Vol 13 No 12, December 2004
1009-1963/2004/13(12)/2091-06

Chinese Physics

© 2004 Chin. Phys. Soc.
and IOP Publishing Ltd

Observation of intermittency in edge plasma of SUNIST tokamak*

Wang Wen-Hao(王文浩)[a)†], He Ye-Xi(何也熙)[a)], Gao Zhe(高 喆)[a)],
Zeng Li(曾 立)[a)], Zhang Guo-Ping(张国平)[a)],
Xie Li-Feng(解丽凤)[a)], and Feng Chun-Hua(冯春华)[b)]

[a)] *Department of Engineering Physics, Tsinghua University, Beijing* 100084, *China*
[b)] *Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing* 100080, *China*

(Received 21 June 2004; revised manuscript received 20 August 2004)

The temporal intermittency of the fluctuation-driven particle transport fluxes is analysed by using data obtained from Langmuir probe array in the edge of the Sino-United Spherical Tokamak (SUNIST). The conditional statistics analysis indicates that the intermittent structures have a characteristic time width of about 30μs, which is the typical fluctuation time scaling. It is also found that the transport fluxes have a multifractal character over the fluctuation time scales, and exhibit a long-time-range correlation character with self-similar parameter $H > 0.5$ in the plasma confinement time scales. Furthermore, the analyses show that the level of the intermittency and the long-range correlation of the fluxes vary with increasing plasma density. These observations are consistent with the prediction of the avalanche-like model.

Keywords: intermittency, spherical tokamak, edge plasma turbulence transport
PACC: 5235R, 5225F, 5270D

1. Introduction

One of the objectives of edge turbulence transport research in the magnetic confinement devices is to find appropriate methods to control the power loss resulting from anomalous transport and improve plasma confinements. It is widely believed that the electrostatic turbulence is responsible for most of the edge particle and energy transport loss in the tokamaks.[1] Experimental observations show that this edge electrostatic turbulence has both intermittent feature, a short time scale (the turbulence decorrelation time scale) behaviour, and the self-similar character, a mesoscale time range transport with long-time-range correlations.[2,3] The experimental evidence emphasizes the difference in characteristic temporal scalings of plasma turbulent fluctuations in different time scale ranges. Some powerful analysis tools, such as the probability distribution function (PDF), the conditional averaging technique, multifractal analysis and the rescaled-range statistics (R/S), etc. have been used to study the intermittency and self-similarity of the edge turbulences.

In this paper we report our experimental results in the edge of the Sino-United Spherical Tokamak (SUNIST). Spherical tokamak (ST) plasmas have a few attractive features compared to conventional large-aspect-ratio tokamaks, such as high β and naturally large elongation κ, which means a drastic reduction in the cost of the magnet system of a device, good confinement and the possibility of steady-state operation at a modest magnetic field, etc. These advantages make STs of growing importance for fusion research. Several new ST devices are planned or under construction around the world. The SUNIST at Tsinghua University of China, the first ST in China, is constructed to study the toroidal plasma characteristics in low aspect ratio configuration.[4] In the first phase of the construction of this programme, SUNIST achieved the first ohmically heated hydrogen plasma at the end of 2002 with 0.15 Tesla of the toroidal field

*Project supported by the National Natura1 Science Foundation of China (Grants Nos 10275041, 10235010 and 10375089) and by China Postdoctoral Science Foundation.
†E-mail: whwang@tsinghua.edu.cn Tel: 010-62776446

and 50kA plasma current.

This paper analyses the temporal behaviour of the turbulence-induced particle flux Γ of the edge plasma in SUNIST. Results indicate, similar to the observations in the traditional aspect-ratio tokamaks, that the particle flux has both temporal intermittency and self-similarity. It may reveal the common property of the edge electrostatic turbulence in the magnetic confinement devices. It should be noted that such phenomena are ubiquitous for edge plasma turbulences, so similar analyses of fluctuations and heat transport fluxes are not reduplicated here.

