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Numerical Measurements of Plasma Turbulent Structures Using the Turbulence Diagnostic Simulator
乱流計測シミュレータを用いたプラズマ乱流構造の数値計測

Naohiro Kasuya, Masatoshi Yagi, Kimitaka Itoh and Sanae-I. Itoh
糟谷直宏, 矢木雅敏[1,2], 伊藤公孝, 伊藤早苗[1)]

National Institute for Fusion Science, 322-6 Oroshi-cho, Toki, Gifu 509-5292, Japan
核融合科学研究所 〒509-5292 岐阜県土岐市下石町322-6
1) Research Institute for Applied Mechanics, Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka 816-8580, Japan
九州大学応用力学研究所 〒816-8580 福岡県春日市春日公園6-1
2) Japan Atomic Energy Agency, 2-166 Omotedate, Obuchi, Rokkasho-mura, Aomori 039-3212, Japan
日本原子力研究開発機構 〒039-3212 青森県六ヶ所村尾駮表舘2番166

Turbulence Diagnostic Simulator is an assembly of simulation codes to clarify the formation mechanism of turbulent structures by numerical diagnostics in magnetically confined plasmas. Global simulations are carried out using a reduced MHD model of drift-interchange mode in helical plasmas, and time series data of 3-D fluctuation fields are produced. Magnitudes of linear contribution and nonlinear couplings from the convective derivative and the parallel derivative are evaluated in the nonlinear saturated states. It is shown that the nonlinear couplings with higher *m* modes in the middle radius contribute to the pressure profile modification, and the toroidal coupling induces the potential oscillation.

1. Introduction

Turbulence in toroidal plasmas forms meso-scale structures, such as a zonal flow, and it is important to clarify their role on anomalous transport [1]. Numerical simulations can give three-dimensional (3-D) turbulent fields, which represent fundamental phenomena in plasmas, so the simulation data are suitable as a test field to carry out detailed analyses for comparison with experimental results [2]. We have been developing Turbulence Diagnostic Simulator (TDS), which is the combination of fluid turbulence codes and numerical diagnostic modules to simulate experimental measurements of plasma turbulence [3]. Several kinds of analyses are possible corresponding to research objects. In this paper, drift-interchange modes in helical plasmas are analyzed, using TDS. The contributions to energy evolutions from nonlinear couplings are evaluated to clarify the formation mechanism of turbulent structures.

2. Model

To provide turbulence data, a simulation code has been developed to calculate the drift -interchange turbulence in helical plasmas with a circular cross-section [3]. The averaging method with the stellarator expansion [4] is applied to give a set of model equations for stream function u, ζ component of the vector potential A and total pressure P. The model in [3] is extended to include the magnetic curvature term in the pressure evolution equation to satisfy the energy conservation.

3. Nonlinear Simulation

Three kinds of simulations are carried out; i) one without the parallel dynamics of electrons, which only includes the interchange mode, ii) one with the parallel dynamics of electrons but without the magnetic curvature term in the pressure evolution equation, and iii) one including all terms in the model. Here we analyze one of the set of turbulence data from simulation ii), because the simulation gives the most dynamical saturation.

The nonlinear simulation is performed, using the following parameters: magnetic field B = 2.0 [T], electron temperature T_e = 1 [keV], minor radius a = 0.6 [m], major radius R_0 = 3.75 [m], viscosities $\mu = \eta = \eta_\perp = 1 \times 10^{-4}$, pole number l = 2, pitch number M = 10. Rotational transform ι is given by a monotonically increasing function with the radius from $\iota(0) = 0.31$ to $\iota(a) = 0.88$, so rational surfaces with m / n = 2 / 1 and 3 / 2 are included, but 1 / 1 is not in the plasma, where m and n are the poloidal and toroidal mode number, respectively. 1024 grids in the radial direction and Fourier modes $-32 \le m \le 32$, $-8 \le n \le 8$ are taken.

