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Self-Organized Criticality Properties of the Turbulence-Induced Particle Flux at the Plasma Edge of the HT-6M Tokamak *

WANG Wen-Hao(王文浩)[1], YU Chang-Xuan(俞昌旋)[1], WEN Yi-Zhi(闻一之)[1], XU Yu-Hong(许宇鸿)[2], LING Bi-Li(凌必利)[2], GONG Xian-Zu(龚先祖)[2], LIU Bao-Hua(刘保华)[2], WAN Bao-Nian(万宝年)[2]
[1]*Department of Modern Physics, University of Science and Technology of China, Hefei 230027*
[2]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031*

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The power spectrum and the probability distribution function (PDF) of the turbulence-induced particle flux Γ in the velocity shear layer of the HT-6M edge region have been measured and analysed. Three regions of frequency dependence (f^0, f^{-1}, f^{-4}) have been observed in the spectrum of the flux. The PDF of the flux displays a Γ^{-1} scaling over one decade in Γ. Using the rescaled-range statistical technique, we find that the degree of the self-similarity (Hurst exponent) of the particle flux in the measured region ranges from 0.64 to 0.83. All of these results may mean that the plasma transport is in a state characterized by self-organized criticality.

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Recently, the self-organized criticality (SOC)[1] models as an effective mechanism to explain the anomalous transport in magnetically confined plasmas have been highly evaluated.[2−4] SOC systems can relax by avalanches (transport events of all sizes up to the system scales), so they are generally less sensitive to underlying parameters such as local fluctuations and gradient drives. SOC systems usually have two characteristic qualities: $1/f$ noise in power spectral "fingerprint"[1] and fractal (self-similar) structure both on temporal scale and in spatial aspects.[5] The $1/f$ behaviour is caused by the random overlap of the avalanches, and the self-similarity of fluctuations is an indication of the existence of long-range correlations. Simulations based on plasma instabilities (the resistive pressure-gradient-driven turbulence[6] and the ion temperature gradient turbulence[7]) have shown the SOC behaviour. Several experimental measurements (the plasma density, the floating potential and particle flux) also displayed the $1/f$ spectrum characteristics of SOC in magnetically confined plasmas.[4] In Ref. [8], we reported our results of the electrostatic fluctuations of the plasma density and the floating potential measured in the HT-6M tokamak. Results showed that, by considering the Doppler effects caused by the plasma $\boldsymbol{E}_{\mathrm{r}} \times \boldsymbol{B}_{\phi}$ flow velocity, all the Fourier power spectra have three distinct frequency regions with the spectral decay indices that are typical of SOC systems (0, -1 and -4). In this letter we focus on the properties of the radial particle transport due to electrostatic fluctuations at the plasma edge of the HT-6M tokamak. Analyses show that the turbulence-induced particle flux Γ has both of the characteristics: $1/f$ spectrum and self-similar structure. Furthermore, the probability distribution function (PDF) of the particle flux Γ also displays a $1/\Gamma$ scaling over one decade of Γ, which is a signature of the outward going particle flux with a long decay tail.

The experiments have been done in the ohmically heated discharges on the HT-6M tokamak. The details of the basic parameters of the device and the discharge conditions are the same as those in Ref. [8]. The plasma duration is about 70 ms with the current flat-top of 20 ms. A square array (side 2 mm) of four single Langmuir probes (each tip 2 mm in length and 0.5 mm in diameter) is used as a triple probe to provide local measurements of the fluctuating electron density $\widetilde{n}_{\mathrm{e}}$ and floating potential $\widetilde{\phi}_{\mathrm{f}}$. Here $\widetilde{n}_{\mathrm{e}}$ is estimated directly from the ion saturation current and floating potential fluctuations with neglecting $\widetilde{T}_{\mathrm{e}}$. The time-resolved turbulent particle flux is defined as $\Gamma(t) = \widetilde{n}_{\mathrm{e}}(t)\,\widetilde{E}_{\theta}(t)/B_{\phi}$, where $\widetilde{E}_{\theta}$ is the poloidal electric field fluctuation and deduced from $\widetilde{\phi}_{\mathrm{f}}$ measured by poloidally separated probes. The probe tips are orientated off the field lines to avoid shadowing of probe tips from each other. The profiles are measured with a shot-to-shot scan, and the measurements at each radial position are carried out in several identical discharges. All the data for analysis were collected during the period of the plasma current plateau and digitized at 1MHz with 12-bit resolution using a multichannel digitizer.

