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Density fluctuations at high density in the ergodic divertor configuration of Tore Supra

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Abstract

The effect of the ergodic divertor on the plasma edge in Tore Supra is to enhance the perpendicular transport through ergodization of the magnetic field lines [Ph. Ghendrih et al., Contrib. Plasma Phys. 32 (3&4) (1992) 179]. Nevertheless, the hot spots observed on the divertor plates during ergodic divertor operation indicate that the cross-field transport driven by the fluctuations is still playing an important role, although measurements by CO_2 laser scattering and reflectometry show a decrease of the turbulence level [J. Payan, X. Garbet, J.H. Chatenet et al., Nucl. Fusion 35 (1995) 1357; P. Beyer, X. Garbet, P. Ghendrih, Phys. Plasmas 5 (12) (1998) 4271]. In order to gain more understanding, fluctuation level and poloidal velocity have been measured with a reciprocating Langmuir probe biased to collect the ion saturation current (j_{sat}) and with a CO_2 laser scattering diagnostic. Though the relative fluctuation level behaves as previously observed at low density, a new interesting result is that this picture is gradually modified when the density is increased. Both diagnostics observe an increase of $\delta n/n$ with density in the ergodic region, which is not the usual behavior observed in limiter configuration. This increase is detected on both sides of the E_r inversion radius and is therefore also affecting the plasma bulk. Finally, the confinement time is found to follow an L-mode law at all densities indicating that the ergodic divertor does not change the global confinement properties of the plasma.

Keywords: Boundary plasma; Divertor plasma; Langmuir probe; Turbulence

1. Experimental

Two fluctuation diagnostics are used for this study. The diagnostic ALTAIR, based on coherent forward scattering from an infrared (10.6 μm) CO_2 laser, gives a signal proportional to the density fluctuations. The laser beam is aligned on a vertical chord with a scattering wave vector tuned to be $k_\theta = 10\ \text{cm}^{-1}$ in these experiments. Using the pitch angle variation of the field lines and an adequate orientation of the analyzing wave vector some partial vertical localization is obtained. As fluctuations are mainly perpendicular to magnetic field lines [2], the scattered signal is coming from a region where the scattering wave vector is perpendicular to magnetic field lines. In these experiments, the scattering volume is reduced to approximately one third of the vertical chord, and set to measure the top of the chamber. A heterodyne detection allows the determination of the poloidal velocity of the fluctuations (V_θ) in the laboratory frame. The fluctuations are measured with a 5 MHz acquisition module which stores 32 kBytes per trigger.

The fast reciprocating Langmuir probe is of the Gundestrup type and is described in [3]. It is composed of six collecting areas distributed around a 2 cm diameter

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cylinder and separated by 60°. It is used to measure the polar diagram and the fluctuations of the ion saturation current together with the density, temperature and floating potential. All these quantities are measured simultaneously on the probe by different probe tips. The Gundestrup probe is located at the top of the chamber on a chord at $R = 2.62$ m, and the maximum displacement is 30 cm. The profile is recovered by a RMS circuit while the fine details of the turbulence are obtained by a 1 MHZ acquisition triggered at a selected probe insertion radius and which stores 16 kBytes per plunge. The probe data analyzed here are obtained by using tips facing the ion parallel flux direction with probe collection lengths of at least several tens of meters.

2. Plasma conditions

A typical plasma scenario is represented in Fig. 1(a). The plasma conditions are as follows: The density is varied during the shot from $\mathrm{Nl} = 1$ to 5×10^{19} m^{-2}. The plasma current is 0.74 MA and the safety factor is about 3.2 at the edge. The minor radius of the plasma is 0.77 m and major radius $R = 2.39$ m. Data from some other shots presented in this paper are obtained with different plasma currents but all are obtained in ohmic heating with the divertor switched on and a value of the safety factor close to 3 at the edge. The main effect which is investigated here is the change of the density.

3. Experimental results

3.1. Relative fluctuation levels

Fig. 1(b) shows the fluctuation profile obtained at three different densities for the plasma scenario presented in Fig. 1(a) by the probe. For the lowest density

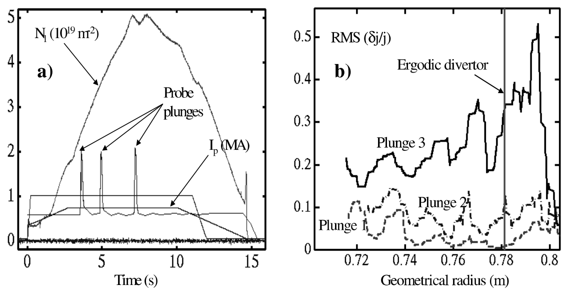

Fig. 1. (a) Typical plasma scenario studied in this paper. The three probe plunges are also represented on the figure. The plunges take place respectively at 2.4, 3.5 and 5×10^{19} m^{-2}. (b) Profile of $\delta j_{sat}/j_{sat}$ (RMS) for the three probe plunges represented in Fig. 1(a). The vertical bar represents the radial position of the ergodic divertor plates.