2. Experiments

The SUNIST is an ST device with major radius 0.30m, minor radius (defined by a set of fixed four-block poloidal limiter) 0.23 m and designed elongation 1.6. The primary diagnostic employed in this experiment is a radially moveable four-tip Langmuir probe located on the outer side of the equatorial plane of the device. All tips are made of molybdenum wire with 3 mm in length and 1 mm in diameter and 3 mm separation between adjacent tips. The probe is operated as a triple probe[5] to obtain the time-averaged electron temperature T_e and density n_e. Two tips located poloidally separated about Δ_θ=4.3 mm are used to measure the floating potential $\tilde{\phi}_f$, from which a fluctuating poloidal electric field $\tilde{E}_\theta(t)$ can be deduced, i.e. $\tilde{E}_\theta(t) = \Delta\tilde{\phi}_f(t)/\Delta_\theta$, whereby a time-resolved radial particle flux $\Gamma_r(t)$ can be derived as

$$\Gamma_r(t) = \tilde{n}_e(t)\tilde{E}_\theta(t)/B_T. \quad (1)$$

All probe tips are orientated off the magnetic field lines to avoid shadowing probe tips from each other. In above measured physical variables, the electron density is determined by the measured I_{si}, ϕ_f and T_e with the Stangeby model:[6] $n_e=\alpha I_{si}T_e^{-1/2}$, where α is a constant coefficient depending on the geometry size of tips.

The experiments were conducted in the ohmic hydrogen discharge with the toroidal magnetic field $B_T \approx$0.13T, plasma current $I_p \approx$30kA and loop voltage of 5V. Normally the plasma discharge durations are 5–6ms with a flat-top phase of 2ms. The short time discharges and low temperature in edge plasmas allow the probe to be inserted into radially deeper edge plasma region without obviously excessive thermal load onto it. A variety of radial profiles are obtained by shot-to-shot measurements. At each radial position 10–15 shots identical discharges are conducted to compute statistic averages. All the data for analyses in this paper are taken from those obtained in the flat-top phase of the plasma current and digitized at 2MHz with 12-bit resolution using a multi-channel digitizer. Figure 1 shows the radial profiles of the T_e and n_e.[7] The horizontal coordinate is the major radius and the shadow region stands for the radial location of the limiter. The error bars are estimated by the statistical error of ensemble average. It can be seen that in the scrape-off layer (SOL, $r > r_{limiter}$) the $T_e \sim$10eV, $n_e \sim 2\times10^{18}$ m^{-3}, and the profiles are relatively flat. But in the plasma edge ($r < r_{limiter}$) the profiles of the T_e and n_e are steeper. The edge temperature and density are in the range T_e=10–60eV and (0.5–8.0)$\times10^{18}$m^{-3} respectively. These results are similar to the edge data obtained in other STs.[8,9]

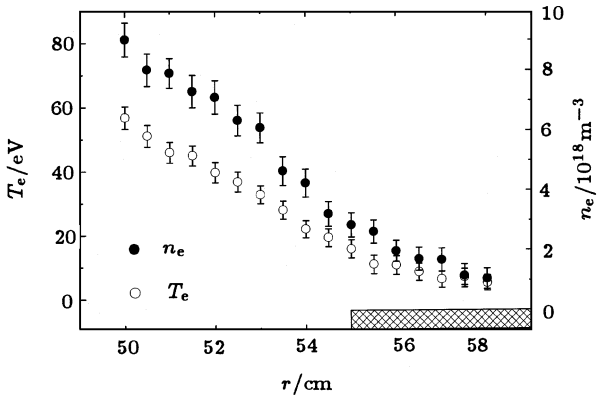


Fig.1. Radial profiles of equilibrium T_e and n_e. The error bars are the statistical errors of the ensemble average. The shadow region stands for the radial location of the limiter.

