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ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 718–722

journal of nuclear materials

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Measurements of Reynolds stress and turbulent transport in the plasma boundary during the static dynamic ergodic divertor operation on TEXTOR

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Abstract

The radial profiles of electrostatic Reynolds stress and fluctuation-driven particle flux have been measured in the plasma boundary using a multi-array of fast reciprocating Langmuir probes during the static 6/2 and 3/1 mode dynamic ergodic divertor (DED) operation on TEXTOR. In the ohmic discharge phase before DED, a large radial gradient of Reynolds stress is observed around the flow shear region, suggesting the importance of turbulence-driven flows in the plasma edge. With DED, it is shown that the magnetic ergodization may suppress the Reynolds stress at the plasma boundary and thus rearrange the profile of poloidal momentum. Before DED, the local turbulent flux displays a reduction in the sheared flow layer. During the static DED phase, it is generally seen that the flux reverses direction from radially outwards to inwards in the ergodic zone. At the high DED current operation in the 3/1 configuration, a strong modification on the radial profile of the turbulent flux is observed. The results may have significant implications for the understanding of the electrostatic turbulence, fluctuation-induced flows and associated transport with magnetic stochastization.
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PACS: 52.55.Fa; 52. 35.Ra; 52. 35.Vd

Keywords: Turbulence; Reynolds stress; Plasma flow; Ergodic divertor

1. Introduction

One of the challenges in the operation of fusion devices is the control of the edge plasma parameters. The results on tokamaks TEXT [1], Tore Supra [2], DIII-D [3] and TEXTOR [4] have demonstrated that an ergodized magnetic boundary can be effective to optimize the plasma-wall interaction. Meanwhile, the local effects of the magnetic ergodization on edge turbulence, turbulence-induced transport and zonal flows have been studied both experimentally [1,5,6] and theoretically [7–9]. Experimental observations [1,5,6] show that in the ergodic divertor (ED) configuration the edge density fluctuations

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doi:10.1016/j.jnucmat.2007.01.059

are decreased whereas the turbulent cross-field diffusivity is less affected. In recent years the role of the electrostatic Reynolds stress in driving mean (or zonal) plasma flows has been widely investigated [10–13]. The Reynolds stress, consisting of small-scale fluctuating radial and poloidal velocities, $\langle\widetilde{V}_r\widetilde{V}_\theta\rangle$, may generate a component of the large-scale plasma flow, via its radial gradient, in the poloidal direction by the advective nonlinearity of an incompressible fluid momentum [10]. With magnetic fluctuations, analytical studies predict a depression of zonal flows on account of the competition of the Reynolds and Maxwell stresses [9]. In this paper, we present the experimental measurements of edge turbulence-induced Reynolds stress and turbulent transport during the dynamic ergodic divertor (DED) operation in TEXTOR.

2. Experimental set-up

The DED has been installed on TEXTOR at the high-field side of the torus ($R/a = 1.75/0.47$ m) [4]. It consists of 16 perturbation coils oriented parallel to the field lines on the magnetic flux surface with a safety factor $q \approx 3$. With different current distributions in the coils, the base poloidal/toroidal modes, m/n, can be adjusted. In the outer plasma layer, the DED induces stochastization of the magnetic field lines, including an ergodic zone with long and a laminar zone with short connection lengths to the wall [14].

