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Effect of Rotating Helical Magnetic Field on the Turbulence Fractal

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Abstract

The turbulence characteristics related to the fractal structure and turbulent transport in the edge plasma of tokamak HYBTOK-II with variation of Rotating Helical Field (RHF) frequency have been studied. It was shown that the turbulence has a multifractal structure. The effect on 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. The intermittent bursts formed by fluctuations with a time scale of 40–100 μs, are more intensive in the RHF experiment.

Keywords:

1. Introduction

The control of edge plasma turbulence and turbulence driven transport is one of the key issues to achieve a steady-state operation of tokamak. To improve the edge plasma conditions the concepts of dynamic ergodic divertor [1] and poloidally rotating helical magnetic field (RHF) [2-4] to induce the plasma rotation at the edge have been proposed. Recently a general approach [5] to controlling chaos in physical systems has been proposed it is based on the existence of unstable periodic orbits within the strange attractor. In the context of chaos control, it was proposed the delayed feedback control with periodical modulation [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 on a small tokamak HYBTOK-II provides a system to drive a rotation with phase controlling by external exciter. Varying the rotation frequency in external coils for the RHF, a selective control (driving or damping) of resonant modes of drift wave turbulence in edge plasma is expected. In this work, we have investigated the edge plasma turbulence and transport characteristics related to the fractal structure in tokamak HYBTOK-II with variation of the RHF frequency.

2. Experimental Setup

HYBTOK-II has the major and minor radii of 40 cm and 12.8 cm, the plasma current of $I_p = 4.9$ kA, the toroidal magnetic field of $B_t = 0.27$ T and operates 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

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two coils are powered by inverter power supplies independently with the phase difference of 90 degrees, and the RHF frequency was of 5–30 kHz in this experiment. The rotation was in the electron diamagnetic drift direction. From the measurement of poloidal magnetic field, the resonance surface for the main mode of m/n = 6/1 was estimated to be around $r \approx$ 8 cm , the magnetic island width of 0.8 cm [8]. Sideband components m/n = 5/1 and 7/1 are resonant near the surfaces $r \approx$ 7 cm and $r \approx$ 9.5 cm, respectively with the same order of the magnetic island widths. The movable Langmuir probe is installed at a midplane of the tokamak. It is composed of 4 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 is deduced from the fluctuations in $\tilde{E}_p(t)$, $\tilde{v}_r(t) = \tilde{E}_p(t)/B_t$. They are used to determine the radial turbulent flux as $\Gamma_r(t) = \tilde{n}(t)\tilde{v}_r(t)$. The radial profile of plasma potential V_p estimated from the floating potential V_f and electron temperature T_e, $V_p = V_f + 3T_e$, is used to estimate the radial electric field E_r. The poloidal $E_r \times B$ drift velocity is estimated from $v_p = E_r/B_t$. We have analyzed the date over the radial range of $6.5 < r < 12.5$ cm, through a sequence of repetitive discharges in tokamak. The data were collected during 7 ms at quasi-steady state phase with a sampling rate of 1.0 MHz.