3. Results and discussion

Intermittency of the particle transport flux normally features itself as a significant number of events above the standard deviation. Figure 2 shows two typical time evolutions of the $\Gamma_r(t)$ signals from two different radial positions, r=52cm (in plasma edge) and r=57cm (in SOL). We can see that the fluctuations of $\Gamma_r(t)$ have different patterns in different regions (in and out of the limiter). In SOL, the $\Gamma_r(t)$ performs as a separated Gaussian-like noise with short-time scale intermittency, but in plasma edge, as density increases, the $\Gamma_r(t)$ looks more "bursty". Such time patterns of fluctuations are universal in our experiments, not only for the particle and heat transport fluxes, but also for the ion saturation current $\tilde{I}_{si}$ and floating potential $\tilde{\phi}_f$.

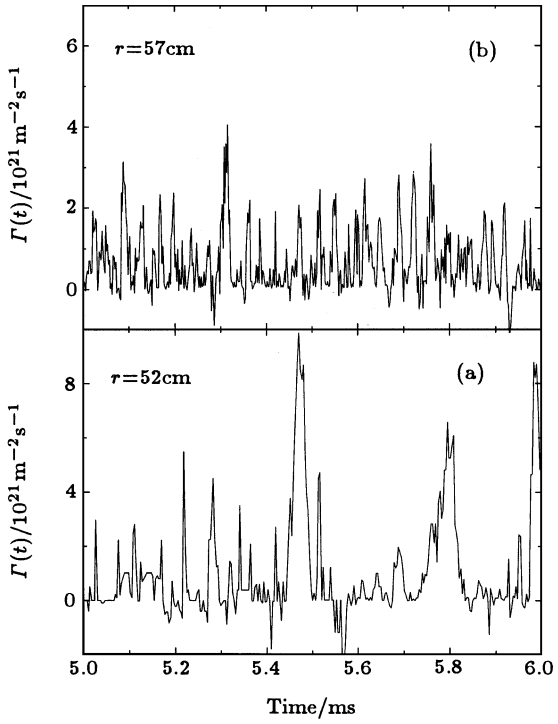


Fig.2. Typical time evolutions of $\Gamma_{\rm r}(t)$ at plasma edge (a) and at SOL (b).

To quantitatively verify the intermittent structures of the fluxes, we apply the conditional averaging technique[10−12] to analyse the flux signals. We select the flux signal at the radial position r=57 cm as the reference signal. A 2.5×rms-level threshold amplitude is used to discriminate the intermittent events in fluxes. Then for these events a 100 μs interval centred at the event is cut out of the original time series and accumulated for subsequent averaging. According to the standard conditional averaging procedure, the above process should be applied at the same time to the other two signals $\tilde{n}_{\rm e}$ and $\tilde{E}_\theta$ which constitute the flux as shown in Eq.(1). But in this paper, we only focus on the intermittency of the flux itself, not on the coherence between $\tilde{n}_{\rm e}$ and $\tilde{E}_\theta$, so corresponding analysis is not given here. In order to make a comparison between the fluxes from different radial positions, similar processes are put on the flux signals from other three radial positions r=58, 52 and 54cm. Figure 3(a) shows the result, where N denotes the number of the intermittent events occurring from the whole time series 2ms long for each signal. We can see that all events, both from the SOL and the plasma edge, have a characteristic time width of about 30μs, the typical fluctuation time scaling. In the edge (r=52cm), the number of the events occurs fewer (half of that from the SOL, r=58cm) but the amplitude of events is two times higher than the latter, similar to the result of the DIII-D.[11] It should be noted that the observation of the intermittency structure of the edge turbulence in STs has not been reported so far as we know, so the comparison of the results here and hereafter will be conducted with that from the traditional aspect-ratio tokamaks.

