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Journal of Nuclear Materials 313–316 (2003) 1309–1313

journal of nuclear materials

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Effect of rotating helical magnetic field on the turbulence fractal structure and transport in the tokamak edge

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Abstract

Plasma edge fluctuations measured with Langmuir probe in relation to the turbulence structure and associated enhanced transport have been studied in the tokamak HYBTOK-II with a variation of the rotating helical magnetic field (RHF) frequency in the range of 5–30 kHz. Edge fluctuations have non-Gaussianity statistics caused by intermittent bursts with time scale of 40–100 μs. The variation in the RHF frequency has a selective effect on the edge turbulent fractal structure and the turbulent flux, demonstrating a selective control of the transport process. A delayed synchronization control of resonant drift wave modes by the RHF is considered as a candidate mechanism to explain the RHF frequency dependence of the edge turbulent fractal structure.

PACS: 52.40.H; 52.35.R; 52.55

Keywords: Plasma-wall interactions; Boundary plasmas; Plasma turbulence

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1. Introduction

Plasma edge fluctuations in fusion devices are results of non-linear processes, chaotic dynamics and self-organization. Experimental measurements have shown a spiky rather than random behavior of the transport in the edge plasma, universality features of transport in magnetized plasmas were observed. The density and particle flux tend to be intermittent in space and time. The coherent structures, being the result of the self-organization, can be responsible for the substantial transport of particles, heat and momentum. The large-scale correlations in space and time due to intermittent structures can cause anomalous spiky transport and lead to a local overheating and erosion of plasma facing materials. In addition, the cross-field transport in the scrape-off layer is directly related to the heat deposition width on the divertor target plate, which is crucial to determine the averaged heat flux on it. Control of the plasma boundary turbulence is one of the way to improve the core confinement and to prevent the surface of the fusion device from the anomalous heat load. To suppress the turbulent transport, the self-organization caused by turbulence fractal structure, should be controlled.

To improve the edge plasma conditions, the concept of dynamic ergodic divertor was proposed [1] in which a poloidally rotating helical magnetic field (RHF) [2–4] is expected to induce the plasma rotation at the tokamak edge. Recently a general approach [5] to chaos control in physical systems has been proposed, which is based on the existence of unstable periodic orbits within the strange attractor. In the context of chaos control, the

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PII: S0022-3115(02)01507-6

delayed feedback control with periodical modulation was proposed [6]. Using such approach, experiment on spatiotemporal open-loop synchronization of drift wave turbulence in a magnetized cylindrical plasma was carried out by phase-shifted sinusoidal driver [7]. The RHF system on a small tokamak HYBTOK-II provides a system to drive a rotation of the magnetic field perturbation by external exciter. Varying the frequency of magnetic filed induced by external coils of the RHF, a selective control (driving or damping) of resonant modes of drift wave turbulence in the edge plasma is expected. In this work, we have investigated the edge plasma turbulence modification and transport characteristics related to the fractal structure in the tokamak HYBTOK-II with a variation of the RHF frequency.

2. Experimental setup

HYBTOK-II has major and minor radii of 40 and 12.8 cm, plasma current $I_p = 4.9$ kA, the toroidal magnetic field $B_t = 0.27$ T and is operated at the edge electron density about 2×10^{18} m^{-3} and the electron temperature T_e about 20 eV. The RHF is created by two sets of local helical coils which are installed outside the vacuum vessel at eight toroidal sections among 16 with the poloidal mode number of $m = 6$ and the toroidal mode number of $n = 1$ [8]. These coils are powered by inverter power supplies independently with the phase difference of 90°, and the RHF frequency was changed between 5 and 30 kHz in this experiment. The rotation was in the electron diamagnetic drift direction. From the measurement of the poloidal magnetic field, the resonance surface for the main mode of $m/n = 6/1$ was estimated to be around $r \sim 8$ cm, and the magnetic island width is about 0.8 cm [8]. Sideband components of $m/n = 5/1$ and 7/1 are resonant near the surfaces $r \sim 7$ and 9.5 cm, respectively with the same order of the magnetic island widths. The movable Langmuir probe is installed at a mid-plane of the tokamak. It is composed of four tungsten tips with 0.5 mm in diameter and 0.5 mm in length. The difference between the floating potentials on the two tips (poloidally separated by 2 mm) is used to determine the poloidal electric field E_p neglecting the electron temperature fluctuations. The density fluctuation $\tilde{n}(t)$ is deduced from the ion saturation current on the third tip, and the fluctuating radial drift velocity $v_r(t)$ is deduced from the fluctuations in $\widetilde{E}_p(t)$, $\tilde{v}_r(t) = \widetilde{E}_p(t)/B_t$. They are used to determine the radial turbulent flux as $\Gamma_r(t) = \tilde{n}(t)\tilde{v}(t)$. The radial profile of the plasma potential V_p estimated from the floating potential V_f and electron temperature T_e, by $V_p = V_f + 3T_e$, is used to estimate the radial electric field E_r. The poloidal velocity is estimated from $v_p = E_r/B_t$. Fluctuation measurement by two poloidally separated probes are used to estimate v_p by wavelet correlation technique.

