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Studies of Spectra of the Edge Plasma Fluctuations in Toroidal Magnetic Confinement Systems

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Abstract

Spectra of fluctuations for the ion saturation current, floating potential, and turbulent transport, measured in the plasma edge of different fusion devices (tokamaks and stellarators) have been compared. Turbulent spectra show a high degree of similarity between devices in the whole frequency range investigated, suggesting universality in plasma edge turbulence.

Keywords:

plasma turbulence, fluctuation phenomena, self-similarity, SOC system, fusion device, Langmuir probe

1. Introduction

Recent theoretical investigations have shown that certain non-equilibrium systems often naturally evolve towards a state that is nearly critical [1,2]. Those dynamical systems are thought to be described in the framework of the self-organized criticality (SOC), that predicts the existence of transport induced by avalanches, generating self-similar behaviour of turbulence in time and space.

It has been argued theoretically, that the SOC models could shed some light to understand some of the observed dynamics in plasmas [3,4]. The existence of a critical profile gradient, transport by avalanches or non-local behaviour in plasmas, could be a consequence of SOC dynamics [5]. Recent experimental works have shown the existence of long-range time correlation in the plasma edge, that shows the potential role of SOC phenomena in plasma transport [6,7].

The similarity observed in the statistical properties of the turbulent transport in different devices, suggests a generic character of the plasma turbulence. A common feature of the radial $\boldsymbol{E} \times \boldsymbol{B}$ turbulent transport, in the plasma boundary region, is that it is bursty [8]. A significant fraction of the total flux can be attributed to the presence of large amplitude and sporadic bursts [9], that might be an indication of transport close to instability threshold (i.e. SOC dynamics).

2. Experimental Set-Up

Edge fluctuations and turbulent transport have been characterized by means of measurements of the ion saturation current (I_s) and floating potential (V_f) signals obtained using Langmuir probes ($I_s \propto n\, T_e^{1/2}$ and $V_f \approx V_p - \alpha T_e$, being n the electron density, T_e the electron temperature, V_p the plasma potential and the parameter α

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Table 1 General characteristics of devices and plasmas under study.

DEVICE	a (m)	R (m)	B (T)	$\tilde{n}_e$ ($\times 10^{19}$ m^{-3})	Other Plasma Characteristics
TJ-I	0.09	0.3	1	1-3	Ohmic Heating Ip ≈ 35 kA
JET	1.2	2.9	2.6	1-2	Ohmic Heating Ip ≈ 2.5 MA
TJ-IU	0.10	0.6	0.67	0.5	ECR Heating 37.5 GHz, 200 kW iota(0) ≈ 0.23
W7-AS(1)	0.17	2.0	1.25	1.5	ECR Heating 70 GHz, 200 kW iota(0) ≈ 0.243
W7-AS(2)	0.18	2.0	2.5	3	ECR Heating 70 GHz, 300 kW iota(0) ≈ 0.355

≈ 3 for hydrogen plasmas) [10]. The time evolution of the radial turbulent particle flux has been computed as $\Gamma(t) = \tilde{n}(t)\tilde{E}_\theta(t)/B$, where $\tilde{n}(t)$ and $\tilde{E}_\theta(t)$ are the fluctuating components of the density and the poloidal electric field respectively and B is the toroidal magnetic field. The poloidal electric field E_θ has been deduced from floating potential signals measured by poloidally separated probes. Table I shows the main characteristics of the devices and plasmas under investigation.

In one of the devices (TJ-IU) poloidal and radial wave-number spectra have been obtained from floating potential signals simultaneously measured by poloidally ($\Delta_\theta \approx$ 0.3 cm), and radially ($\Delta_r \approx$ 0.6 cm) separated probes [11].

3. Spectral Analysis

Fourier spectra of the fluctuations, have been determined in the plasma edge region of the above mentioned devices. In order to avoid Doppler shift effects, the compared spectra have been obtained from data measured at the zero flow position, $v_\theta \approx 0$, that is to say, at a probe position close to the velocity shear layer location [10]. Figure 1 shows the ion saturation current fluctuations spectrum of the TJ-IU edge plasma. The fluctuation spectrum is consistent with the existence of three distinct frequency ranges: In the low frequency region ($f <$ 10 kHz) the spectra are rather flat; at higher frequencies ($f >$ 100 kHz) the spectra fall approximately as $1/f^{(2\text{-}3)}$ and for an intermediate frequency region the spectrum decay index is close to −1. In the framework of SOC models, this $1/f$ behavior arises from the existence and random superposition of avalanches.

Figure 2 shows the I_s fluctuations spectra measured in different devices. The shape of the frequency spectra

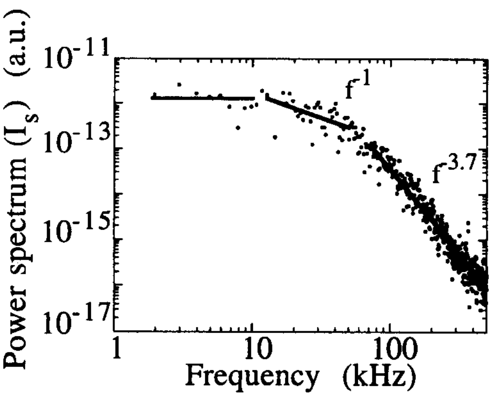

Fig. 1 Ion saturation current fluctuations spectrum obtained in the zero flow position of the TJ-IU plasma.