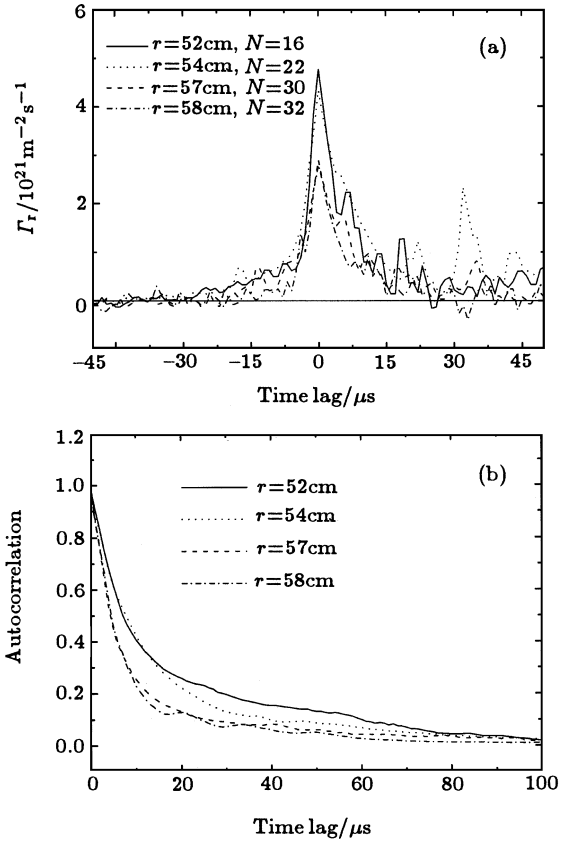


Fig.3. (a) Conditional averaging results and (b) autocorrelation functions (the positive wings) of the fluxes from four radial positions.

Another better way to research this intermittent transport is by comparing the autocorrelation function (ACF) of the fluxes. Figure 3(b) shows the ACFs of the fluxes from the four radial positions. Each plot results from averaging over 10–15 samples from reproducible discharges with 4000 points for each sample. It is clear that the ACFs from the edge (r=52cm) have longer tails than that from the SOL (r=58cm), suggesting that the long-range correlation transport events in the edge is more important than that in the SOL. This trend may result from the plasma density change. Carreras *et al*[3] analysed the relation between the intermittent structures of the floating potential fluctuations and the average density in the far SOL region of the Alcator C-Mod device and obtained similar results, that is, as the density increases, the level of the intermittency and long range correlation

time significantly increase.[3]

As a complement of the long-range dependence research, we use the R/S statistics [13] to evaluate the Hurst exponent, which is an indication of the long-range time correlations of the flux time series. Figure 4 shows the profile of Hurst exponents versus the electron density. Each value of H is averaged over 10–15 shots. Error bars are estimated by the combination of the errors of the power fit to R/S curve for each shot data and the statistical error of ensemble average. We can see that at all measured positions the value of H is greater than 0.5, i.e. there exist long-range time dependencies in the turbulent transport. In the low density region ($n_e < \times 10^{18}\mathrm{m}^{-3}$ in SOL), the values of H remain roughly constant between 0.6 and 0.7. But in the plasma edge, as the density increases, the values of H are greater than 0.8, indicating a stronger long-range time dependence. This result agrees with the ACF result of Fig.3(b) and similar to the profile of H of the fluctuations observed in the edge plasmas of other devices.[14−16]

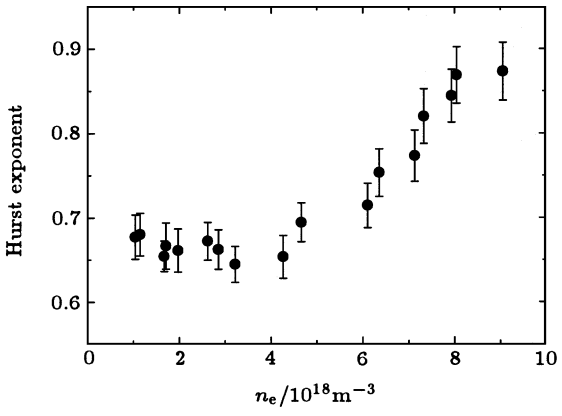


Fig.4. Profile of the Hurst exponents versus the electron density.