3. Effect of the rotating helical magnetic field on the edge turbulence fractal structure

Radial profiles of the averaged n_e, E_p, T_e are not changed significantly with application of the RHF. It was observed that the RHF affects on the structure of the edge plasma fluctuations. To characterize this effect we use the spectral, statistics and multifractal analysis for the experimental signals.

The signals of the density and radial particle flux Γ_r shown in Fig. 1(a) possess a high frequency part and the peaks of total intensity (referred as the bursts) caused by the intermittent structure. There exist fluctuations in each burst and maxima are separated by a time greater than the auto-correlation time. The characteristic time scale of the bursts is of 40–100 μs. These bursts appear to contain a non-negligible amount of the turbulence intensity with respect to the background turbulence. Fig. 1 demonstrates that the RHF effects on the bursty behavior of density and flux Γ_r: intensity of the bursts is increased with the RHF, at the same time the averaged values are not changed significantly. Several scaling ranges with respect to the frequency are registered in the frequency spectra (Fig. 1(b)). We note that no $1/f$ behavior of the spectra and no significant change with the RHF in the high frequency range.

To characterize the structures in the signal, probability distribution function (pdf), obtained from a histogram of the signal, is studied. A deviation from a Gaussian (fully random process) pdf could be due to existence of coherent events. This is called an intermittency. A deviation from the best fit by a Gaussian (plotted by dashed line for the reference in Fig. 1(c)) is exhibited by the flatness (fourth-order moment) (Fig. 1(d)) illustrating the RHF effect at the resonant surface $r = 7.8$ cm.

In understanding of the plasma turbulence we often compare the dynamics of plasma with neutral fluid turbulence [10]. Plasma has more non-linear instabilities and wider dissipation ranges. Hence, it probably has a very limited or non-existent inertial range. To clarify the features of the self-similarity one needs a variety of measures of plasma dynamics. We follow the methods developed for the multifractal analysis of fluid turbulence [9] to understand a deviation from pure self-similarity. A characteristic value related to the energy dissipation scales in three-dimensional turbulence is the intermittency. The energy dissipation rate $\mu = \upsilon/2(\mathrm{d}u_i/\mathrm{d}x_j + \mathrm{d}u_j/\mathrm{d}x_i)^2$ is considered, where u_i is the i component of the velocity, υ is the viscosity. To estimate the energy dissipation rate we can consider a quadratic form [9] of the density fluctuation squared as a measure of

