Abstract

We applied conditional and wavelet analyses to identify coherent structures in the non-Gaussian intermittent electrostatic fluctuations in the scrape-off layer at CASTOR tokamak.

1. Introduction

Turbulent electrostatic fluctuations are measured systematically with poloidal arrays of Langmuir probes in CASTOR tokamak. The Probability Density Functions (PDF) of the observed turbulence deviates from the Gaussian behavior [1]. These features show the existence of intermittency with formation and destruction of coherent structures. Here, we applied the following statistical techniques to obtain information about intermittency, coherent structures, and their nonlinear interactions at the scrape-off layer of this tokamak.

- **Conditional averaging technique** [2] follows the statistical evolution of selected conditions in the measured fluctuations. If a strongly coherent component exists in the fluctuation, this component should exhibit correlation lengths and lifetimes significantly larger than most of the fluctuation levels examined.

- **Wavelet technique** resolves short-lived events, pulses, and intermittency. Definitions of cross-spectrum and cross-coherence with wavelets are analogous to the usual definitions of Fourier analysis. The coherence spectrum provides the correlation evolution between two time series at a particular frequency band [3].

- **Bicoherence technique** detects phase coupling between short lived wavelets rather than between modes as Fourier bicoherence [4-6].

2. Results and Discussion

Here we analyze data measured by two arrays (ten tips spaced poloidally by 5 mm) of Langmuir probes, which are spaced toroidally by 10.5 mm. The first array measures the ion saturation current ($I_{sat}$) and the second one measures the floating potential ($\varphi$) [1]. The plasma current is kept at $I_p = 6$ kA ($q(a) \approx 15$). Signals were digitized with the rate 3.25 μs/sample.

Gaussian signals have skewness $S=0$ and kurtosis $K=3$. In our data the $I_{sat}$ fluctuations deviate from the Gaussian distribution significantly. Fig. 1 shows the PDF for $\varphi$
(S=0.04±0.02, K=3.07±0.04), and \( I_{\text{sat}} \) (S=0.66±0.02, K=3.40±0.04). Similar results are obtained with all probes suggesting intermittency with long-scale length coherent structures.

Coherent structures are detected by means of conditional averaging of the fluctuation amplitudes. The conditional average, \( \varphi_{\text{cond}}(r+\delta r, \tau) \) is approximated by a power series representation around the condition, \( \Phi_c \), applied to the signal at the reference point \( r \), and time \( t \); \( \varphi_{\text{cond}}(r+\delta r, \tau) \approx \sum_{i=1}^{\infty} \alpha_i(\delta r, \tau) [\Phi_c]^i \);

where the coefficients \( \alpha_i \) depend only on the separation, \( \delta r \), and the time delay, \( \tau \), between the signal at the reference probe and the signal of the other probes [2]. Fig. 2 shows the conditional averages at \( r=9.0 \) cm for \( I_{\text{sat}} \) fluctuations.

The same aspect is obtained for \( \varphi \) fluctuations. Cross-correlation functions for \( \varphi \) fluctuations are in good approximation to conditional average. However, this is not so for the \( I_{\text{sat}} \) fluctuations. The conditional correlation length, \( L_d \), and lifetime, \( L_t \), can be obtained by fitting the decay of the peak of the conditional average to an exponential function. Figs. 3 show \( L_d \) and \( L_t \) for conditions \( \Phi_c \) ranging from -2.0\( \sigma \) to 3.0\( \sigma \) for \( \varphi \) and for \( I_{\text{sat}} \) fluctuations. The changes in correlation lengths and lifetimes for different conditions for \( \varphi \) fluctuations are less than 7\%. For \( I_{\text{sat}} \) the variation in \( L_d \) for different conditions is \( \approx \)8\%, while the variation in \( L_t \) is \( \approx \)32\%. Moreover, we observed a pronounced asymmetry between positive and negative conditions. Larger correlation lengths and lifetime occur at larger conditions. This result seems consistent with the hypothesis that coherent structures, at larger amplitudes, would have long lifetimes compared with structures with a smaller condition.
Wavelet power spectra of \( \varphi \) and \( I_{\text{sat}} \) show intermittency at low frequencies. Fig. 4 shows the temporally resolved coherence between two poloidally separated probes for \( \varphi \), (a), and \( I_{\text{sat}} \) (b). Noise level is \( \approx 0.15 \) for low frequency components. The coherence is highly intermittent for both kind of fluctuations lifetimes compared with structures with a smaller condition.

Since the wavelet scale lengths can be interpreted as inverse frequencies, the wavelet-bispectrum can be interpreted as the amount of coupling between wavelets of frequencies such that \( f = f_1 + f_2 \). The squared wavelet-bicoherence \( [b^w(f_1,f_2)]^2 \) is the normalized squared bispectrum with values between 0 and 1. The summed wavelet-bicoherence is defined as \( [b^w(f)]^2 = \sum [b^w(f_1,f_2)]^2 \). Wavelet-bicoherences are calculated on a frequency grid with 256 points from 0 to 307.7 kHz and selecting five data sections of \( \approx 3.3 \) ms. Figs. 5 show the summed wavelet-bicoherence for \( I_{\text{sat}} \) at two intervals of the discharge (0-3.3 ms and
13.2-16.5 ms). The summed wavelet-bicoherence shows that the maxima are mainly due to sum frequencies in the range of 10-30 kHz. Although, turbulent structures are not constant in time, the interval from 13.2-16.5 ms shows a rather strong bicoherence. Two peaks at $\approx 10$ and 20 kHz indicate a structure that is not clearly present at the interval 0-3.3 ms and even in the other intervals. Further results about turbulent particle flux and wavelet bispectral analysis will be reported later in a full-length article.

This work supports the efficacy of wavelet analysis in analyzing nonstationary plasma fluctuations and demonstrates a better detection of turbulence nonlinearity that could be compared with numerical models of chaos and turbulence.

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References