We also calculated intermittency coefficients with the multifractal analysis proposed by Carreras *et al.*[3] The specific method is described as follows. Given a time series of the fluxes $\{\Gamma_r(i),\ i=1,\ 2,\ \ldots,\ N\}$, the fluctuations of the $\Gamma_\mathrm{r}(i)$ is defined as $\tilde{\Gamma}(i) = \Gamma(i) - \langle\Gamma(i)\rangle$, here and hereafter $\langle\cdots\rangle$ is the time average, the variance of the $\Gamma_\mathrm{r}(i)$ is written as Var Γ_r. Now we introduce a measure

$$\varepsilon(1,i) = \tilde{\Gamma}_\mathrm{r}^2/\mathrm{Var}\Gamma_\mathrm{r}(1,i). \tag{2}$$

Then we construct a set of new records by averaging the measure over overlapping subblocks with time scale, T, different from that of the original flux series $\Gamma_\mathrm{r}(t)$. The averaged measure is defined as

$$\langle\varepsilon(T,i)\rangle = \frac{1}{T}\sum_{j=0}^{T-1}\varepsilon(1,i+j-m). \tag{3}$$

Here m is the overlapping number of two neighboring subblocks. For a self-similar time series, its q-moment of the measures over the scale T, $\langle\varepsilon(T,i)^q\rangle$, may have a power law as follows:

$$\langle\varepsilon(T,i)^q\rangle \approx (T/N)^{-K(q)}\,. \tag{4}$$

If the series is a pure self-similarity case (monofractal behaviour), the $K(q)$ scales asymptotically as a linear function of q. But for the multifractal case, the $K(q)$ has a nontrivial dependence on q. Knowing the $K(q)$, we can define the intermittency parameter $C(1)$:

$$C(1) = \mathrm{d}K(q)/\mathrm{d}q\,|_{q=1}\,. \tag{5}$$

For our experimental data, we take $T = 1, 2, \ldots,$ 200μs, then calculate $\langle\varepsilon(T,i)^q\rangle$ with different q for signals from each radial position. Figure 5 (a) illustrates the results of $\langle\varepsilon(T,i)^q\rangle^{1/q}$ versus T for the data from the radial position r=52cm. Here we have taken the $1/q$ power to make it easy to fit them into the same plot. In Fig.5 (a) we plot five curves with q=2, 4, 6, 8 and 10. Each curve is the averaged result over 10–15 shots and at least 20 data subsets of 4000 points for each shot. It can be seen that for each q, the curve has a power law (a linear function in log–log reference frame) in the time scaling from T=5μs to 50μs. When $T > 100\mu$s all curves tend to a saturation value 1, i.e. $\langle\varepsilon(T,i)^q\rangle^{1/q} \to 1$. In other words, in the long-time range of $T > 100\mu$s, the moments of measure are nearly independent of T, so the exponent $K(q)$ is practically zero. This feature reflects a monofractal structure of measure in the long-range of scales.

By fitting the plot of $\langle\varepsilon(T,i)^q\rangle^{1/q}$ versus T the power exponent $K(q)$ for each q can be obtained and thereby the intermittency parameter $C(1)$ can be deduced from the slope of the $K(q)$ based on Eq.(5). For data from each radial position we have repeated above calculations and a profile of the $C(1)$ versus the density n_e is obtained, as shown in Fig.5(b). The error bars include the statistical errors from fitting the moments of measure with a power function for each shot data and the statistical error of ensemble average. Figure 5 (b) clearly shows the intermittency level changing with density. In the low density region, the values of the $C(1)$ change little within 0.1–0.12. As the probes move radially inwards and the density increases, the intermittency level corresponds to rise till

up to 0.2. This result agrees with the bursty feature of the fluctuations of fluxes at high density (see Figs.2(a) and 3(a)).