$\delta j_{sat}/j_{sat}$ is found to be lower than in the limiter case (less than 5% at the divertor plate radial position) on all the measured profile. The CO_2 laser system does not measure any global change in fluctuation level at $k_\theta = 10$ cm^{-1} compared to the limiter case, when the density is low. This is consistent with the previous measurements, also done at low density, which indicated that the turbulence decrease was observed only for $k_\theta < 6$ cm^{-1}. At high density, we have no data available with this diagnostic for comparison.

The new feature is that the average relative fluctuation level measured by the probe increases with Nl and becomes very comparable to the one obtained in limiter case at the highest density. A similar increase of $\langle(\delta n/n)^2\rangle$ with Nl is observed by the CO_2 laser scattering and shown in Fig. 2.

Fig. 2(b) shows the turbulence measured in the outer plasma region located beyond the E_r inversion radius. This region is composed of the ergodic zone and the scrape off layer. The relative fluctuation level starts to increase from $\mathrm{Nl} = 2.5$ to 5×10^{-19} m^{-2}. As the observation k is 10 cm^{-1}, only scales of about 6 mm are observed. The probe data which is sensitive to lower k values prove that large scales are also increased. The Langmuir probe diagnostic shows an increase of $\delta j_{sat}/j_{sat}$ for the three probe plunges with Nl (Fig. 1(b)), so that a priori this is not a threshold phenomenon. Fig. 2(a) monitors the turbulence in the inner part of the plasma with respect to the the E_r shear layer. The turbulence increase is comparable to the one shown in Fig. 2(b).

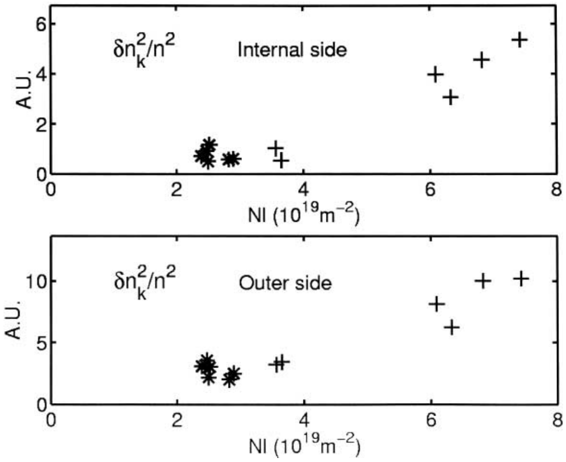

Fig. 2. (a) (top): Change of $\langle(\delta n/n)^2\rangle$ measured by the CO_2 laser diagnostic at $k_\theta = 10$ cm^{-1} in the plasma bulk. Stars: Plasma with $\mathrm{Ip} = 0.8$ MA, Crosses: $\mathrm{Ip} = 0.5$ MA. The level starts to increase at 3.8×10^{19} cm^{-1} but the measurements made by the probe (Fig. 1(b)) indicate that there is no threshold. (b) (bottom): Same for outer plasma (beyond the shear layer). The increase of $\langle(\delta n/n)^2\rangle$ is slightly larger in the outer part of the plasma.

We conclude that as the density increases the turbulence globally increases and overlaps the E_r inversion radius region. One of the key point is that the behavior observed in Fig. 1(b) or Fig. 2 is different from the one observed in limiter case. In the latter, as the density increases, the relative fluctuation level measured by the CO_2 laser in the inner part of the plasma is always found to decrease and saturate as shown in [4].

3.2. Fluctuation poloidal velocities

The profiles of the poloidal velocity of the fluctuations (V_θ) and $\delta j_{sat}/j_{sat}$ are compared. V_θ is obtained by calculating the delay in the cross-correlation function of the turbulence signal from two nearby probe tips separated poloidally. The result is shown in Fig. 3. V_θ is radially modulated, as are the fluctuations themselves, and we find by calculating the correlation between V_θ and $\delta j_{sat}/j_{sat}$ that they are in phase. Note that V_θ is decreasing as the probe gets deeper into the plasma. In fact, at the deepest probe position, V_θ is dominated by the parallel contribution.

$V_\theta \approx v//B_\theta/B_{tot}$ [5], but the decrease of V_θ which is observed in Fig. 3 can be attributed to the decrease of the perpendicular velocity contribution ($E \times B$) term. The parallel velocity component impedes the reversal of V_θ as the probe moves deeper in the ergodic zone.

