Long-Range Correlation Analysis of Plasma Turbulence

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Introduction

Some characteristics of transport in fusion plasmas indicate that it may be a manifestation of a self-organized and critical system (SOC) [1]. These characteristics are: a) the existence of critical gradients, b) the existence of transport events that do not obey diffusive equations and c) global scalings involving space scales that exceed diffusive scales [2]. If a magnetically confined plasma is a SOC system, this would profoundly change our view of plasma transport and might lead to novel ways of controlling turbulence. In the present paper, we summarize the evidence accumulated to date supporting the SOC hypothesis.

The clearest evidence would involve simultaneous time- and space-resolved measurements. However, lacking these, much insight can be gained from auto- and cross-correlation and spectral analysis. In the following, we will enumerate various characteristics of the turbulent signals that can be detected and their relation to the SOC hypothesis. Most analyses were done with Langmuir probe signals at various devices.

Self-Similarity

In earlier work we have focused on the accurate determination of the self-similarity parameter, H (the "Hurst coefficient"), which is closely related to the decay of the auto-correlation function (ACF) at long lags, and implies the existence of long-range time correlations [2, 3]. We found strong indications for the existence of self-similar behaviour in all plasma edge turbulent data we examined, which included data from a wide range of magnetic confinement configurations (tokamak, stellarator, RFP) [2, 3]. The value of H was determined for time lags greater than the turbulence decorrelation time (the asymptotic regime) to exclude trivial linear correlation effects. Remarkably, the value of H in the edge plasma of all devices examined is between 0.6 and 0.74, a rather narrow range, and significantly different from the uncorrelated noise value of $H = 0.5$, a significance that could be illustrated experimentally by scrambling the phase information of the sampled signals, thus reducing H to 0.5 as expected. By contrast, the range of values in the scrape-off layer (SOL) displays a much larger variation, between 0.5 and 1, possibly due to the open field line configuration in the SOL, with strongly different characteristics from one machine to another. A non-fusion device (Thorello) yielded $H = 0.5$ (no self-similarity) [2]. At W7-AS, a radial profile of H was obtained that proved to be reproducible in various similar discharges, having a minimum near the separatrix. It was therefore conjectured that the high flow shear near the separatrix destroys the long-range correlations and thus reduces the self-similarity of the turbulent signals. This is in accordance with the observation of increased Gaussianity near the shear flow layer as reported in [4].

In conclusion, self-similarity and long-range correlations are present in the plasma edge of fusion devices. This is consistent with SOC, although other mechanisms might also generate this behaviour.

Cross analysis

The Hurst analysis was extended to the cross-correlation function [5, 6]. This novel analysis permits determining whether the long-range correlations in time that are detected persist radially and thus affect radial transport (through "large transport events"). The technique was shown to be much more robust than the usual cross correlation analysis, although closely related. For the sandpile model, clear evidence for long-range correlations in time *and* space were obtained. The application of this technique to experimental data is promising, but clean and steady-state data from various radial points simultaneously are required. An initial application to beam-emission spectroscopy (BES) data at DIII-D [6] showed the existence of long-range spatial correlations. A similar analysis of BES data at W7-AS is in progress.

Probability Distribution Functions

Since the turbulence is self-similar, the Probability Distribution Functions (PDF) may also be expected to display self-similarity, i.e. when averaging the signal over time, the PDF changes amplitude but not shape. Indeed, the study of the rescaled PDF of the measured flux as a function of the averaging parameter, m, yields two regions (Fig. 1). In the first region, for m smaller than or equal to the turbulence decorrelation time, the behaviour is highly self-similar ($H = 0.85$), and the fluxes have long "tails" that decay slowly, the PDF being slightly skewed towards outward flux. Due to the slow decay, a large fraction of the transport is carried by the relatively scarce large events, as was shown earlier in [7, 8]. On the other hand, in the second region, for m larger than the turbulence decorrelation time ($\approx 20\ \mu$s or 40 points), the self-similarity parameter is reduced somewhat ($H = 0.58$), but the asymmetry is strongly increased. The negative part of the PDF all but disappears, so that nearly all transport events are outward.

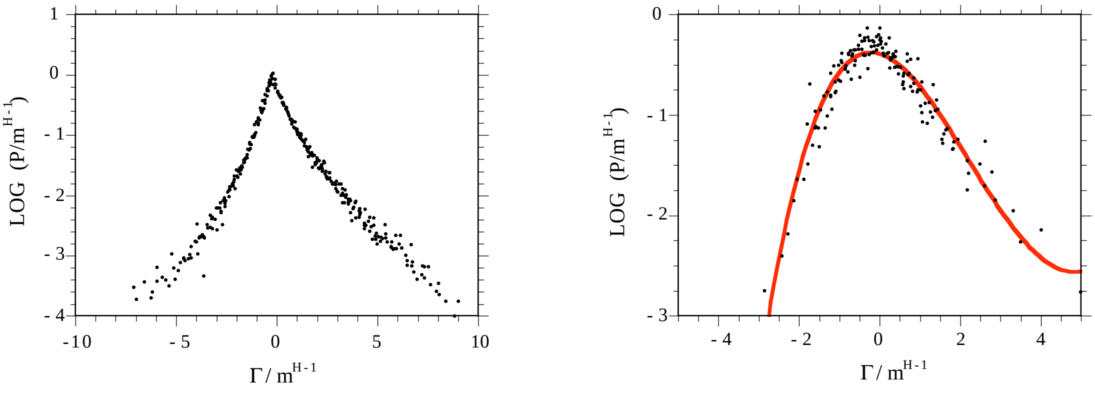

Fig. 1 Probability Distribution Function, data from a Langmuir probe at W7-AS, 100.000 points at 2 MHz. Left: superposed rescaled PDFs for m=1, 2, 4, ..., 32. Right: superposed rescaled PDFs for m=64, 128, ..., 1024.