3. Effect of the RHF on the Edge Turbulence Fractal Structure

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

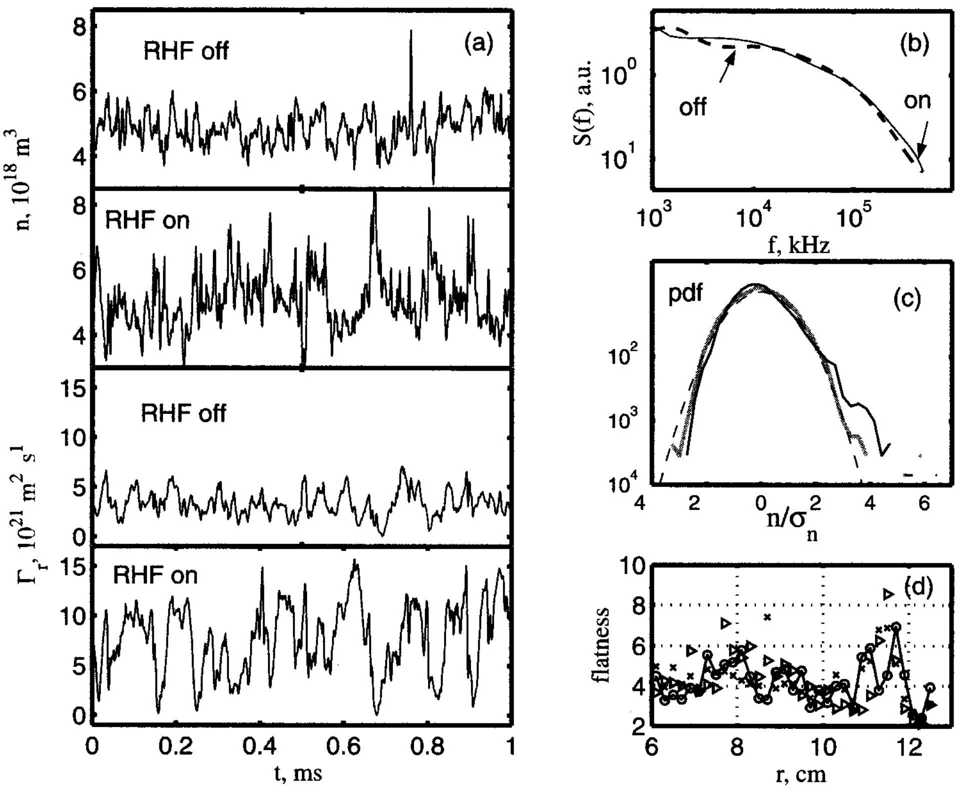

Fig. 1 (a) Time traces of density n and driven radial particle flux Γ_r. Bursty character is observed to change with the RHF at r = 8.1 cm. (b) Power spectra $S(f) = |\tilde{n}(f)|^2$ of the density fluctuations. (c) Probability distribution function of the density fluctuations normalized by standard deviation σ_n(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 an effect of the RHF on the pdf's tails.

The signals of the density n and radial particle flux Γ_r (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. This bursts appear to contain a non-negligible amount of the turbulence intensity with respect to the background turbulence. Figure 1 demonstrates that the RHF effects on the bursty behaviour 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.

The analysis of fluctuation statistics is an instrument to characterize the structures in the signal. For this, 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. The deviation of the pdf from a Gaussian is characterized by third (skewness) and fourth (flatness) order moments of the pdf that are of 0 and 3 for a Gaussian respectively. For density fluctuations, the positively skewed pdf's change with the RHF near the resonance surfaces (Fig. 1(c)). 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 (Fig. 1(d)).

In understanding of plasma turbulence we often compare the dynamics of plasma with neutral fluid turbulence. For the fully developed turbulence, Kolmogorov deduced the self-similarity of the turbulent velocity fluctuations in a simple model and defined the inertial range [12]. Plasma has more nonlinear instabilities and dissipation ranges. Hence, it probably has a very limited or nonexistent inertial range. Experimental evidence of the intermittency in the plasma fluctuations suggests a different scaling of the fluctuations in different time scale ranges. The structure of this process is more complicated than a single fractal structure. 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]. Multifractal analysis is a powerful tool to understand a deviation from pure self-similarity. A characteristic value related to the energy dissipation scales in three-dimension turbulence is the intermittency. The energy dissipation rate $\mu = \nu/2(du_i/dx_j + du_j/dx_i)^2$ is considered, u_i is the i component of the velocity, ν is the viscosity. To estimate energy dissipation rate we can consider a quadratic form [9] of the density fluctuation squared as a measure of energy. To describe the multifractal character of the plasma turbulence the scaling of the measures should be considered over different time scales. We construct the following measures from thetime series of density data $\{n_i = n(t_i),\ i = 1,2,\ldots, N\}$,

$$\mu_i = \frac{\left(n_i - \langle n_i\rangle\right)^2}{\frac{1}{N}\sum_{i=1}^{N}\left(n_i - \langle n_i\rangle\right)^2} \tag{1}$$

To calculate the measure over different time scales, it is averaged over subblocks of data of a length T, $\mu(T,i) = \frac{1}{T}\sum_{k=0}^{N}\mu_i + k$. The moments of the measure averaged over the number of block, i, $\langle\mu(T,i)^q\rangle$, scale as a power