Spatio-temporal data of turbulent fields are generated by this global simulation [5]. The calculation with a fixed pressure source, which forms a pressure profile peaked at r = 0, is carried out. Low m, n modes whose rational surfaces exist in the plasma are excited in the linear growing phase, and saturation is obtained. In the saturated state, mode structures of low m, n modes, such as $(m, n) = (1, 1)$ and $(2, 1)$, spread broadly in the radial direction, and those of medium m, n modes, such as (3, 2) and (8, 4), are localized near their rational surfaces. Here, we assume that variable u represents the normalized electrostatic potential ϕ.

4. Nonlinear Coupling Process

The ϕ_{00} component, which gives a mean poloidal flow, is produced in the saturated state. Figure 1 shows the frequency and radial wavenumber spectrum of ϕ_{00}, which has a characteristic frequency $f \sim 0.02$. The radial structure is rather global, though there exists perturbations with $k_r = 3$ - 9 in some moments. Here we analyze its generation mechanism by calculating the linear and nonlinear contributions to the energy evolution.

The evolution equation of the electrostatic potential energy includes the contributions from the linear term (LT), ballooning term to give a linear coupling with neighboring modes (TC), nonlinear terms from the convective derivative (NT1) and the parallel derivative (NT2). NT2 comes from electromagnetic fluctuations in the $\nabla_{//}J$ term. The volume integration of each term shows that TC is the largest, so the main cause of the ϕ_{00} oscillation is the coupling between ϕ_{00} and $P_{\pm 10}$.

For P_{10}, competition between negative LT and positive NT1 determines the evolution, so both the profile modification, which contributes to the variation of LT, and the nonlinear couplings, which contribute to NT1, must be taken into account. Figure 2 shows the radial profile of the nonlinear contribution to the P_{10} formation, where NT1 is decomposed into ones with each poloidal mode number. There is a region where the contributions from modes with higher m mode numbers are strong in $r / a = 0.5$ - 0.8. The profile modification arises in this region, and propagates to the other regions. In addition, the dominant mode changes according to the radial position.

For ϕ_{32}, which has large amplitude, LT+TC and NT1+NT2 are comparable. Among the nonlinear contributions, NT2 is larger than NT1, and bursts of NT2 affect the evolution.

For P_{00}, the radial profile of NT1 indicates the characteristic regions; $r / a < 0.3$: strong mode excitation, 0.4 - 0.7: existence of various modes, > 0.8: existence of small number of dominant modes, corresponding to the different features shown in the time evolution of the 2-D contour on the poloidal cross-section in [5].

Numerical diagnostics to simulate experimental measurements are also carried out, whose results will be presented in the poster.

5. Summary

In summary, global simulations are carried out using a reduced MHD model in helical plasmas, and obtained time series data of 3-D fluctuation fields are analyzed. Magnitudes of linear and nonlinear contributions are evaluated. It is shown that the nonlinear couplings with higher m modes in the middle radius contribute to the P_{10} modification, and the toroidal coupling between ϕ_{00} and P_{10} induces the ϕ_{00} oscillation. In this way, the data analysis using TDS is effective to clarify the structural formation mechanism.

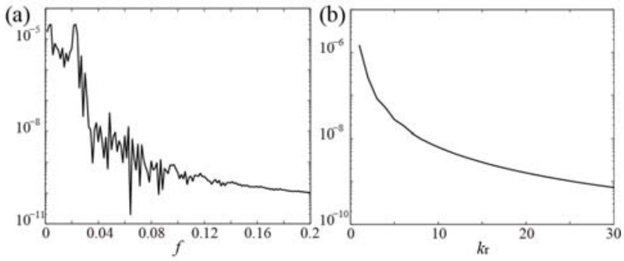

Fig.1. (a) frequency spectrum at $r / a = 0.5$ and (b) radial wave number spectrum of ϕ_{00}.

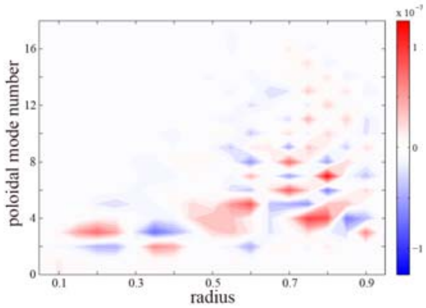

Fig.2. Radial profile of the nonlinear contribution to the P_{10} evolution, which is decomposed into each poloidal mode number component.

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