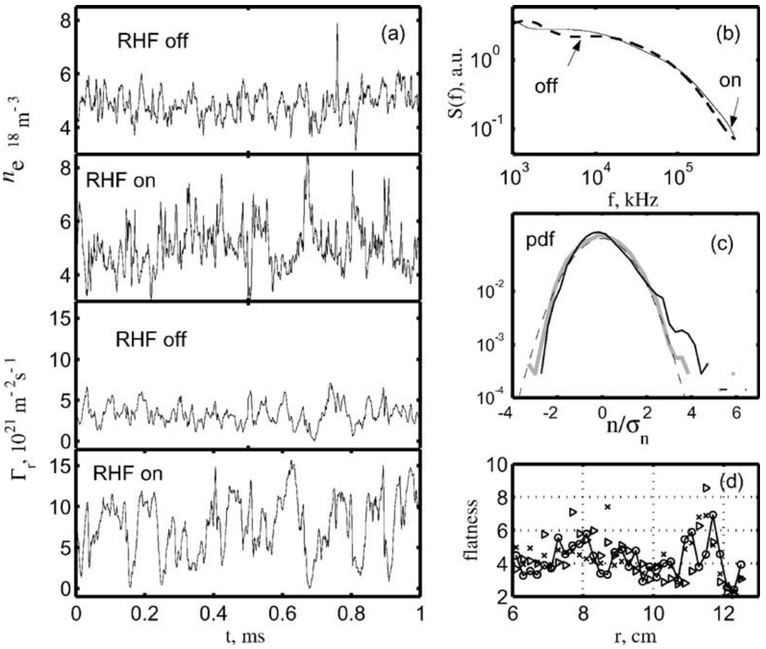

Fig. 1. Time traces of density n and driven radial particle flux Γ_r. Bursty character is observed to change with the RHF at $r = 8.1$ cm. (b) Power spectra $S(f) = |\tilde{n}(f)|^2$ of the density fluctuation. (c) Probability distribution function of the density fluctuation normalized by standard deviation σn (gray: RHF off, solid line: RHF on) demonstrates a deviation from the Gaussian (dashed line). (d) Radial dependence of the pdf's flatness (solid line: RHF off, ×: 5 kHz, ▹: 15 kHz) illustrates the effect of the RHF on the pdf's tails.

energy. We construct the following measures from the density time series,

$$\{n_i = n(t_i), i = 1, 2, \ldots, N\}, \quad \mu_i = \frac{(n_i - \langle n_i \rangle)^2}{\frac{1}{N}\sum_{i=1}^{N}(n_i - \langle n_i \rangle)^2}.$$

To calculate the measure over different time scales, it is averaged over subblocks of data of a length T, $\mu(T,i) = 1/T\sum_{k=0}^{T-1}\mu_{i+k}$. The moments of the measure averaged over the number of block, i, $\langle\mu(T,i)^q\rangle$, scale as a power of the time scales T, $\langle\mu(T,i)^q\rangle \approx (T/N)^{-\Lambda(T,q)}$. The intermittency is defined as $C(T) = \mathrm{d}\Lambda(T,q)/\mathrm{d}q|_{q=1}$. To calculate $C(T)$ the scaling exponent $\Lambda(T,q)$ is processed. An error in the estimation of $C(T)$ is about 10% in the experiments. For a monofractal (pure self-similar) structure $C(T) = 0$ and the scaling exponent $\Lambda(T,q)$ is a linear function of q. For multifractal structure $0 < C(T) < 1$ and $\Lambda(T,q)$ is non-linear function of q. In Fig. 2(a) is plotted the typical moments of the measure. For a monofractal structure all curves should collapse into a single curve. In the experiment, it is observed the non-trivial function of q in the range of time scales $T \sim 1$–300 μs. It illustrates a multifractal character of the edge turbulence. In the mesoscale range $T > 300$ μs a monofractal behavior was observed. Typical behaviour of $C(T)$ has a maximum in the range $T \sim 10$–100 μs as shown in Fig. 2(b). This maximal value of $C(T)$, that is in the range of $C \sim 0.2$–1 in the experiment, is referred as intermittency parameter of the signal. The time scale T corresponding to the maximum in $C(T)$ is referred as a characteristic time scale of the intermittent events. It was observed that the intermittency parameter has non-trivial variation; it may change with radius and the frequency of the RHF (Fig. 2(c)), exceeding the parameter estimated for the 'RHF off' case. Exceeding may change with the RHF frequency, maxima in the radial profile of the intermittency are observed in different radial domains (Fig. 3). These regions are close to the resonant surface positions; $m/n = 5/1$ ($r \sim 7$ cm), 6/1 ($r \sim 8$ cm), 7/1 ($r \sim 9.5$ cm) [8]. Layers corresponding to the magnetic islands around resonant surfaces are shown in Fig. 3 for the reference. Several domains on the f–r plane are identified where the intermittency parameter grows up to higher level $C = 0.7$–1. The effect depends on the RHF frequency. Frequency range of 10–20 kHz seems to be more effective one to reconstruct the multifractal structure near the resonant surfaces and in the SOL. We note that this frequency bandwidth corresponds to the characteristic time scale of 40–100 μs of the bursts observed in the fluctuations as shown in Fig. 1(a).

