a competition between the driving and the suppression of turbulence. These results are consistent with the suppression of turbulence by the $E \times B$ velocity shear.

1. Introduction

Recent results [1-4] point to the beneficial effects of negative magnetic shear on plasma performance in tokamaks. In these experiments, magnetic configurations with a non-monotonic safety factor q have been obtained using a variety of techniques. The common result is a strong peaking of the pressure profile, which indicates a reduction of plasma transport in the central region with negative shear. Since short scale turbulence is considered to be the source of anomalous losses in tokamaks, these results appear to be consistent with theoretical predictions that negative shear can suppress geodesic curvature driven instabilities, such as trapped particle modes [5], the toroidal ion temperature gradient mode [6], and high-n ballooning modes [7].

In order to study the effects of negative magnetic shear on plasma turbulence in tokamaks, we have conducted an experimental study of turbulent fluctuations in plasmas with reversed magnetic shear on the Tokamak Fusion Test Reactor (TFTR) [8]. These are deuterium plasmas with a major radius R=2.6 m, a minor radius

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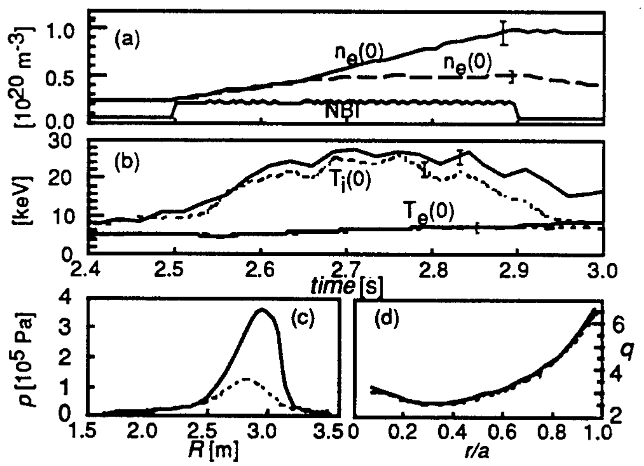

FIG. 1. Time evolution of central electron density (a) and of temperatures (b) in ERS (solid line) and RS (dashed line) plasmas with 29 and 27 MW of balanced NBI, respectively. The bottom graphs show the radial profile of the plasma pressure (c) at t=2.9 s and the safety factor (d) at the bifurcation time.

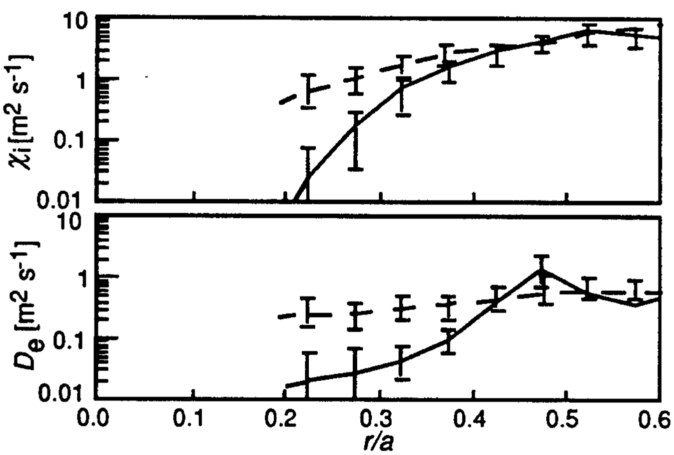

FIG. 2. Ion thermal conductivity (χ_i) and electron particle diffusivity (D_e) in the ERS (solid line) and RS (dashed line) plasmas of Fig. 1 (t=2.75 s).

a=0.94 m, a toroidal magnetic field B=4.6 T, and a plasma current I_p=1.6 MA. The central plasma region with negative shear is created early in the discharge by a combination of heating and current drive. Under intense auxiliary heating with neutral beam injection (NBI), these plasmas are observed to bifurcate into two different states [3], the reversed shear (RS) and the enhanced reversed shear (ERS) mode (Fig. 1). While the RS mode is similar to the *supershot regime* which is normally observed in TFTR with monotonic q-profiles, the ERS mode is characterized by highly peaked