The plasma $\boldsymbol{E}_{\mathrm{r}} \times \boldsymbol{B}_{\phi}$ rotation effect on the spectral decaying indices of the edge fluctuations has been thoroughly discussed in Ref. [8]. For the turbulence-induced fluxes, the calculation showed that the effect is similar. Therefore, to avoid unnecessary repetition and to make it easy to compare with the predictions of SOC models, in this letter we mainly approach the data from the position where $E_r \approx 0$, except for the radial profile of the H exponent.

Figure 1 shows the temporal behaviour of the normalized particle flux Γ_{n} episode. Γ_{n} is defined as $\Gamma_{\mathrm{n}} \equiv \Gamma(t)/\langle\Gamma_{\mathrm{n}}(t)\rangle$, where angular brackets mean the time averaged over the duration of 20 ms. We can

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see that most of the time the particle transport is directed radially outwards and intermittent, i.e. a great many parts of the flux are carried out by a few large events within a very short time duration. To check this quantitatively, we integrated the transport events in magnitude and corresponding time intervals. The results show that nearly 10% of the largest outward flux events are responsible for 50% of the total transport. Similar results have also been obtained from other devices.[9,10] To explore further the properties of the flux, we need to study its probability distribution function and the Fourier power spectrum.

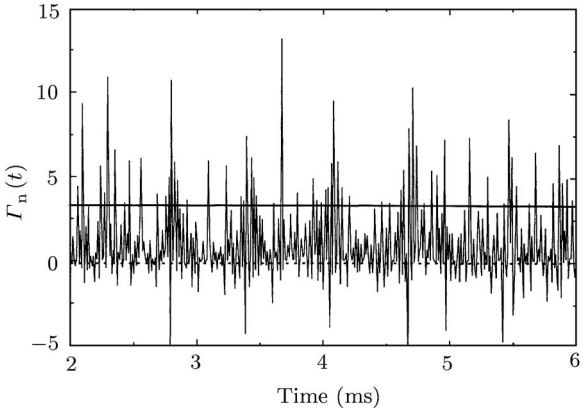


Fig. 1. Time signal of the radial normalized particle flux $\Gamma_n(t)$. Data are taken from the position where $E_r \approx 0$. The solid horizontal line refers to the fact that the large outward events above it within about 10% of the time hold a 50% portion of the total transports.

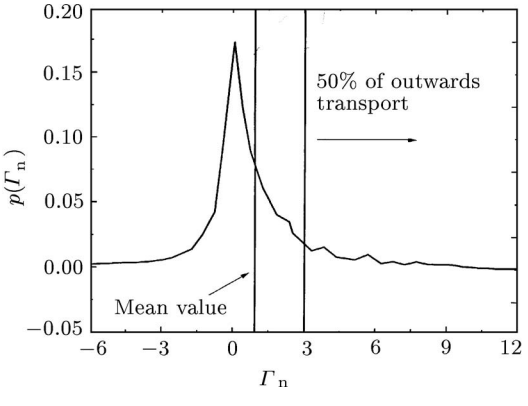


Fig. 2. The PDF of the flux $\Gamma_{\rm n}(t)$ shown in Fig. 1.

The PDF of the normalized turbulence-induced particle flux $p(\Gamma_{\rm n})$ is calculated by $p(\Gamma_{\rm n}) = N_{\Gamma_{\rm n}}/N$.[10] $N_{\Gamma_{\rm n}}$ is the number of values of $\Gamma_{\rm n}$ that fall within the range $\Gamma_{\rm n} \pm W/2$, where W is the length of an interval centered at $\Gamma_{\rm n}$ and N the total number of data points in the sample. Figure 1 shows that values of $\Gamma_{\rm n}$ mainly range from -10 to 20, hence, the full range of $\Gamma_{\rm n}$ values can be divided into 60 intervals of equal length ($W = 0.5$). The $p(\Gamma_{\rm n})$ of the local flux is plotted in Fig. 2. Apparently, the curve is asymmetric and has a long decaying tail that is caused by the large burst events. It is the tail that reveals the characteristic property of the long-range correlations of turbulent transport, i.e. the self-similar nature. We will further discuss this later in this letter.