Fig. 4(a) illustrates a radial profile of the averaged turbulent flux, $\Gamma_r = 1/T\int\tilde{n}(t)\tilde{v}(t)\,\mathrm{d}t$. The increase of the flux in the SOL and at $r = 7$–8 cm is mainly caused by the change in the correlation between density and poloidal electric field fluctuations. The cross-phase shift

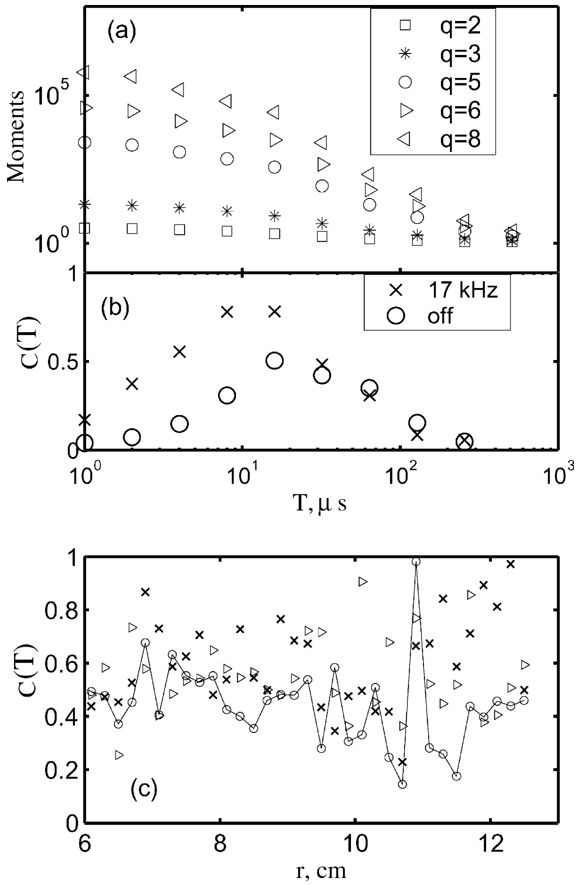

Fig. 2. (a) Moments of the measure. Non-trivial function of q illustrates a multifractality in the range of time scales $T \sim$ 1–300 μs. (b) Intermittency parameter $C(T)$ depending on time scales T at $r = 7.1$ cm. (c) Radial behavior of C (solid line: RHF off, ×: 17 kHz, ▷: 30 kHz).

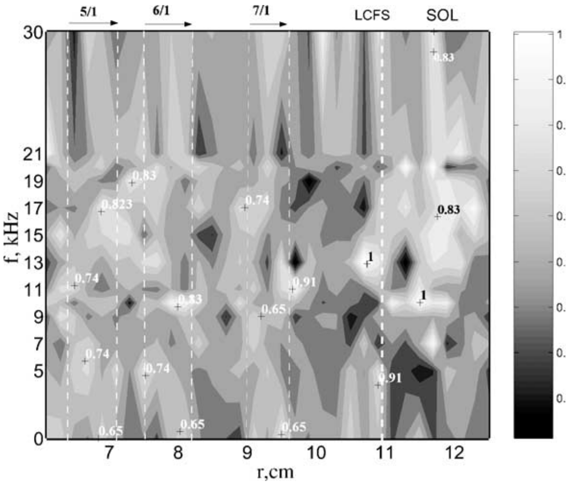

Fig. 3. The intermittency parameter C on the RHF frequency–radius plane. Intermittency is affected by the RHF in the layers (magnetic islands) around resonant surfaces $m/n = 6/1$ ($r \approx 8$ cm), 7/1 ($r \approx 9.5$ cm), 5/1 ($r \approx 7$ cm) shown by white dashed lines, and in the SOL. Last closed flux surface (LCFS) shown by bold dashed line.

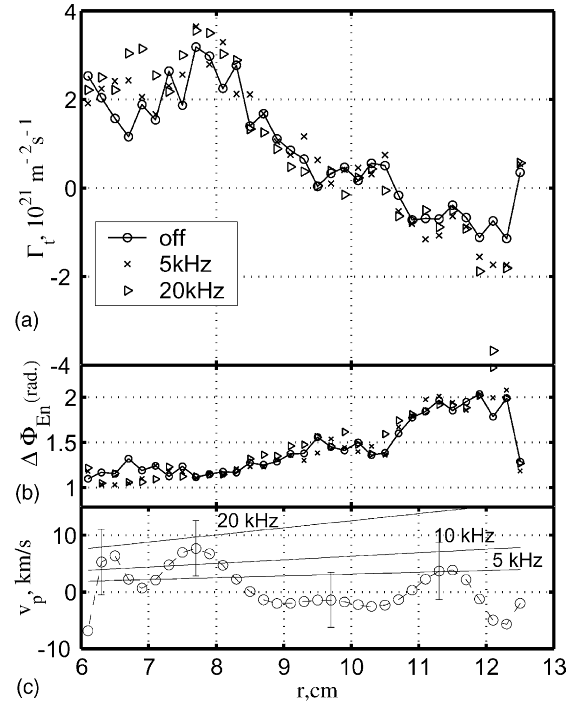

Fig. 4. (a) The radial profiles of turbulence driven particle flux (time-averaged), (b) phase shift between the fluctuations in density and poloidal electric field. (c) $E_r \times B$ poloidal drift velocity v_p (circles) and the phase velocities of the RHF with frequency of 5, 10, 20 kHz (lines). Positive direction of the velocity in the electron diamagnetic drift one.

