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Statistical Properties of Plasma Edge Turbulent Flux in L-2M Stellarator

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Abstract

In the present work we have studied the statistical properties of edge plasma fluctuations and turbulent transport in L-2M stellarator. Time-resolved frequency spectra and coherence coefficients from two separate probe system (wavelet spectral analysis) showed the existence of long-living dynamic structures in low-frequency edge turbulence. The measured fluctuation induced fluxes had burst character. A significant part of the total particle flux was carried out by sporadic transport bursts. The probability distribution function of the fluctuation transport had significant non-gaussian features (the local particle flux was intermittent). Resistive interchange MHD instabilities are considered as a mechanism for the observed turbulent characteristics in the plasma edge region of L2-M stellarator.

Keywords:

turbulence, transport, flux, plasma instabilities, stellarator

1. Introduction

Turbulent transport in the edge plasma region is considered as one of the processes that can influence on the global plasma confinement in the toroidal devices with various magnetic field configurations. Therefore, the investigation of edge plasma fluctuation characteristics (fluctuation spectra, radial correlation lengths, statistical properties and the dependencies on magnetic shear) is an important issue in the fusion research community [1,2 and references therein]. With this goal the experiments were carried out in the L-2M stellarator [3] to investigate the statistical properties and the radial structure of fluctuations and turbulent transport in L2-M plasma boundary region.

2. Experimental Set-up and Analysis Tools

The experiments considered in the present work were carried out in the plasma boundary region of the L2-M stellarator (R=100 cm, average plasma radius $<a_p>$ =11.5 cm, B_T=(1.2−1.4) T) [3]. A characteristic feature of the L-2M device is the high value of magnetic shear, $Q=(d\iota/dr)\, r^2/(R\iota)$ (ι being the rotational transform, r is the averaged radius of the magnetic surface), in the plasma boundary region whereas magnetic shear is small at the plasma core. In particular, in the edge plasma region magnetic shear decreases from Q=0.3 at x=1 to Q=0.1 at x=0.8 ($x=r/r_s$, r_s being the separatrix radius). Edge fluctuations were investigated using Langmuir probes in ECRH plasmas: P_{ECRH}=100−200 kW, gyrotron pulse duration 12 ms (starting from 49 ms), $<n>=1.5\times10^{13}$ cm^{-3}, $T_e(0)$= 400 eV. At the edge region (x=0.8−0.9) T_e=30−40 eV and $n_e=2-3\times10^{12}$ cm^{-3}.

To investigate the radial structure of fluctuations and turbulent transport two radially separated (Δr=7

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mm) and moveable triple probes were used [4-6]. Two tips of each set of triple probes aligned perpendicular to the magnetic field and poloidally separated (Δ= 7 mm) are used to measure fluctuations of the poloidal electric field $\tilde{E}_\theta$ deduced from floating potential and neglecting electron temperature fluctuation effects (*i.e.* $\tilde{E}_\theta=(\tilde{\varphi}_1-\tilde{\varphi}_2)/\Delta$). Another tip is biased at a fixed voltage in the ion saturation current regime to measure density fluctuations ($I_s \propto \tilde{n}$). The turbulent radial particle flux has been computed from the measured values of ion saturation current and electric field fluctuations. We neglect of $\tilde{T}_e/T_e$ effects on turbulent radial particle flux in accordance with the results on other devices and computer estimations [1,2 and references therein].

Signal were digitized at 1 MHz using a 10 bit digitizer. Wavelet analysis tools have been used to characterize the structure of fluctuations [7]. The power distribution function (PDF) of time resolved turbulent transport ($\Gamma_n=\tilde{\Gamma}_n/<\tilde{\Gamma}>$) had been computed.

3. Experimental Results

3.1 Plasma profiles and radial structure of fluctuations

The power distribution function (PDF) of the computed turbulent local flux is non symmetric. Figure 1 shows the PDF of the turbulent fluxes computed at the plasma edge region. In agreement with previous experiments, large amplitude bursts account for significant part of the total local flux [8]. Furthermore, the non-gassuian features of the PDF increase for measurements taken radially inward in the plasma edge region.

3.2 Cross correlation of fluctuations and turbulent fluxes

The time resolved radial coherence for ion saturation current fluctuations were measured by probes radially separated Δr=7 mm. During the ramping up of the plasma density the radial coherence is quite small, whereas the radial coherence increases during the plasma flat top (55–60 ms) for high frequency fluctuations (> 100 kHz). Similar results were found for floating potential fluctuations. Figure 2 shows the frequency resolved cross coherence for ion saturation current fluctuations computed during the time window (55–60) ms at different radial locations ($0.86<x<1$). In the proximity of the separatrix ($x=1$) the radial coherence is dominated by low frequencies. On the contrary, at the plasma edge ($x=0.9$) the radial coherence increases (up to 0.9–1) for high frequency components (> 100 kHz) whereas coherence for the low frequency components (< 100 kHz) is less than 0.5. These highly radially correlated fluctuations (with frequencies above 100 kHz) do not contribute significantly to the fluctuation spectra dominated by low frequencies (less than 100 kHz). The radial coherence of the turbulent particle flux is smaller than the radial coherence of fluctuations and the turbulent flux is mainly determined by the low frequency components.