In this study, the measurements were conducted in two different static DED (DC current on the coils) configurations with $m/n = 6/2$ and 3/1. To obtain effective impacts of the DED at the plasma boundary, the discharge conditions have been optimized as follows: For $m/n = 6/2$, $I_p = 270$ kA, $B_T = 1.9$ T, $R/a \cong 1.73/0.46$ m, DC DED current $I_{DED} = 6$ kA; for 3/1, $I_p = 250$ kA, $B_T = 1.9$ T, $R/a \cong 1.75/0.48$ m, $I_{DED} = 1 \sim 2.5$ kA. The line-averaged plasma density in both cases is $(1.5–2.0) \times 10^{19}$ m^{-3}. The DED current is applied during the stationary phase of the ohmic discharge, ramping up from zero to a certain constant value, for which I_{DED} is defined. In 6/2, for the given value of $I_{DED} = 6$ kA, no external tearing mode (ETM) is excited nor the global confinement is affected. However, in the 3/1 DED operation, with different values of I_{DED}, varied from 1 to 2.5 kA, applied in different discharges, the 2/1 and 3/1 ETMs are routinely excited by the DED at certain current thresholds [15]. In the present discharges, the critical values of the DED current for the onset of 2/1 and 3/1 ETMs are around 1.5 kA and 2.3 kA, respectively. To show the difference in 3/1 DED with/without ETMs, the measurements of the Reynolds stress and turbulent flux will be shown for two I_{DED} cases: one for $I_{DED} = 1.0$ kA without ETMs and the other for $I_{DED} = 2.5$ kA with ETMs.

In this investigation, the Reynolds stress and turbulent flux are detected by two Langmuir probe arrays installed on a fast reciprocating manipulator plunged from the outer midplane of TEXTOR. The electrostatic Reynolds stress $RS \equiv \langle\widetilde{V}_r\widetilde{V}_\theta\rangle$ is measured by a triple probe array with two tips separated by 4 mm and 3 mm from the third in the radial and poloidal directions, respectively. Here, $\widetilde{V}_r(\widetilde{V}_\theta)$ represents the fluctuating radial (poloidal) velocity. The RS tensor is related to the $E_r \times B$ drift and hence computed by $-\langle\widetilde{E}_\theta\widetilde{E}_r\rangle/B_\phi^2$, where $\widetilde{E}_\theta(\widetilde{E}_r)$ is the poloidal (radial) electric field fluctuation and $\langle\cdots\rangle$ denotes an ensemble average. Neglecting electron temperature fluctuations, $\widetilde{E}_\theta(\widetilde{E}_r)$ is deduced from the two poloidally (radially) spaced measurements of floating potential fluctuations. The turbulent particle flux Γ_{fl} is measured by another standard triple probe array (square array, side $\approx$3 mm) [16] and is calculated from the fluctuating density $\tilde{n}_e$ and $\widetilde{E}_\theta$ by $\Gamma_{fl} = \langle\tilde{n}_e\widetilde{E}_\theta\rangle/B_\phi$. The fluctuation data were sampled at 500 kHz.

3. Results and discussion

Fig. 1 plots typical discharge waveforms of related parameters in a static 3/1 DED operation ($I_{DED} = 2.5$ kA). Fig. 1(a) shows that plasma current (I_p) and loop voltage (V_l) both keep constant throughout the discharge. The perturbation DED current is applied from $t = 1.3$ s and ramped up linearly until $I_{DED} = 2.5$ kA at 1.7 s, and then kept constant for 0.3 s, as seen in Fig. 1(c). When the DED current rises to 1.5 kA, the 2/1 ETM is excited, which causes a clear drop in plasma stored energy (E_{dia}) and line-averaged density ($\bar{n}_e$) as well (see dashed line in Fig. 1(b), note that the quick recovery in $\bar{n}_e$ is caused by the feedback control of plasma density by gas puffing). This means that the onset of 2/1 ETM deteriorates the plasma confinement. Details on these aspects have been depicted in Ref. [15]. With further increase of the DED current up to 2.3 kA, the 3/1 ETM is soon excited at $t \approx 1.67$ s. The onset of 3/1 ETM seems to evoke very small effects on the global confinement, as seen in the E_{dia} and $\bar{n}_e$ signals. It should