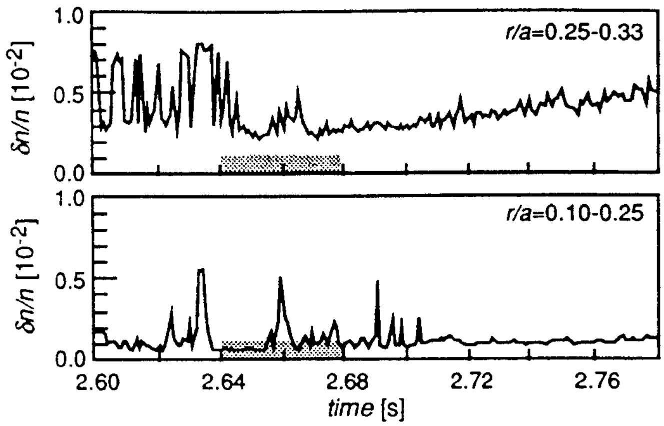

FIG. 3. Time evolution of density fluctuations in the ERS mode. The shaded area represents the time of bifurcation.

density and plasma pressure profiles (Fig. 1). Since at the time of bifurcation the q-profiles are very similar in the two regimes, the observed phenomenon cannot be ascribed solely to the negative magnetic shear.

A transport analysis, ignoring particle pinches, shows a greatly reduced plasma transport in the ERS mode (Fig. 2). In particular, the precipitous drop of the ion thermal conductivity inside the reversed shear region to values below those of conventional neoclassical theory [3] reveals the formation of a transport barrier.

2. Turbulent Fluctuations

Short scale turbulent fluctuations have been studied with X-mode microwave reflectometry in the frequency range 123-142 GHz [9]. Figure 3 shows the time evolution of density fluctuations at two radial locations inside the negative shear region of an ERS plasma. From these results, it appears that large bursts of turbulence, initially present in the discharge, disappear after the transition into the ERS mode.

By using the displacement of the reflecting point of the probing wave, caused by the plasma density rise, we get the amplitude of density fluctuations shown in Fig. 4 as a function of the normalized minor radius r/a. The abscissas in this figure are the

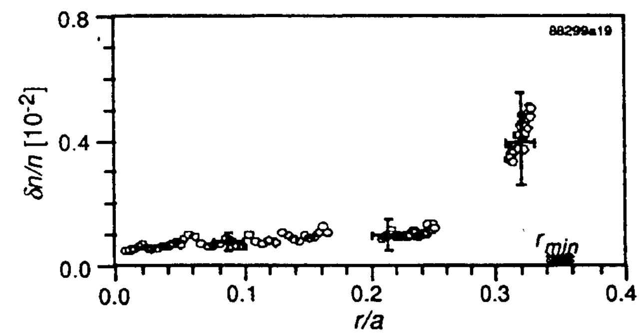

FIG. 4. Amplitude of density fluctuations in the ERS mode of Fig. 1 at t=2.72-2.78 s; r_{min} is the radial position with minimum q.

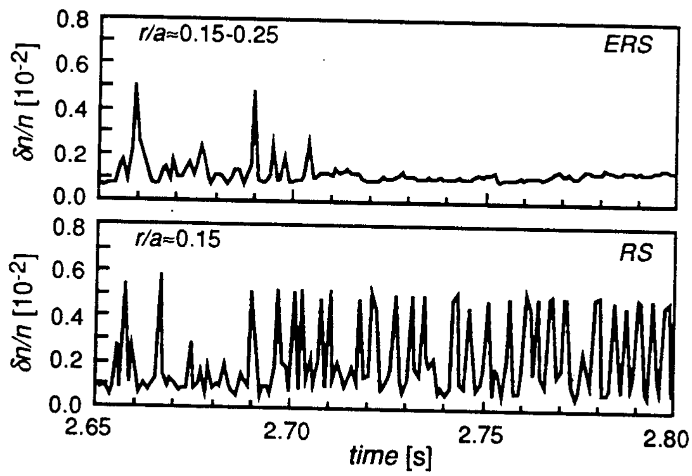

FIG. 5. Time evolution of density fluctuations in ERS and RS modes.

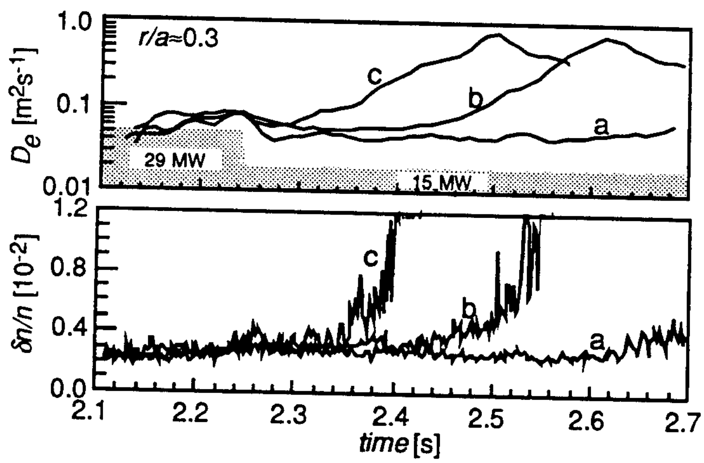

FIG. 6. Electron particle diffusivity and amplitude of density fluctuations at $r/a \approx 0.3$. a: Balanced injection; b: co/counter=5/1; c: co/counter=6/0.