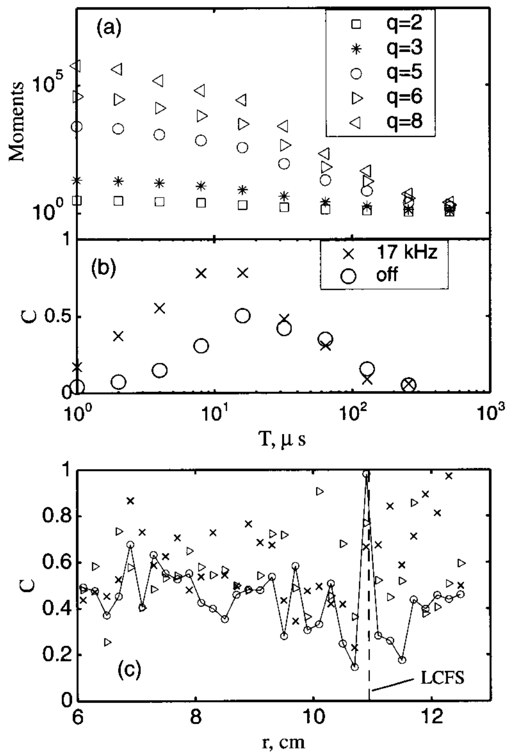

Fig. 2 (a) Moments of measure. Nontrivial function of q illustrates a multifractality in the range of time scales $T \sim$ 1–300 μs. (b) Intermittency parameter $C(T)$ depending on time scales T. at r = 7.1 cm. (c) Radial behaviour of C (solid line - RHF off, × - 17 kHz, ▷ - 30 kHz)

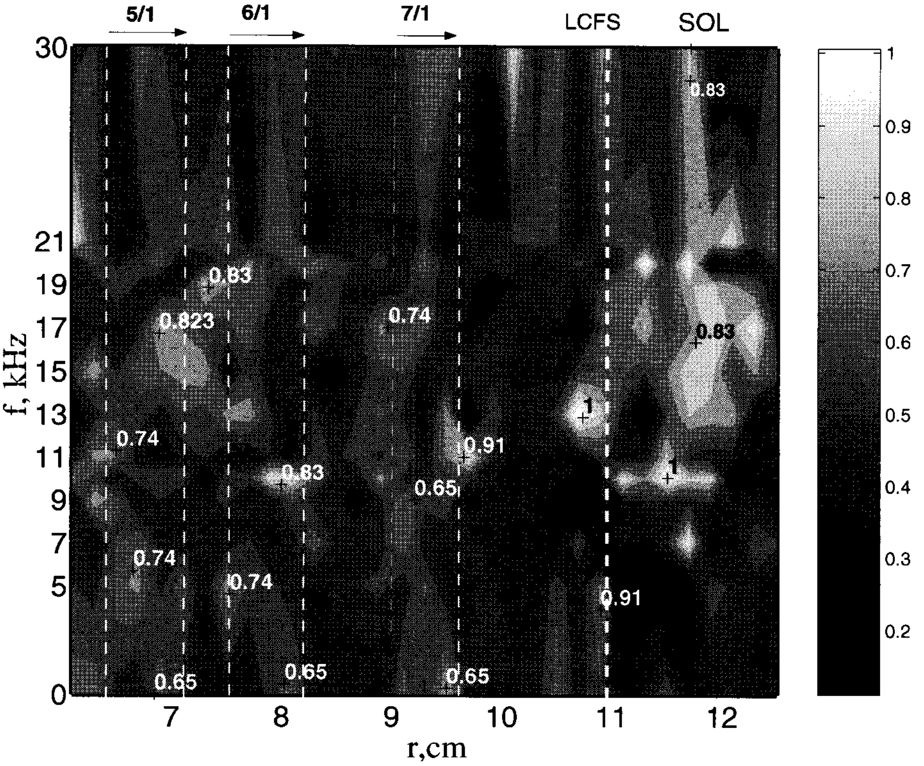

Fig. 3 The intermittency parameter C on the RHF frequency-radius plane. Intermittency is effected by the RHF in the layers (magnetic islands) around a resonant surfaces m/n = 6/1 ($r \approx$ 8 cm) , 7/1 ($r \approx$ 9.5 cm), 5/1 ($r \approx$ 7 cm) shown by white dashed lines, and in the SOL. Last Closed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

of the time scales T, $\langle \mu(T,i)^q \rangle \approx (T/N)^{-\Lambda(T,q)}$. The intermittency is defined as $C(T) = \mathrm{d}\Lambda(T,q)/\mathrm{d}q\,|_{q=1}$. 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 $0 < C(T) < 1$ and $\Lambda(T,q)$ is non-linear function of q. We have studied a range of time scales of T = 1–1000 μs. 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 experiment, it is observed the nontrivial function of q in the range of time scales T ~ 1–300 μs. It illustrates a multifractal character of the turbulence. In the mesoscale range $T >$ 300 μs a monofractal behavior was observed. To calculate $C(T)$ the scaling exponent $\Lambda(T,q)$ is processed. An error in the estimation of C is about 10 % in the experiments. Intermittent structures are characterized by intermittency parameter $C > 0$. Typical behaviour of $C(T)$ has a maximum in the range T ~ 10–100 μs as shown in Fig. 2(b). This maximal value of $C(T)$, that is in the range of C ~ 0.2–1 in the experiment, is referred as intermittency parameter of the signal. The time scale T corresponded to the maximum in $C(T)$ is referred as a characteristic time scale of the intermittent events. It was observed that the intermittency parameter may change with radius and the frequency of the RHF. Fig. 2(c) illustrates radial profile of the intermittency parameter for different frequencies of the RHF. We note that the intermittency parameter in experiments with the RHF exceeds the parameter estimated for the "off" case (Fig. 2(c)). Increasing of the intermittency parameter in experiment with the RHF was observed in the SOL and several radial domains. This regions are close to the resonant surface positions: m/n = 5/1 (~ 7 cm), 6/1 (~ 8 cm), 7/1 (~ 9.5 cm) [8]. Layers corresponded to the magnetic islands around resonant surfaces are shown in Fig. 3 for the reference. Exceeding of the intermittency parameter over the "off" case may change with the RHF frequency. The intermittency radial profile behaviour is not repeated with variation in the RHF frequency: maxima in the radial profile of the intermittency are observed in different radial domains. This non-trivial variation of the intermittency radial profile for different frequencies of the RHF is shown in Fig. 3. It is observed several domains on the $f - r$ plane where intermittency

