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Plasma structures and transport in the SOL of the T-10 tokamak

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Abstract

Plasma regions (or structures) with high density are formed at or near the last closed flux surface (LCFS) in the T-10 tokamak. Plasma density inside the plasma structures is 1.5–2.5 times higher than the density of the background plasma. The structures move in radial direction and lead to an increase of the turbulent particle flux to the wall. The probability distribution function (PDF) of the turbulent particle flux is positively skewed in the scrape-off layer (SOL). The PDF is near Gaussian at the LCFS: the skewness is equal to zero, and the flatness is equal to 3. Negative particle flux bursts in this region correlate with lower-than-average density fluctuations, and are therefore interpreted as lower density plasma regions propagating towards the plasma core.

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1. Introduction

It was shown recently that enhanced convective radial transport could be responsible for the SOL widening in tokamaks [1]. There is much evidence to show that density profiles in the SOL are non-exponential and are often flat far away from the LCFS [2–6]. Possible mechanism that could result in additional perpendicular transport in the plasma periphery is intermittency in the plasma fluctuations [7–14]. Intermittent transport is considered as the universal mechanism of radial convective transport in the SOL of different magnetically confined plasmas [15]. Intermittent convective transport leads to an essential increase of particle and energy flux reaching the wall of the vacuum chamber.

Much attention has been devoted to the statistical properties of the turbulent transport [7,9,16,17]. There are a number of the studies [10,12,18] pointing out that the probability distribution function (PDF) of the transport in the SOL is not described by a normal distribution. Deviation from Gaussian distribution is the results of the intermittent events. At the same time, it was found in JET that the statistical properties of the turbulence are near-Gaussian in the naturally occurring velocity shear layer [13]. In DIII-D [19] the skewness of PDF is about zero or even changes sign near the LCFS indicating that the negative intermittent events are present.

Fast convective transport of particles and energy has attracted much theoretical attention. Models based on electrostatic plasma turbulence were proposed [20–22].

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According to these models the formation of convective cells or plasma blobs takes place near the LCFS. The blobs are polarised by $B \times \nabla B$ and curvature drifts and move radially due to the electrical drift.

In this paper, experimental investigation of radial distribution of the peripheral intermittent transport performed in the T-10 tokamak is presented. Experiments were carried out in regimes with pure ohmic plasma heating. Langmuir probes installed in the T-10 were used to study the turbulent characteristics of SOL and edge plasmas and the associated anomalous transport.

2. Experimental set-up and plasma parameters

Experiments were performed on the T-10 tokamak [23] (major radius $R_0 = 1.5$ m) which is equipped by a full poloidal graphite limiter of radius $a_0 = 0.33$ m and a graphite rail limiter inserted in the vacuum chamber through the bottom port of the tokamak. For the experiments described below the minor plasma radius a_L determined by the rail limiter was 0.30 m. The experiments were performed in deuterium plasma. The average electron density $\bar{n}_e$ measured along a central chord was 6×10^{19} m^{-3}, the toroidal magnetic field induction $B_t = 2.4$ T, the plasma current $I_p = 0.3$ MA.

Measurements of the SOL parameters were performed using two movable probe systems [24]. The first probe system, probe No. 1, consists of six carbon tips (length 0.25 cm, diameter 0.2 cm) evenly distributed in the radial direction. The radial distance between the tips is 0.3 cm. This six-tip array is used for measurements of the radial profiles of plasma parameters.

The second probe system, probe No. 2, consists of 10 tungsten tips. Probe tips can be combined in different measurement schemes for measurement of the various plasma parameters. This probe system was applied for measurements of the ion saturation current I_s, the floating potential U_{fl}, the electron temperature T_e using the triple probe scheme and the fluctuation of the ion saturation current and the poloidal electric field for calculation of the radial particle flux. Time resolution of the data acquisition system is 2 μs.