We speculate that the two distinct regions of the PDF correspond to two transport mechanisms. In the first (low-m) region, the flux is simply due to Gaussian electric field and density fluctuations with a small level of correlation between them. This would correspond to the usual eddy-type transport and generates the PDF as observed [8]. To explain the PDF at high *m*, however, one would need fluctuation pulses with a high degree of coherence. A simple explanation for such a situation can be found in transport by avalanches (a change in turbulence level at a given position affects the average gradients, which are free energy sources, thus triggering turbulence in the vicinity). However, other explanations cannot be ruled out.

Spectra

As is well known from the original papers on SOC (e.g., [1]), this hypothesis leads to power spectra of the relevant quantities that decay roughly as 1/*f*. Therefore, we made a considerable effort to quantify the spectral shapes of the turbulence in plasma edge turbulence. A first obstacle is the fact that measurements are not made in the plasma reference frame, which rotates at high speed. Therefore, the spectra are necessarily distorted by the Doppler effect. As we show in [9, 10], this strongly affects the decay exponent α in the spectral shape $P(\omega) \propto \omega^{-\alpha}$. Consequently, we only studied spectral shapes near the radial point where the poloidal velocity is close to zero. We have shown that spectra from many different devices can be mapped onto one another through a simple scaling transformation $P(\omega) = P_0 g(\lambda\omega)$. This is a rather remarkable result that may have escaped attention earlier because the influence of the Doppler effect was underestimated, and is a strong indication for universal behaviour in edge turbulence.

A further refinement of this analysis involves the identification of several frequency ranges in the spectra, each with their own decay index, rather similar to the existence of various self-similarity regimes in the Hurst analysis or the analysis of the PDF mentioned above. The spectra were found to display three distinct ranges: at low frequencies, $\alpha = 0$, at intermediate frequencies, $\alpha \approx 1$, and at high frequencies, α = 3-5. The frequency transition or "break" points are machine-dependent as shown in the previous paragraph, but interestingly it was found that at least in the two devices for which such data were available (JET and W7-AS), the spectral flux function [11] peaks in the region where $\alpha \approx 1$ (Fig. 2), indicating that the 1/*f* self-similar regime is essential to global transport, and not marginal as has been suggested.

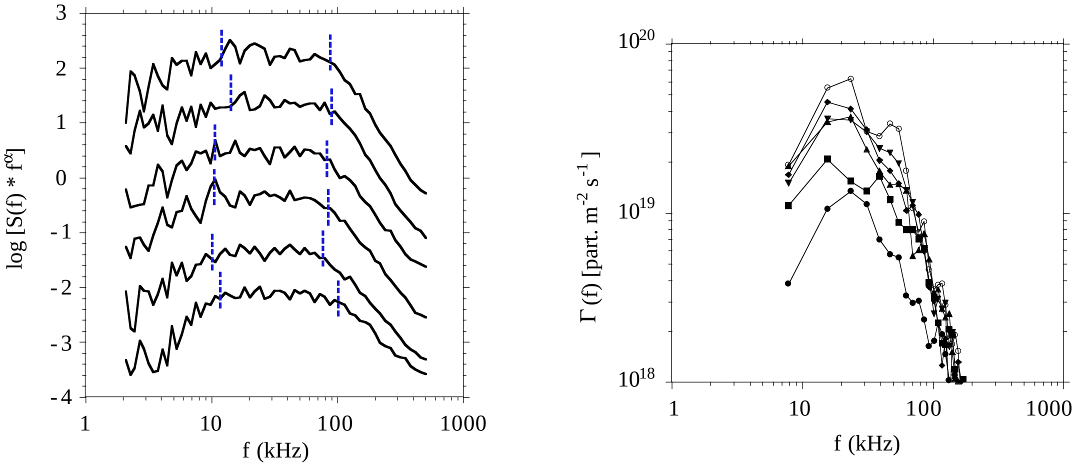

Fig. 2: Power spectra for 4 different discharges at W7-AS. Left: Power spectra at various time windows (20 ms length) near the shear flow layer, multiplied by f^{α} to flatten the central region. Right: spectral flux function showing that the major contribution to the total flux is in the intermediate frequency region.

Conclusions

In the present paper, we have summed up the experimental evidence for SOC. We have clear self-similarity of the fluctuations in the plasma edge in all fusion devices studied, with the self-similarity parameter *H* being clearly distinct from its uncorrelated value. This is equivalent to the statement that there exist long-range correlations. We found indications that *H* may be reduced through decorrelation by shear flow. We have shown how this analysis may be extended to the cross correlation.

The shape of the PDF was studied as a function of a smoothing parameter *m*. The PDF was found to separate into two distinct self-similarity regimes, associated with the *H* value. An explanation of the shape of the PDF in terms of eddy transport and avalanches was put forward.

The shape of turbulent spectra in many devices was compared, taking into account the Doppler effect. The spectral shapes of the turbulence in many devices was found to be quite similar, pointing towards the possible existence of universality in edge turbulence. Closer analysis revealed the existence of three distinct frequency regions in the spectra, with the central region decaying like $1/f$ and coinciding with the peak in the spectral flux function, so that this self-similar regime contributes strongly to global transport.

Together with the rather general observations about global transport in the introduction, these observations form a considerable body of evidence in favour of a SOC description of plasma transport. However, other explanations cannot be ruled out until temporally *and* spatially resolved data become available for analysis.

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