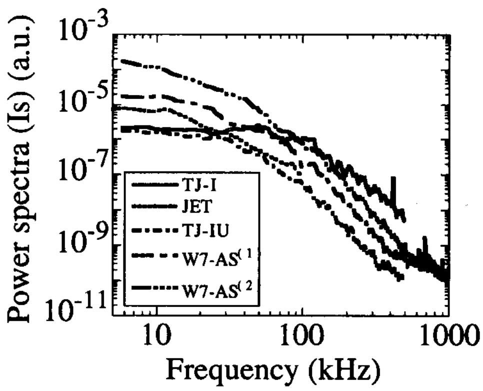

Fig. 2 Frequency spectra of fluctuations of the ion saturation current.

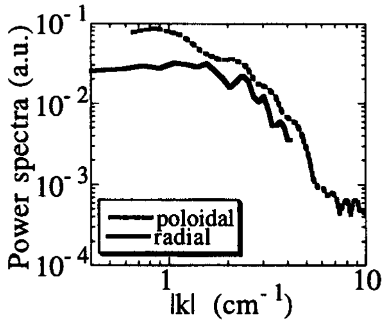

Fig. 3 Poloidal and radial k-spectra in the plasma edge of the TJ-IU (r_{shear}-r) ≈ 2 cm.

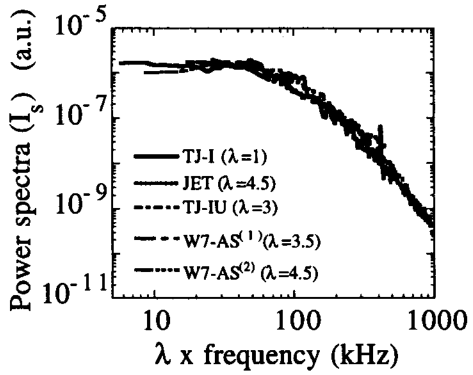

Fig. 4 Re-scaled frequency spectra of the ion saturation current fluctuations.

and the frequency range over which the $1/f$ holds, change from machine to machine and with plasma conditions. In a sand pile, the $1/f$ range depends on the size of the pile, L, and on the probability of dropping sand. For fusion experiments it is very difficult to set up, a priori, a parameter dependence of the frequency range. An empirical approach is taken, by re-scaling the spectra in the manner described below.

Self-similarity in turbulence is believed to occur in both space and time. The comparative study of k-spectra could give a valuable information to complete the picture of the turbulence behaviour in plasmas. Also a better understanding about the instabilities threshold is expected from the comparison between the poloidal and radial wave-number of the plasma fluctuations. Poloidal and radial k-spectra, simultaneously obtained in the plasma boundary of TJ-IU, are shown in Fig. 3. Experiments are under way to compare the spatial structure of fluctuations in different devices.

4. Scaling of Experimental Data

Techniques of finite size scaling have been applied to compare between the fluctuation spectral distribution of sand-piles $P(\omega)$, that depends only on the frequency ω and the size of the sand-pile L :

$$P(\omega, L) = L^{-\beta} g(\omega / L^{\nu}), \tag{1}$$

where the fixed scaling function g and the β and ν parameters are to be determined [12]. The function g, if it exists, reflects the universal character of the subjacent process [13,14].

In the case of fluctuation measurements in fusion plasmas, the fluctuations spectra have been re-scaled using the ad-hoc expression:

$$P(\omega) = P_0 g(\lambda \omega), \tag{2}$$

where λ and P_0 are parameters to be determined for each machine and operational conditions. If the function g exists, there is a universal class that the spectra belong to. The P_0 parameter normalizes the maximum value of the fluctuation level between the different devices. The value of λ gives an indication of how to compare frequency ranges between different machines.

Figure 4 shows the re-scaled frequency spectra of the ion saturation current fluctuations for TJ-I, TJ-IU, W7-AS and JET using the TJ-I tokamak as reference (i.e. $\lambda_{TJ\text{-}I} = 1$). The obtained values for λ, are also shown in Fig. 4. The size of the machine is not directly related to the λ parameter or at least it is not the only parameter that affects its value. Although there is a high degree of similarity among the spectra from different devices, the form of the scaling assumed in Eq. (2) might be an oversimplification, and turbulent decorrelation effects at the shear location might contribute to explain the similarity.

5. Conclusions

The obtained results support the view that plasma turbulence displays universality, and are an indication of edge plasma turbulence evolving into a critical state independently of the size and plasma characteristics of the device. It is not clear the relation between the scaling parameter λ and the global plasma parameters.

In order to verify the existence of finite size scaling (unique to critical systems) in the statistical properties of plasma fluctuations it is important to investigate fusion plasmas with similar plasma properties (magnetic topology, collisionality, etc.) but with different plasma sizes.

As many transport models (i.e. SOC) require the gradients to be close to a threshold, a systematic study of the spatial and temporal structure of fluctuations as a function of the proximity to instabilities threshold is needed.

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