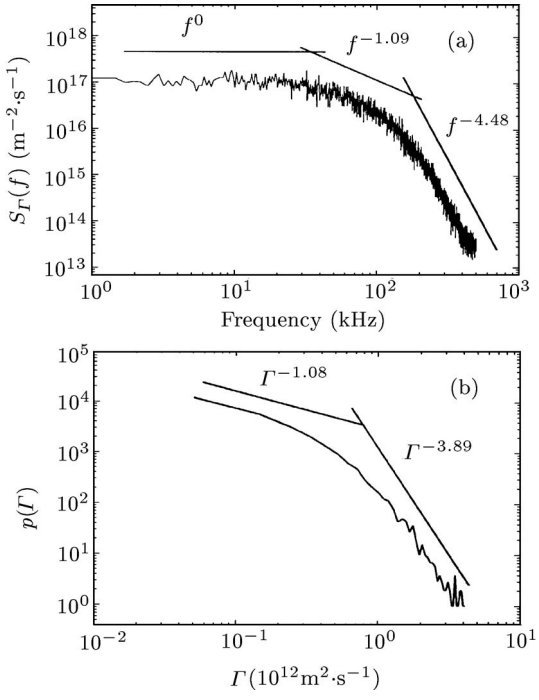


Fig. 3. (a) Power spectrum of $\Gamma(t)$, guidelines show f^0, f^{-1} and f^{-4}scalings; (b) PDF of $\Gamma(t)$, guidelines show Γ^{-1} and Γ^{-4} scalings.

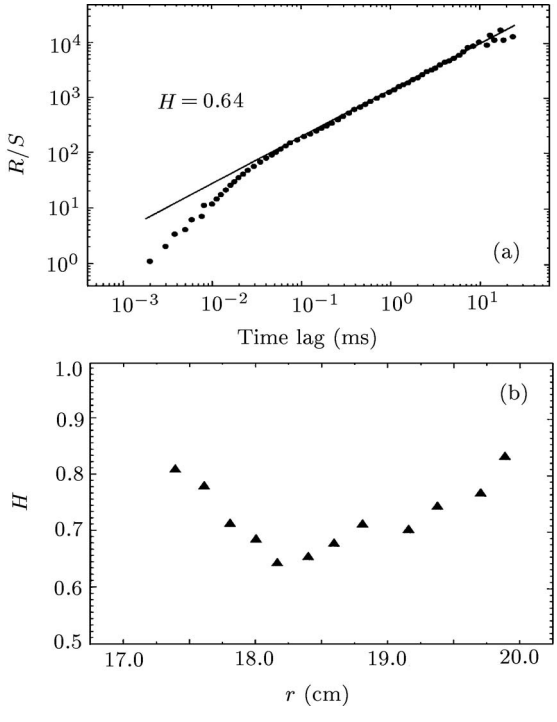


Fig. 4. (a) R/S as a function of time lag. Data are taken from the same sample as in Fig. 1. (b) The radial profiles of values of H of $\Gamma(t)$. Data are obtained from the proximity of the velocity shear layer. The position of the maximum velocity shear where $E_r \approx 0$ is located at 18.2 cm in radius.

Figure 3 shows the power spectrum and the PDF of $\Gamma(t)$. It is easily found in Fig. 3(a) that the spectral structure has three decay regions (f^0, f^{-1} and f^{-4}) which is the typical feature of the SOC system. According to the explanations of Hwa *et al.*,[11] the low frequency f^0 scaling region exhibits system-wide discharge events; the intermediate frequency regime with f^{-1} scaling accounts for the random superposition of avalanches and the high-frequency region of f^{-4} dependence (the indices of 3.5 to 4.5 are reasonable, for example see Ref. 4) is dominated by single avalanches. In addition, the PDF of the flux, $p(\Gamma)$, also shows two distinct power law dependent ranges, Γ^{-1} and Γ^{-4}, as shown in Fig. 3(b). In the region proportional to Γ^{-1} scales over one decade of Γ, the flux has a self-similar nature and, further, all events are equally important in terms of their contribution to the transport.[4] Note that in Fig. 3(b) only the outward part of the flux is plotted, with the inward portion being omitted for its much smaller magnitude.

To determine accurately the long decaying tail of the flux (i.e. self-similarity structure) in finite time series, a rescaled-range statistics (R/S) method[12] has been proposed. This method uses the Hurst exponent (H)[13] as an indication of the degree of the long time correlation. Thus the Hurst exponent (H) is called the self-similarity parameter. For a time series of length n, $X \equiv \{X_t : t = 1, 2, \cdots, n\}$, with a mean value $\overline{X}(n)$ and variance $S^2(n)$, the R/S ratio is defined as

$$\frac{R(n)}{S(n)} = \frac{\max(0, W_1, W_2, \cdots, W_n) - \min(0, W_1, W_2, \cdots, W_n)}{\sqrt{S^2(n)}}.$$

Here $W_k = X_1 + X_2 + \cdots + X_k - k\overline{X}(n)$. The expected value of R/S scales as $E[R/S] \xrightarrow{[n\to\infty]} \lambda n^H$, where H is the Hurst exponent. For $0.5 < H < 1$, there are long-range time correlations in time series; for $0 < H < 0.5$ one sees long-range anticorrelations; $H = 1$ means the process is deterministic and $H = 0.5$ corresponds to a short-range dependences.