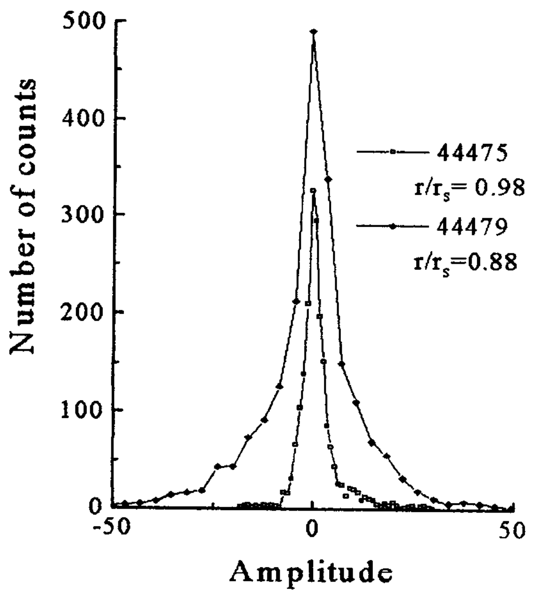

Fig. 1 PDF of the turbulent fluxes computed at the plasma edge region.

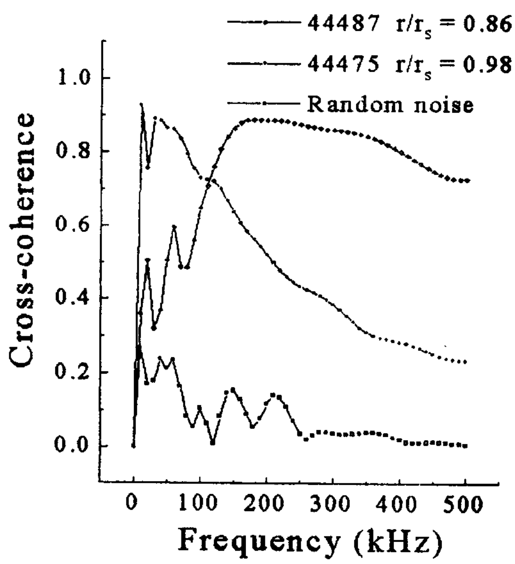

Fig. 2 Ion saturation radial coherence for ion saturation current fluctuations measured by probes radially separated Δr=7 mm at different radial locations in L2-M stellarator.

The structure of density fluctuations is bursty. It is possible to distinguish two kind of bursts: those with fast rise time (a few μs) an with slow decay time (*i.e.* asymmetric bursts) and bursts with relatively slow rise time (tens of μs). For example, the time evolution of ion saturation current fluctuations measured simultaneously at two different radial locations (Δr=7 mm) in a short time window (2 ms) is shown in Fig. 3(a). It is interesting to note that I_s-bursts are radially correlated and this correlation is detected in the wavelet cross-coherence (Fig. 3(b)); I_s bursts with fast rise time coincide in time with an increase in the value of the frequency wavelet cross-coherence at high frequencies.

Wavelet coherencies in the poloidal and in the radial directions were investigated for I_s and V_f fluctuations (Fig. 4). Whereas the radial coherence of fluctuations is dominated by high frequencies (>100 kHz), the poloidal coherence is higher in the low frequency range. This result shows that the frequency resolved radial and poloidal coherence of fluctuations are asymmetric in the plasma edge region of L-2M stellarator.

The influence of the limiter position (r_L) on the radial structure of fluctuations has also been investigated. Interestingly, the radial coherence of high frequencies disappears when the limiter is inserted in the plasma edge (r_L/r_s=0.8) leaving the probes at limiter shadow.

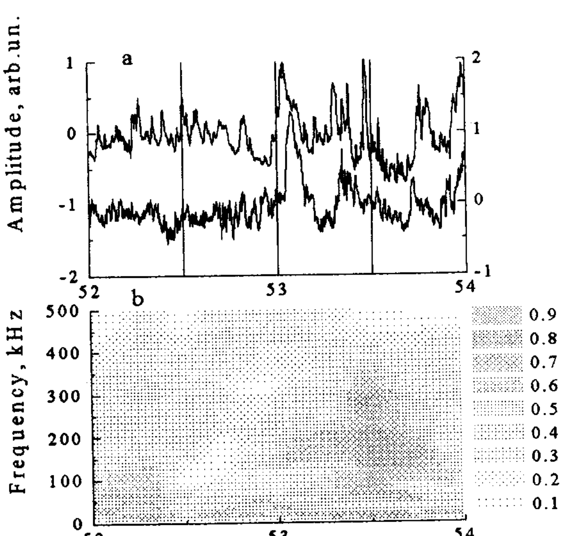

Fig. 3 a)The time evolution of ion saturation current fluctuations measured simultaneously at two different radial locations (Δr=7 mm). b) The time evolution of frequency resolved wavelet cross-coherence of the same signals.