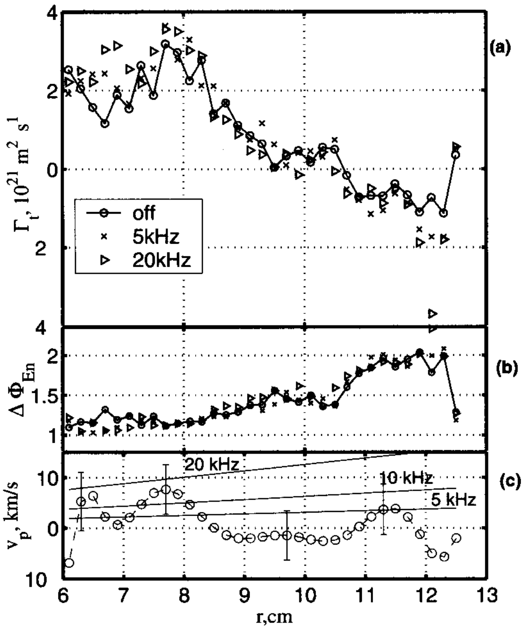

Fig. 4 (a) The radial profiles of turbulence driven particle flux (time-averaged), (b) phase shift between the fluctuations in density and poloidal electric field. (c) $E_r \times B$ poloidal drift velocity v_p (circles) and the phase velocities of the rotating helical magnetic field with frequency of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

parameter growths to high level $C \sim 0.7$–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 (Fig. 1(a)).

Figure 4(a) illustrates a radial profile of the averaged turbulent flux, $\Gamma_r = \frac{1}{T}\int \tilde{n}(t)\tilde{v}_r(t)\mathrm{d}t$, resulted from the level of fluctuations in $\tilde{n}(t)$ and $\tilde{v}_r(t)$, and coherency between them. The increasing of the flux in the SOL and r = 7–8 cm is mainly resulted from the change in the correlation between density and poloidal electric field fluctuations: cross-phase shift ($\Delta\Phi_{nE_p}$) defined from Fourier analysis of $\tilde{n}(t)$ and $\tilde{v}_r(t)$, varies with the RHF frequency (Fig 4(b)). The change in the flux seems to response from a reconstruction of the fractal structure in the RHF experiments.

4. Discussion

The observed effect of the fractal structure reconstruction can be resulted from several mechanisms. One of them is a reconstruction of magnetic structure near resonant surfaces: magnetic islands have been observed to grow in the RHF experiments [8]. The hierarchy of the magnetic islands is involved in the dynamics of the process, 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 can not explain the observed fractal modification in the Scrape-off-Layer (SOL) where no magnetic structure modification was observed with the RHF.

Another mechanism is a delayed synchronization control discussed in the Introduction. 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. The poloidal drift velocity v_p is estimated from E_r to change its direction and amplitude across the plasma column (Fig .4(c)). Supposing that v_p profile reflects the behaviour of the drift modes phase velocity, it offers the key to understand the process. 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)), variation in the RHF frequency may select a radial domain for a resonance with the drift modes. 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 nonlinear coupled drift modes involved in the process reflecting in the reconstruction of fractal structure. We note that this discussed resonance effect may be more complicated than a resonance of a single mode with the RHF, because of the poloidal phase velocity of drift modes at given r is expected to be distributed over broad range of the values. It is needed the measurements of the poloidal phase velocity distribution for the detailed analysis of the control effect. 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 the 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 candidate mechanism to explain a dependence of the effect on the RHF frequency. Detailed measurements are needed to clarify the selective character of this effect.

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