We apply the R/S method to the flux time series obtained from different radial positions near the velocity sheared layer. A typical plot of R/S of the $\Gamma(t)$ versus time lag is shown in Fig. 4(a) (data are obtained from the same position as in Fig. 1). We can see that, except for the initial phase which may be linked with the decorrelation time of $\Gamma(t)$ (about $20\,\mu$s), the plot tends toward an "asymptotic" power law over a broad range of time lags from the order of 10^{-1} to 10 ms. The upper limit of the range is set by the sampled data length (20 ms). A fitting line gives $H \approx 0.64$. Figure 4(b) provides the radial profile of H of the particle flux $\Gamma(t)$ near the velocity sheared layer. The H values vary between 0.64 and 0.83, well above 0.5. A noticeable feature is that at $E_r \approx 0$ position H value of the flux reaches its minimums, almost the same as for $\widetilde{n}$ and $\widetilde{\phi}_{\rm f}$ (neither shown here). These results support the assumption of the SOC models that the shear flow can suppress long-range correlation[2] and are similar to H calculations for data from other devices.[14]

From all above results we can infer that the turbulence-induced transport in the edge of HT-6M is mostly caused by the huge burst events. These events have intermittent and long time correlation characteristic properties, thus can be seen as avalanches. In other words, the transport is an SOC-type behaviour.

In conclusion, to better understand the underlying transport dynamics, the power spectral analysis and the rescaled range statistics techniques (R/S) are applied to the turbulence-induced particle flux and its PDF measured by Langmuir probes. Three regions of frequency dependence (f^0, f^{-1}, f^{-4}) have been observed in the spectrum of the flux. The PDF of the flux displays a Γ^{-1} scaling over one decade in Γ. By the R/S technique, we find that the degree of the self-similarity (Hurst exponent) of the particle flux in the measured region ranges from 0.64 to 0.83. All these results are well consistent with the characteristic properties of an SOC system. This means that the edge plasma turbulence in the HT-6M tokamak may evolve into a critical state independent of local plasma parameters. It should be noted that investigations here are only for temporal behaviour. To fully understand the mechanism of the edge plasma turbulence-induced transport in magnetically confined devices, the exploration of the self-similarity in spatial scale is urgently needed. The relevant experiments are underway.

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References

[1] Bak P, Tang C and Weisenfelf K 1987 *Phys. Rev. Lett.* **59** 381
Bak P, Tang C and Weisenfelf K 1988 *Phys. Rev.* A **38** 364
[2] Diamond P H and Hahm T S 1995 *Phys. Plasmas* **2** 3640
Newman D N et al 1996 *Phys. Plasmas* **3** 1858
[3] Terry P W 2000 *Rev. Modern Phys.* **72** 109
Hayashi T et al 1999 *Plasma Phys. Control. Fusion* **41** A229
[4] Rhodes T L et al 1999 *Phys. Lett.* A **253** 181
Pedrosa M A et al 1999 *Phys. Rev. Lett.* **82** 3621
[5] Mandelbrot B B 1967 *Suppl. Phys. Fluids* **10** S302
[6] Carreras B A et al. 1996 *Phys. Plasmas* **3** 2903
[7] Garbet X and Waltz R E 1998 *Phys. Plasmas* **5** 2836
[8] Wang W H et al 2001 *Chin. Phys. Lett.* **18** 254
[9] Endler M et al 1995 *Nucl. Fusion* **35** 1307
[10] Carreras B A et al 1996 *Phys. Plasmas* **3** 2664
[11] Hwa T and Kardar M 1992 *Phys. Rev.* A **45** 7002
[12] Mandelbrot B B et al 1969 *Water Resour. Res.* **4** 909
Mandelbrot B B et al 1969 *Water Resour. Res.* **5** 422
[13] Hurst H E 1951 *Trans. Am. Soc. Civil Eng.* **116** 770
[14] Carreras B A et al 1998 *Phys. Rev. Lett.* **80** 4438