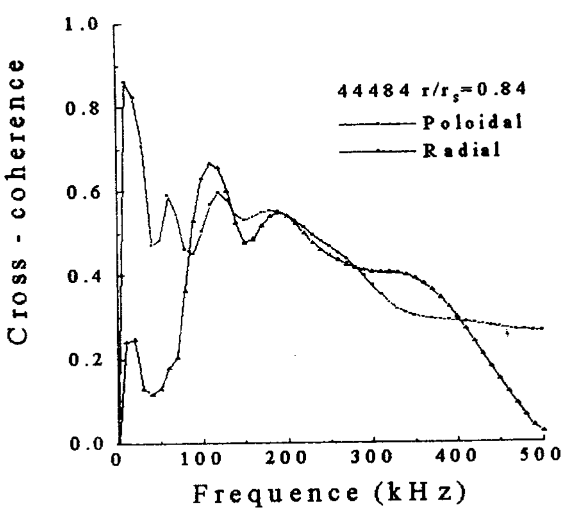

Fig. 4 Frequency resolved radial and poloidal coherence of fluctuations in L2-M. Experiments were done in the plasma edge (x=0.84) and $\Delta r \approx \Delta\Theta \approx 7$ mm.

It should be noted that the presented wavelet coherence spectra were computed for signals measured by two probes (Δr=7 mm) with time delay zero. Increasing the delay time between signals (Δt=3 μs), the coherence coefficient decreases remarkably, and at Δt=10 μs coefficient falls down to the noise level.

4. Discussion

The experimental results presented in the previous section rise a number of questions. In particular, what is the nature of the mechanisms providing a high radial coherence of fluctuations in the high frequency range in L2-M and why this correlation decreases in the shadow of the limiter.

The performed theoretical analysis showed that under relevant experimental conditions plasma is stable with respect to ideal MHD modes, but can be unstable with respect to resistive-pressure-driven-MHD modes. Two processes are in competition here: "self-stabilization" effects in high-shear system tends to create and to deepen the magnetic well, while ballooning-like effect tends to destabilize modes. The L2-M plasma is unstable with respect to resistive pressure-driven-MHD modes in the plasma edge region where $0.5 \le x \le 1$ [9]. Calculations show that rise time of bursts is consistent with linear increments γ of these modes. For example, an upper bound for the rise time of burst is of 20×10^{-6} s, is consistent with characteristic time (γ^{-1}) for mode with m=30 (m is the poloidal mode number). For L-2M edge plasma minimal rise time of burst is 0.5×10^{-6} s and is close to maximal possible increment, that corresponds to the fast interchange mode regime. In order to explain the large radial correlation of fluctuations in the high frequency range, the importance of linear coupling processes have been considered [10]. A critical ingredient is the degree of overlapping between modes radially localized in the proximity of (rational) resonant magnetic surfaces. The radial width of the resonant modes as well as the degree of overlapping between adjacent modes depend on the shape of the q(rotational transform)-profile. Estimations show, that radial coherent structures under this criteria can be formed at sufficiently large poloidal mode number $m \approx 300$.

5. Conclusion

The statistical properties and the radial structure of edge fluctuations have been investigated in the plasma boundary region of the L-2M stellarator with significant magnetic shear. The obtained results can be summarized as follows:

a) Normalized fluctuation levels are in the range 3–6% in the edge plasma region ($r < r_s$) and fluctuations are dominated by frequencies bellow 200 kHz.

b) The structure of fluctuations and turbulent flux is bursty with rise time of turbulent bursts in the range 10^{-5}–10^{-6} s.

c) Whereas the radial coherence of fluctuations is due to high frequency fluctuations (higher than 100 kHz) the poloidal coherence is dominated by low frequency components (lower than 100 kHz). There are asymmetries in the poloidal and radial structure of fluctuations.

d) High frequency fluctuations are radially correlated in plasma edge region with a radial velocity in the range of 4×10^4 m/s. However, this correlation decreases drastically in the shadow of the limiter.

e) Resistive interchange MHD instabilities are considered as a mechanism to explain the observed turbulent characteristics in the plasma edge region of L2-M stellarator.

f) Mode coupling effects appear as a candidate to explain the existence of highly radially correlated fluctuations in the high frequency range.

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