3. Experimental results

Previous investigation [24] of the plasma periphery in the T-10 tokamak has shown that character of I_s fluctuations has a strong dependence on the average electron density. At low plasma density the ion saturation current is characterised by low level of the fluctuation $\tilde{I}_s/\bar{I}_s \approx 10\%$ to 15% ($\tilde{I}_s$ is the root-mean-square, $\bar{I}_s$ is the time average ion saturation current). An increase in the average electron density from 0.25 to 0.5 of the Greenwald density limit leads to an essential change in the ion saturation current fluctuations. The relative level of the fluctuation increases from 10–15% to 50–60%.

As it was marked previously [24], the bursts can be observed simultaneously in I_s signals measured by several tips of the array No. 1. However, assuming a radial propagation of the plasma structures [24] one could expect time delay between the bursts measured by different tips. In this paper we applied the procedure of conditional averaging (CA) [25] for determination of the correlation between bursts in different signals. All fluctuations with the relative amplitude above adjusted threshold level are detected as intermittent bursts within a time window $\Delta t = 20$ ms. A threshold of $2.5 \times$ RMS fluctuation level was chosen. A time interval $\Delta\tau = 100$ μs is centered at the each burst maximum and then all detected bursts are averaged over the given time interval $\Delta\tau$. The time $\Delta\tau$ is taken to be twice shorter than time interval between two neighboring bursts. Hence for a frequency of the bursts of 3–4 kHz, the selected time $\Delta\tau$ is appropriate for bursts resolution. A signal from the first tip (the nearest tip to the LCFS) of the probe array No. 1 was used as the primary signal for CA. Next tips were used as the secondary signals. Result of the conditional averaging is shown in Fig. 1. The time delay between the averaged bursts measured by different tips is obviously seen from the figure. This time shift can be considered as consequence of the radial propagation of the plasma structures.

It is generally accepted that intermittency could be a reason of the enhanced radial flux in the plasma periphery of many devices, of different types. The probe technique is the most common method for the measurements of cross-field flows and the radial plasma velocity.

The probe technique was also applied to the measurement of the radial turbulent particle flux in the T-10. For this purpose the probe system No. 2 was used. The perpendicular particle flow $\Gamma_\perp$ was calculated by using of the standard procedure [26]:

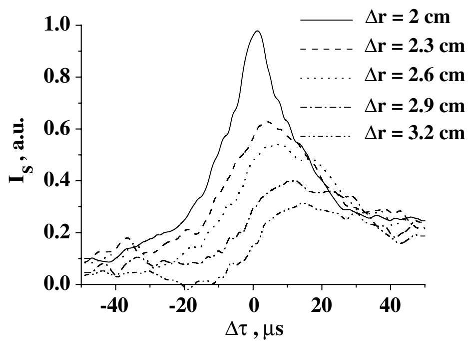

Fig. 1. Conditional averages of ion saturation current fluctuations for different radial separations. $I_p = 0.3$ MA, $\bar{n}_e = 6 \times 10^{19}$ m^{-3} ($0.6n_G$).

$$\Gamma_\perp = \langle n v_r \rangle = \frac{c}{B}\langle n E_\theta \rangle = \frac{c}{B}\gamma_{n,E}\tilde{n}\widetilde{E}_\theta, \qquad (1)$$

where $\tilde{n}$, $\tilde{v}_r$, $\widetilde{E}_\theta$ are the root-mean-square values of the density, the radial flux velocity and the poloidal electric field, $\gamma_{n,E}$ is a coefficient of the cross correlation between fluctuations of the I_s and the E_θ. Since the amplitude of the electron temperature fluctuations is less than the amplitude of the ion saturation current fluctuations, fluctuations of T_e are neglected.

The averaged perpendicular electrostatic turbulent particle flux, $\Gamma_\perp$, defined by formula (1) is plotted in Fig. 2(a). The maximum of the flux is observed at a radius $\Delta r = +1$ cm ($\Delta r = r - a_L$). The particle flux decreases rapidly with the radius. In the vicinity of the LCFS $\Gamma_\perp$ is approximately twice lower than the flux measured at $\Delta R = +1$ cm, which is presumably associated with the presence of the bursts with a high negative amplitude. An effective diffusion coefficient D_{eff}, obtained as $D_{eff} = \Gamma_\perp/\nabla n$, is shown in Fig. 2(b). Radial profile of the D_{eff} is similar to that of the perpendicular particle flux with the maximum at $\Delta r = +1$ cm.