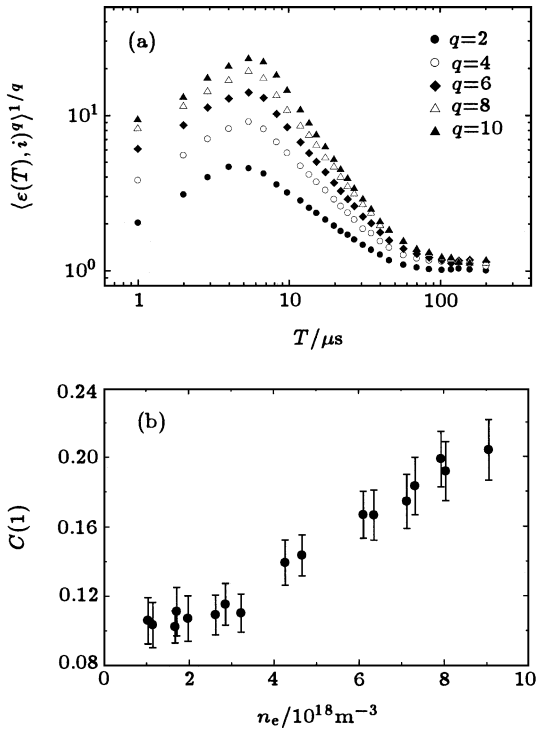


Fig.5. (a) $1/q$ power of the moments of the flux measure in the fluctuation range of time scales for the data from the radial position r=52cm; (b) the profile of the intermittency coefficient of the fluxes as a function of the electron density.

The increase of bursty events with increasing density means that those infrequent but large transport events play a more important role in higher density cases. This point can be testified by comparing the functional forms of the flux probability distribution functions (PDFs) at different radial positions. In order to make comparability of the PDFs of fluxes, we first normalize the fluxes to their averaged values, $\Gamma_n \equiv \Gamma(t)/\langle\Gamma(t)\rangle$. Then we calculate the flux PDF according to the following method:

$$p(\Gamma_n) = N_\Gamma/N, \tag{6}$$

where N_Γ is the number of values of Γ_n that fall within the range $\Gamma_n \pm W/2$, W is the interval length centred at Γ_n, and N is the total number of data points in $\Gamma(t)$. Typically, the value of Γ_n is in the range -20 to $+20$, and the full range of Γ_n is divided into 80 intervals of equal length (W=0.5). Finally, we conduct a similarity transformation $p(\Gamma_n) \to p(\Gamma_n) \times \langle\Gamma(t)\rangle$ to obtain a comparable function form for all measured positions. A comparison of four curves (whose original flux data are the same as that in Fig.3) is shown in Fig.6. We can see that all four PDFs have a clear non-Gaussian long time lag tails, which are the signature of long-range correlation transport events. Furthermore, the PDFs in the high-density case (at plasma edge) have a little larger tails than that in the low-density case (at SOL). The calculation of the contribution of the outward flux tail of the PDF to the overall outward flux can exactly verify it. The results calculated from Fig.6 show that 50% of the total flux is carried by the largest 7% of the flux events in the high-density case (for r=52cm). In contrast, in the low-density case (for r=57cm) the largest 10% of the flux events is needed to carry the same fraction of the total flux. These results are consistent with the experimental observations shown in Fig.2(a). This underlines the crucial importance of understanding and controlling the long-range transport events in spherical tokamak edge.

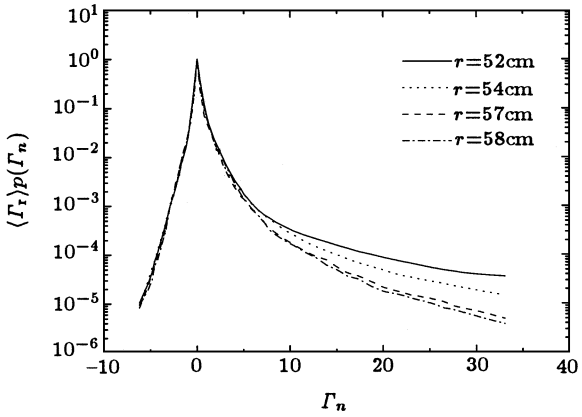


Fig.6. Comparison of the normalized PDF of the fluxes measured in four different radial positions.