$\Delta\Phi_{nEp}$ shown in Fig. 4(b) is defined from Fourier analysis of $\tilde{n}(t)$ and $\tilde{v}_r(t)$. The change in the flux seems to relate with a reconstruction of the fractal structure in the RHF experiments.

Fluctuations in density are investigated by wavelet correlation technique [11] to analyze poloidal movement of the turbulent structures. The technique is based on the wavelet analysis using the fluctuating signals of two probes separated poloidally by 4 mm. Radial profile of this velocity shown in Fig. 5 changes with the RHF. At the resonant surfaces ($r = 7.8$ and 9.4 cm) velocity grows up, which might be related to the effect of the RHF on the rotation.

The observed effect of the fractal structure reconstruction may result from several mechanisms. One of them is a reconstruction of magnetic structure near resonant surfaces such that the magnetic islands have been observed to grow in the RHF experiments [8]. The hierarchy of the generated magnetic islands is involved

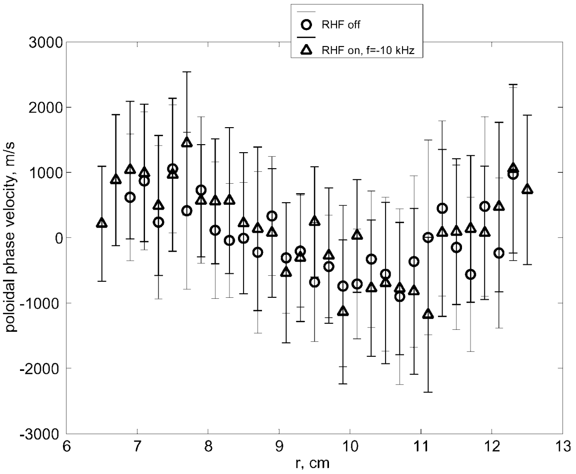

Fig. 5. Poloidal phase velocity deduced from two probe signals by wavelet correlation analysis. Positive direction of the velocity in the electron diamagnetic drift one.

in the dynamics of the process and modification of the hierarchy is reflected in the fractal structure with higher level of multifractality. This mechanism is not expected to depend directly on the RHF frequency and cannot explain the observed fractal modification in the SOL where no magnetic structure modification was observed with the RHF. Another mechanism is a delayed synchronization control discussed in Section 1. This mechanism has a frequency selective nature and it is supposed to play a role in the modification of the turbulence structure in the RHF experiment. Estimated poloidal phase velocity of the RHF becomes close to the poloidal drift velocity in the SOL and in the radial layers at $r = 6.5$–8 cm (Fig. 4(c)) and variation in the RHF frequency may select a radial domain for a resonance. Frequency dependence of the intermittency modification seems to reflect a delayed synchronization control of resonant drift wave modes in these radial domains. This mechanism modifies the set of the non-linear coupled drift modes involved in the process reflecting in the reconstruction of fractal structure. We note that this discussed resonant effect may be more complicated than a resonance of a single mode with the RHF, because the poloidal phase velocity of drift modes at given r is expected to be distributed over broad range of the values.

4. Summary

In conclusion, the turbulence characteristics related to the fractal structure and turbulent transport in the edge plasma of tokamak HYBTOK-II with a variation of RHF frequency have been studied. It was shown that the turbulence has a multifractal structure. The intermittent bursts formed by fluctuations with a time scale of 40–100 μs, are more intensive in the RHF experiment. The effect on edge turbulence fractal structure and transport characteristics depends on the RHF frequency. The intermittency parameter as a measure of multifractality level and turbulent flux are increased with the RHF near the resonant surfaces and in the SOL. A delayed synchronization control of resonant drift wave modes by the RHF is considered as a possible mechanism to explain the RHF frequency dependence. Detailed measurements are needed to clarify the selective property of this effect. This work has been partially supported (V.B.) by JSPS (Japan Society for the Promotion of Science).

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