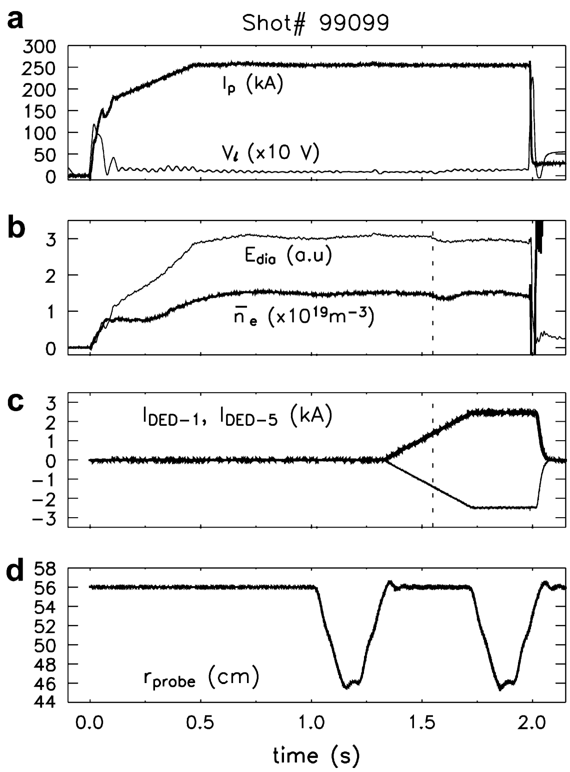

Fig. 1. Time evolution of plasma parameters in a static $m/n = 3/1$ DED discharge in TEXTOR tokamak. (a) Plasma current and loop voltage; (b) total plasma stored energy and central line-averaged density; (c) DC DED currents in coil-1 (thick line) and coil-5 (thin line) and (d) radial position of fast reciprocating Langmuir probe arrays. The vertical dotted lines in (b) and (c) denote the onset of the external tearing 2/1 mode excited by DED.

be noted that in the present study, for the operation of 6/2 static DED with $I_{DED} = 6$ kA *or* 3/1 DED with $I_{DED} < 1.5$ kA , both E_{dia} and $\bar{n}_e$ stay constant throughout the discharge as no ETMs are triggered. The probe measurements are carried out by two fast plunges into the plasma: one before and the other during the plateau of I_{DED}, as shown by probe traces (r_{probe}) in Fig. 1(d). The radial position of the probe covers both the laminar and erdogic zones during the DED phase.

Fig. 2 shows the radial profiles of Reynolds stress (RS) measured in the 6/2 ($I_{DED} = 6.0$ kA) and 3/1 ($I_{DED} = 1.0$ and 2.5 kA) static DED discharges. In the figure, the vertical solid line denotes the limiter position. The dashed line roughly separates the ergodic zone (EZ-left side) and the laminar zone (LZ-right side). In Fig. 2(b), the dashed line separating EZ/LZ is corresponding to $I_{DED} = 2.5$ kA. The distinction is mainly made by the connection length of field lines, L_c, which is about 3–4 poloidal turns at the position of the dashed line as predicted by calculations [14]. As such, the L_c in the EZ is longer than the Kolmogorov length, which is a statistical measure of the *e*-folding length of the exponential separation of adjacent field line trajectories, whereas in the LZ the L_c is shorter. The Chirikov parameter, defined as the ratio of the averaged island width to the radial distance between the neighboring island chains, is larger than 1 in the EZ. Before DED, we can see that the RS profile (see solid circles) in either case displays a radial gradient, especially in the vicinity of the limiter position, where a sheared poloidal flow layer has been identified [17]. The local radial gradient of RS, i.e., $d\langle \widetilde{V}_r \widetilde{V}_\theta \rangle / dr$, is around the order of 10^7–10^8 m/s^2, similar to that observed in the ISTTOK tokamak [11]. With a damping rate $\mu \approx 10^4\ s^{-1}$ estimated in Ref. [11] and the poloidal flow $V_\theta \approx 10^3$ m/s measured [17], the damping term of the plasma rotation can be expressed as $\mu V_\theta \approx 10^7$ m/s^2, close to the driving term of the *RS* gradient. This result suggests the importance of turbulence-driven flows in the plasma edge of TEXTOR during the ohmic discharge phase. With DED, the magnetic perturbations completely mitigate the RS profile in 6/2 DED; while in 3/1 case the radial structure of RS is less suppressed. Fig. 2(b) further shows that the RS profile is more depressed with the increase of I_{DED} from 1 to 2.5 kA. And thus, it appears that the modification of the RS structure depends on the strength of magnetic perturbations. Despite the difference between the 6/2 and 3/1 DED discharge conditions, a common feature is shown that the magnetic ergodization may suppress the RS at the plasma boundary and thus rearrange the profile of poloidal momentum. Whether such suppression of the RS structure is related to enhanced magnetic fluctuations [9] during DED is under investigation.