The time dependencies of the radial particle flow Γ_r calculated by using the plasma density n and the poloidal electric field E_θ ($\Gamma_r = c/BnE_\theta$) are shown in Fig. 3 (the flux Γ_r is obtained according to Eq. (1), but without averaging). The plasma density was obtained from the ion saturation current measurements. Fig. 3 shows the existence of a strong radial dependence of the radial particle flux. In the SOL (Fig. 3(a)) the time signal of Γ_r reveals the intermittent behavior with high amplitude positive bursts. PDF of the particle flux is positively skewed. In the vicinity of the LCFS (Fig. 3(b)), the relative level of the positive fluctuations decreases. The amplitudes of the negative bursts in the particle flux signal increases leading to an expansion of the particle flux in the plasma core direction. The skewness of the PDF is close to zero in this case.

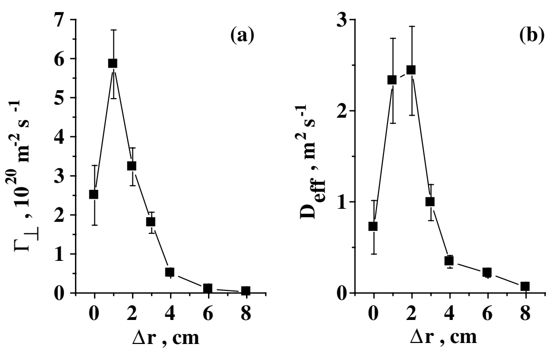

Fig. 2. Radial profile of the total radial electrostatic turbulent flux $\Gamma_\perp$(a) and effective perpendicular diffusion coefficient D_{eff} (b). $I_p = 0.3$ MA, $\bar{n}_e = 6 \times 10^{19}$ m^{-3} (0.6n_G).

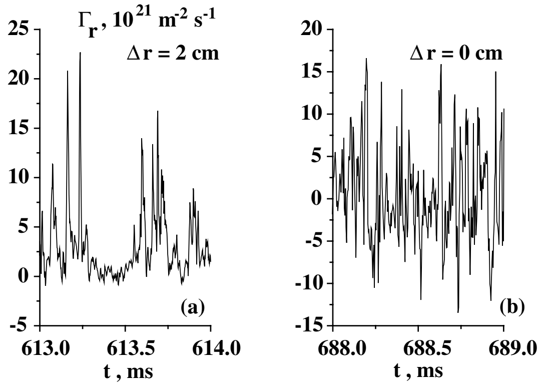

Fig. 3. The time evolution of the radial turbulent particle flux. $I_p = 0.3$ MA, $\bar{n}_e = 6 \times 10^{19}$ m^{-3} (0.6n_G).

For investigation of a contribution of the positive and negative events to the total particle flux the procedure of conditional averaging was applied. The electron density n_e and the poloidal electric field E_θ were used as the signals for the CA procedure. As the positive and negative bursts are observed in experimental signals, the positive and negative threshold levels were used. The results of the CA procedure are presented in Fig. 4 for the SOL and Fig. 5 for the LCFS. In the SOL, the positive bursts of the electron density correlate only with the positive fluctuations of the poloidal electric field. The positive fluctuations of E_θ mean that the resulting $E \times B$ drift is toward the wall. No correlation between the positive bursts of n_e and the negative bursts of E_θ as well as between the negative bursts of E_θ and the

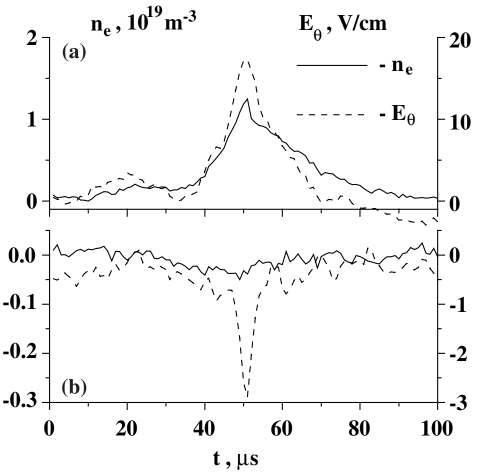

Fig. 4. Results of conditional averaging, SOL. (a) Auto CA of the positive n_e fluctuations and cross CA of the E_θ fluctuations for the condition $n_e > \bar{n}_e + 2.5\tilde{n}_e$. (b) Auto CA of the negative E_θ fluctuations and cross CA of the n_e fluctuations for the condition $E_\theta < -2.5\widetilde{E}_\theta$.