A large number of the observations of intermittency properties of the edge turbulence have been made using a variety of techniques on many traditional aspect-ratio tokamaks and stellarators, as simply reviewed in Ref.[17]. Generally, the observations of the edge turbulence-induced particle transport fluxes in SUNIST are qualitatively similar to the previous observations in other magnetic devices, indicating both intermittency in short time scale and a self-similarity in long-range time scale. The common properties of these observations suggest that the anomalous transport in magnetic confinement devices may result from the same underlying dynamics such as edge parameter gradients, although the spherical tokamak structures have many advantages in suppressing MHD instabilities, compared with the traditional tokamak magnetic figures. It is difficult to estimate and judge the causes

of some differences in measurements between the STs and the traditional tokamaks. But the measurements here are important for enhancing the understanding of the anomalous transport. It is also noteworthy that in edge plasma of the NSTX the intermittent structure, called blobs, was also found with other than Langmuir probes (by imaging method) for Ohmic, L- and H-mode plasma conditions,[8] which support our measurements to an extent.

4. Conclusion

Measurements and analyses of the turbulence-driven transport fluxes in the plasma edge and the SOL region of SUNIST spherical tokamak have been performed by using data obtained from Langmuir probe array. Results show that the fluxes have both intermittency and a long-range correlation characters. The conditional statistics analysis indicates that the intermittent structures have a characteristic time width of about 30μs that is the typical fluctuation time scaling. Furthermore, the fluxes exhibit a multi-fractal character over the fluctuation time scales and a long-range correlation character with self-similar parameter $H > 0.5$ in the plasma confinement time scales. The levels of the intermittency and long-range correlation of the fluxes vary with the plasma density change. Specifically, in the low density (SOL region) case, fluxes show a low level of intermittency and self-similarity. But in the high density case, the intermittency, correlation time, and long-range dependence increase significantly, and the bursty events seem to mean the presence of block-like (or vortex-like) structures. These observations are consistent with the prediction of the avalanche-like model.

References

[1] Wootton A J *et al* 1990 *Phys. Fluids* B **2** 2879
[2] Carbone V *et al* 2000 *Phys. Plasmas* **7** 445
[3] Carreras B A *et al* 2000 *Phys. Plasmas* **7** 3278
Carreras B A *et al* 2001 *Phys. Plasmas* **8** 3702
[4] He Y X 2002 *Plasma Sci. Technol.* **4** 1355
[5] Chen S L and Sekigchi T 1965 *J. Appl. Phys.* **36** 2363
[6] Stangeby P C and McCracken G M 1990 *Nucl. Fusion* **30** 1225
[7] Wang W H *et al* 2004 *Chin. Phys. Lett.* **21** To be published
[8] Zweben S J *et al* 2004 *Nucl. Fusion* **44** 134
[9] Synakowski E J *et al* 2002 *Plasma Phys. Control. Fusion* **44** A165
[10] Johsen H *et al* 1987 *Phys. Fluids* **30** 2239
[11] Boedo J A *et al* 2001 *Phys. Plasmas* **8** 4826
[12] Rudakov D L *et al* 2002 *Plasma Phys. Control. Fusion* **44** 717
[13] Mandelbrot B B and Wallis J R 1969 *Water Resour. Res.* **4** 909
[14] Wang W H *et al* 2004 *Phys. Plasmas* **11** 2075
[15] Carreras B A *et al* 1998 *Phys. Rev. Lett.* **80** 4438
[16] Wang W H *et al* 2001 *Chin. Phys.* **10** 139
[17] Antar G Y *et al* 2001*Phys. Plasmas* **5** 1612