calculated positions of the reflecting cutoff on the low field side of the equatorial plane, including a relativistic correction [10] which ranges from 2 to 6 cm. As described elsewhere [9], to obtain the amplitude of density fluctuations from reflectometry measurements requires the knowledge of the shape of the radial spectrum of fluctuations. Unfortunately, in the rapidly evolving plasmas of the present experiment, this is difficult to obtain with radial correlation measurements. Fortunately, all previous theoretical and experimental studies of short scale fluctuations in large tokamaks indicate that the bulk of the turbulent activity occurs at wavelengths larger than the ion Larmor radius (ρi), typically in the range of radial wave numbers $0.2 < k_r \rho_i < 1$. Accordingly, the values in Fig. 3 and 4 have been obtained assuming $k_r = 1$ cm^{-1}, which corresponds to $k_r\rho_i \approx 0.5$, and we have calculated the error bars by taking the extreme values of $k_r\rho_i = 0.2$ and 1, respectively. In spite of these uncertainties, we draw the conclusion that the level of fluctuations is very small in the main core of ERS plasmas, and that it rises near the point where q reaches its minimum value. Both of these phenomena are reminiscent of the radial dependence of the plasma transport coefficients (Fig. 2).

Turbulent fluctuations in the RS mode are substantially different from those in the ERS mode, as illustrated in Fig. 5 which shows the time evolution of the fluctuation amplitude in the middle of the negative shear region. From these data, it appears that bursts of turbulence, reaching the maximum detectable level, persist throughout the entire plasma pulse. Closer to the plasma center (r/a<0.1), this phenomenon disappears and the measured level of fluctuations becomes similar to that in the ERS mode. This indicates that a central quiescent region exists in the RS mode as well, but with a much smaller radial extent than in the ERS mode.

The observed correlation between the decrease in fluctuations and the transition into the ERS mode implies that a surge of turbulence must occur at the back-transition from the ERS to the RS mode. This is indeed what is observed, as illustrated in Fig. 6 which shows the time evolution of the electron particle diffusivity and the level of turbulence across a back-transition. The latter occurs when, for achieving steady state conditions, the NBI power is lowered from 29 to 15 MW. The three cases shown in Fig. 6 differ on the co-counter NBI power ratio. It has been found [11] that, while balanced (case a in Fig. 6) and counter-dominated injection produces plasmas which remain in the ERS mode until the end of NBI, co-dominated injection causes a back-transition into the RS mode (cases b and c in Fig. 6). Figure 6 illustrates very clearly that the loss of ERS confinement, which is represented by the rise in the value of D_e, coincides with a sharp increase in the level of turbulent fluctuations.

3. Discussion

We have compared the experimental observations with the theoretical predictions for toroidal electrostatic drift-type modes. Figure 7 shows the linear growth rate of the most unstable mode (γ) which was calculated with a kinetic toroidal eigenvalue code [12]. Surprisingly, we find the largest values of γ in the ERS mode, which provides further evidence that shear reversal is not the only cause of turbulence suppression in these plasmas. Furthermore, the size of the central stable region is the same in both plasma regimes. These results, which were confirmed by those obtained with a toroidal gyrofluid code [13], demonstrate that other phenomena, besides the reversed shear, play a role in the ERS/RS dynamics.

A possible mechanism for the suppression of turbulence is the decorrelation of turbulent fluctuations by a large **ExB** velocity shear which may exist in regions of large pressure gradient [14-22]. This mechanism, which in the past has been invoked for explaining the reduction in the level of fluctuations at the edge of plasmas in the H-mode [14-18], might also be at work in the central plasma region with negative magnetic shear [19-22]. The numerical simulations in Ref. [19] indicate that turbulence is suppressed when the linear growth satisfies the condition $\gamma \leq \omega_s$, where ω_s is the characteristic **ExB** shearing rate which was derived in Ref. [20]. On the tokamak midplane, we obtain $\omega_s \approx |(RB_\theta / B)\partial(E_r / RB_\theta)/\partial R|$, where B_θ is the poloidal magnetic field, and E_r is the radial electric field. The latter can be obtained from the radial component of the force balance equation, using measured quantities