In Fig. 3, the radial profiles of the ensemble-average turbulent flux, $\langle \Gamma_{fl} \rangle$, measured in the 6/2 ($I_{DED} = 6.0$ kA) and 3/1 ($I_{DED} = 1.0$ and 2.5 kA) DED are plotted. It is noted that before DED, $\langle \Gamma_{fl} \rangle$ in either case exhibits a local reduction inside the limiter location (see solid circles at the range of $0.96 < r/a < 1$), which might be attributed to the local decorrelation role of the sheared E_r, as observed in our case [17] and also earlier in other machines [18]. In Fig. 3(a), it is interesting to see that the $\langle \Gamma_{fl} \rangle$ in the 6/2 DED changes its sign from radially outwards (>0) to inwards (<0) in the ergodic region. A similar situation is also seen in

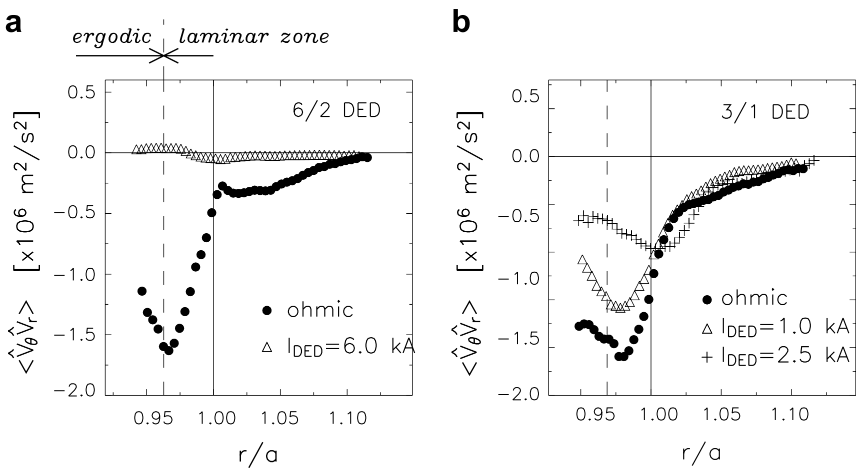

Fig. 2. Radial profiles of the electrostatic Reynolds stress measured by a fast reciprocating probe array before (ohmic) and during the static (a) $m/n = 6/2$ DED ($I_{DED} = 6.0$ kA); and (b) 3/1 DED ($I_{DED} = 1.0$ and 2.5 kA (in the presence of ETMs)). The radial locations are normalized by a. The vertical dashed line roughly separates the ergodic (left side) and laminar (right side) zones. The dashed line separating EZ/LZ in (b) corresponds to $I_{DED} = 2.5$ kA.

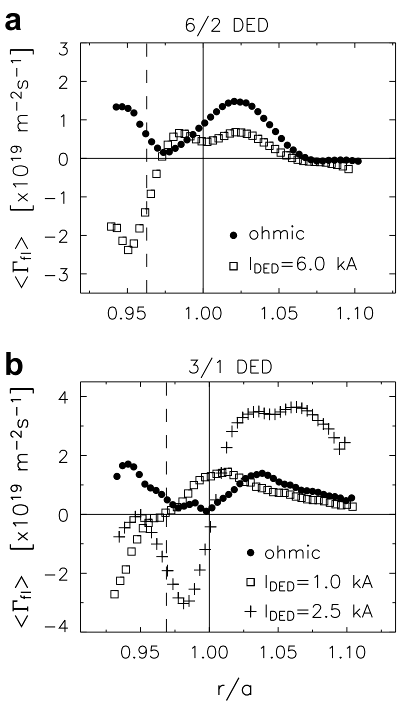

Fig. 3. Radial profiles of ensemble-average of turbulent particle flux, $\langle \Gamma_{fl} \rangle$, measured before (ohmic) and during the static (a) $m/n = 6/2$ DED ($I_{DED} = 6.0$ kA); and (b) 3/1 DED ($I_{DED} = 1.0$ and 2.5 kA (in the presence of ETMs)). The radial locations are normalized by a. The vertical dashed line roughly separates the ergodic (left side) and laminar (right side) zones. The dashed line separating EZ/LZ in (b) corresponds to $I_{DED} = 2.5$ kA.