The mean value of V_θ is reduced as the line density is increased. This is observed by the CO_2 laser scattering measurements in Fig. 4(a) which shows a decrease of V_θ at $k_\theta = 10$ cm^{-1} in the outer and inner regions. The values of the velocities measured in the outer region are in good agreement with the ones measured by the probe. The difference of velocity between the outer and inner regions plotted in Fig. 4(b) is found to decrease as the line density is increased as is also observed in limiter case. As a consequence, the shear at the E_r inversion radius may probably also decrease if the radial extent of the shear layer stays constant. This would allow the turbulence detected at high density to propagate in the plasma bulk. At low densities, although the shear of V_θ measured by the probe can be large, numerical simulations, indicated that the large scale structures were

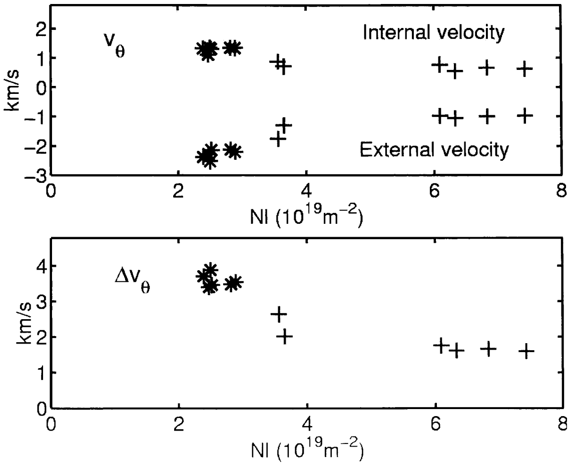

Fig. 4. Velocity shear measured with coherent scattering: (a) (top): V_θ measured on both sides of the E_r inversion radius (they have an opposite sign) by the CO_2 laser diagnostic at $k_\theta = 10$ cm^{-1}. For this diagnostic, a negative velocity means rotation in the ion diamagnetic drift direction. (b) (bottom): Inner/outer velocity difference. The data are plotted for different ohmic shots, with ergodic divertor, and density scans. Stars: Plasma with Ip = 0.8 MA, Crosses: Ip = 0.5 MA. The velocities and their difference are found to decrease with the line integrated density.

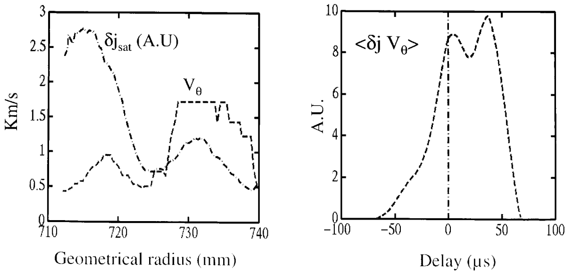

Fig. 3. (a) Profile of δj_{sat} and V_θ measured in the ergodic zone simultaneously on two probe tips. Both profiles are modulated radially. V_θ decreases as the probe moves deeper in the plasma. (b) Correlation function of the level and velocity of the fluctuations. The delay is 4 μs between δj and V_θ. This is radially negligible, therefore the maximum of the δj signal corresponds to a maximum of V_θ.

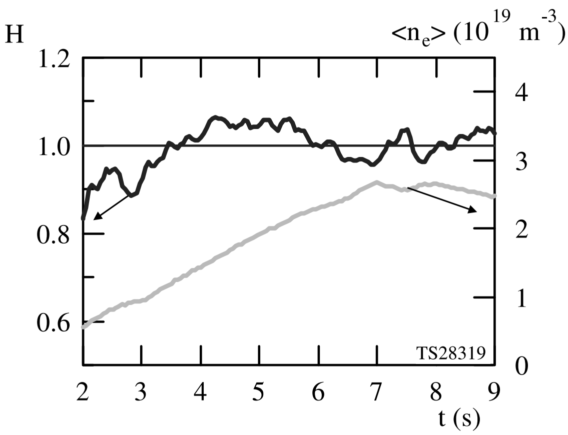

Fig. 5. Improvement factor relative to the ITER 96 thermal law and mean plasma density as a function of time for the shot presented in Fig. 1(a). The use of the ergodic divertor at all densities does not change the basic confinement properties of the plasma.

destroyed by the magnetic field line radial separation induced by the ergodic divertor [1].

Finally we have checked that the energy confinement time follows the L-mode scaling at all densities. This is illustrated in Fig. 5 which shows the improvement factor H as a function of line density. It follows the L-mode ITER 96 thermal type mode scaling.

4. Conclusion

The basic results obtained in the previous analysis of the divertor have been recovered at low density, i.e., decrease of the large scales of the turbulence and of the global fluctuation level in the ergodic zone. However, we have measured an increase of the fluctuation level in the ergodic zone of the plasma but also in the outer region of the plasma bulk when the density is increased. The behavior of the turbulence in ergodic divertor (δ_j/j_{sat} increases with density) is different from the one the one usually observed in limiter plasmas. The turbulence does not modify the global equilibrium of the plasma as the confinement time is found to follow the L-mode ITER 96 thermal scaling law.

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