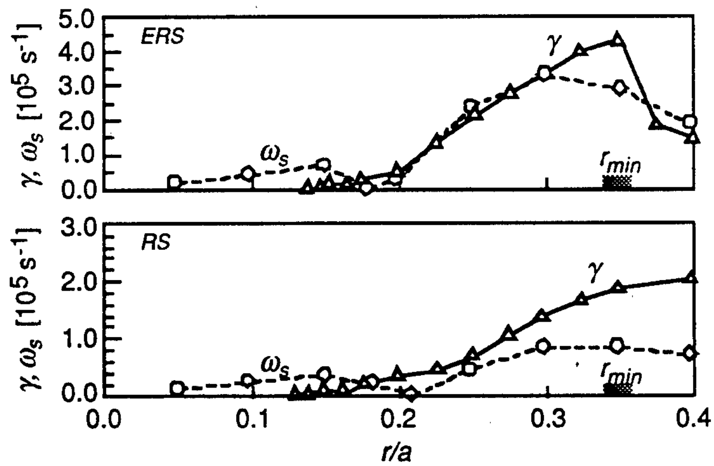

FIG. 7. Maximum linear growth rate γ (triangles) and shearing rate ω_s (circles) for the ERS and RS plasmas of Fig. 1 at t=2.75 s.

and the neoclassical poloidal velocity. In the unstable part of the reversed shear region, where $\gamma > 0$, we obtain $\gamma \leq \omega_S$ for the ERS mode, and $\gamma > \omega_S$ for the RS mode (Fig. 7). Similarly, we find that the ERS relaxation in Fig. 6 is caused by a decrease in the shearing rate below the calculated value of γ [11]. The observed difference in the co/counter NBI injection is, then, explained by the sign of the term containing the toroidal velocity in the force balance equation, which in the case of co-injection causes a reduction in E_r.

From these results, we draw the conclusion that the observed reduction of fluctuations in ERS plasmas is consistent with the suppression of turbulence by the ExB velocity shear.

4. Conclusion

In conclusion, the results presented in this paper provide the first experimental evidence of a correlation between the low level of turbulent fluctuations and the improved confinement in the main core of plasmas with reversed magnetic shear (ERS). We have also detected large bursts of fluctuations in plasmas with similar magnetic shear but with a poorer confinement (RS), suggesting a competition between the driving and the suppression of turbulence.

These observations are consistent with the suppression of turbulence by a decorrelation of turbulent fluctuations from the **ExB** velocity shear.

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REFERENCES

[1] HUGON, M., et al., Nucl. Fusion **32** (1992) 33.
[2] LAZARUS, E.A., et al., Phys. Fluids B **4** (1992) 3644.
[3] LEVINTON, F.M., et al., Phys. Rev. Lett. **75** (1995) 4417.
[4] STRAIT, E.J., et al., Phys. Rev. Lett. **75** (1995) 4421.
[5] KADOMTSEV, B.B., POGUTSE, O.P., Sov. Phys. — JETP **24** (1967) 1172.
[6] COPPI, B., et al., Phys. Fluids **10** (1967) 582.
[7] CHANCE, M.S., GREENE, J.M., Nucl. Fusion **21** (1981) 453.
[8] MAZZUCATO, E., et al., Phys. Rev. Lett. **77** (1996) 3145.
[9] MAZZUCATO, E., NAZIKIAN, R., Phys. Rev. Lett. **71** (1993) 1840.
[10] MAZZUCATO, E., Phys. Fluids B **4** (1992) 3460.
[11] SYNAKOWSKI, E.J., et al. (in preparation).
[12] REWOLDT, G., et al., Phys. Fluids **30** (1987) 807.
[13] BEER, M.A., PhD Thesis, Princeton Univ., NJ (1994).
[14] BIGLARI, H., DIAMOND, P.H., TERRY, P.W., Phys. Fluids B **2** (1989) 1.
[15] SHAING, K.C., et al., Phys. Fluids B **2** (1990) 1492.
[16] BASU, B., COPPI, B., Phys. Fluids B **4** (1992) 2817.
[17] DONG, J., HORTON, W., Phys. Fluids B **5** (1992) 1581.
[18] HINTON, F.L., STAEBLER, G.M., Phys. Fluids B **5** (1993) 1281.
[19] WALTZ, R.E., et al., Phys. Plasmas **1** (1994) 2229.
[20] HAHM, T.S., BURRELL, K.H., Phys. Plasmas **2** (1995) 1648.
[21] LAO, L.L., et al., Phys. Plasmas **3** (1996) 1951.
[22] LEBEDEV, V.B., et al., IAEA-CN-64/D1-3, these Proceedings, Vol. 2.

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