Fig. 3(b) for 3/1 DED when $I_{DED} = 1.0$ kA (see open squares). The reversal of the $\langle \Gamma_{fl} \rangle$ direction, in principle, indicates a change in the phase shift between $\tilde{n}_e$ and $\widetilde{E}_\theta$. As the global confinement is not altered in both cases (6/2 DED with $I_{DED} = 6.0$ kA and 3/1 with $I_{DED} = 1.0$ kA), a compensation of outflux should arise either from the fluctuation-driven flux at other locations or from the ergodic particle transport across the stochastic layer [2]. Fig. 3 further shows that during static DED without the onset of ETMs, the influence on $\langle \Gamma_{fl} \rangle$ profile is quite similar for the 6/2 and 3/1 configuration, as shown by open squares in the figure. In 3/1 DED, when I_{DED} is increased from 1.0 to 2.0 kA which excites 2/1 ETM (see Fig. 1), the radial profiles of $\tilde{n}_e$, $\widetilde{E}_\theta$ and $\langle \Gamma_{fl} \rangle$ are almost unchanged (not shown here). This means that the onset of 2/1 ETM does not affect the radial dependence of edge turbulence and turbulent transport. However, when I_{DED} is further increased to 2.5 kA (both 2/1 and 3/1 ETMs appear), a dramatic variation occurs on the $\tilde{n}_e$ and $\langle \Gamma_{fl} \rangle$ profiles. The fluctuation amplitudes of $\tilde{n}_e$ are about three-four times higher than that of $I_{DED} = 2.0$ kA (the latter is approximately the same level as that in ohmic phase) in the scrape-off layer (SOL) and in most of the perturbation area. Meanwhile, the radial dependence of $\langle \Gamma_{fl} \rangle$ is significantly changed, as illustrated in Fig. 3(b) by cross symbols. In the ergodic zone $\langle \Gamma_{fl} \rangle$ is slightly enhanced close to zero; in the laminar region $\langle \Gamma_{fl} \rangle$ is much depressed; while in the SOL imposed by the limiter $\langle \Gamma_{fl} \rangle$ is strongly increased. As the $\widetilde{E}_\theta$ profile is not much altered, the results imply an enhanced 'in-phase' between

$\tilde{n}_e$ and $\widetilde{E}_\theta$ in the SOL and 'out-phase' of them in the laminar zone during the 2.5 kA DC DED current operation in 3/1 configuration. It is not clear yet if these changes are linked to the onset of 3/1 ETM.

4. Conclusion

In conclusion, we report the experimental measurements of the electrostatic Reynolds stress and turbulence-driven particle flux at the plasma boundary of the TEXTOR tokamak using a multi-array of fast reciprocating Langmuir probes during the static 6/2 and 3/1 mode DED operation. In the ohmic discharge phase before DED, a large radial gradient of Reynolds stress is observed around the flow shear layer, suggesting the importance of turbulence-driven flows in the plasma boundary. During DED, it is found that the radial structure of Reynolds stress is suppressed, and hence, the profile of poloidal momentum is rearranged by the magnetic ergodization. In the ohmic discharge, the local fluctuation-induced particle flux displays a depression in the sheared flow layer. With DED, it is found that the turbulent flux reverses sign from radially outwards to inwards in the ergodic area. In the 3/1 DED operation, when the DED current increases to certain threshold, at which the 2/1 and 3/1 external tearing modes are routinely excited, a strong modification on the radial profile of the turbulence-driven flux occurs, leading to a large enhancement of flux in the SOL. The results may have significant implications for the understanding of the electrostatic turbulence, turbulence-induced flows and associated transport in the presence of magnetic ergodization.

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