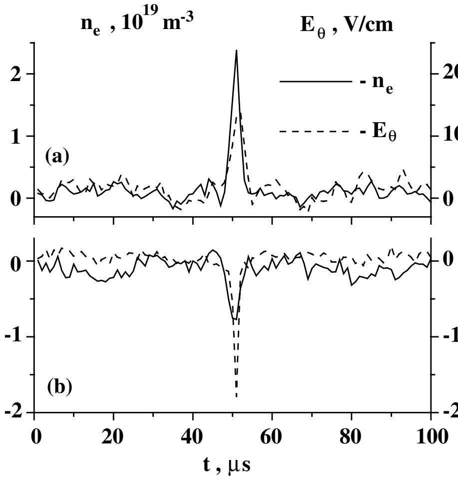

Fig. 5. Results of conditional averaging, LCFS. (a) Auto CA of the positive n_e fluctuations and cross CA of the E_θ fluctuations for the condition $n_e > \bar{n}_e + 2.5\tilde{n}_e$. (b) Auto CA of the negative n_e fluctuations and cross CA of the E_θ fluctuations for the condition $n_e < \bar{n}_e - 2.5\tilde{n}_e$.

negative bursts of n_e was found (it is necessary to note that the negative bursts of the density with amplitude exceeding $-2.5 \times$ RMS are absent in the SOL). It means that in general the high density plasma structures moving to the wall exist in the SOL. On the contrary, low density plasma regions propagating to the plasma core are observed at the LCFS along with the high density structures directed to the wall. Fig. 6 shows that there is a correlation between the positive bursts of the density and the positive fluctuations of the electric field and between the negative bursts of E_θ and the negative bursts of the n_e.

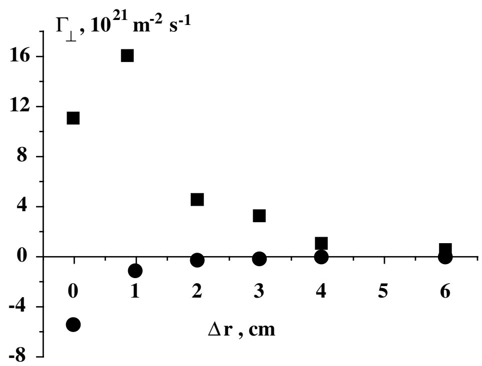

Fig. 6. Radial profile of the conditionally averaged peaks of the radial particle flux. Positive values mean that the flux is directed to the wall of the vacuum chamber, negative ones to the opposite direction.

The conditional averaging was applied for a definition of the average bursts of the cross-field flux of particles. The results are shown in Fig. 6 where a radial dependence of the average amplitude of the positive and negative peaks is presented. As it is obvious from the figure the positive amplitude exceeds the negative one in the SOL and only near the LCFS the amplitudes of fluctuations of different polarity are comparable. This result is consistent with calculations of the averaged turbulent particle flux presented in Fig. 2.

4. Conclusions

Langmuir probe measurements of SOL plasma parameters indicate that intermittent events can play a significant role in the cross-field transport. Intermittent behavior of the plasma parameters is associated with formation and propagation of the plasma structures with high density.

Measurements of the radial turbulent particle flux Γ_r using a probe array show that there is a strong radial dependence of the flux. In the SOL, the time evolution of Γ_r reveals the intermittent behavior with high amplitude positive bursts. In the vicinity of the LCFS, the relative level of the positive fluctuations decreases, while the amplitude of the negative (inward-directed) transport events increases, leading to the reduction of the net outward-directed particle flux.

Acknowledgments

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