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New transport picture in turbulent plasma introduced by novel measurements of turbulence
先進プラズマ乱流計測が描く新乱流輸送像

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Here we report research methods of plasma turbulence and turbulence transport. Development of advanced data analysis methods and novel diagnostic tools will propel us to quantify elementary processes of plasma turbulence. (i) Cross-correlation between heterogeneous diagnostic signals succeeded to discover a new fluctuating structure with a long distance radial correlation. (ii) Conditional averaging technique is used to extract the dynamic response of turbulence and turbulence transport precisely and allows us to observe the hysteresis in the flux-gradient relation. (iii) Utilization of the microwave frequency comb technique is very promising for developing the spatiotemporal structure of turbulence with ultra-high-spatial- and temporal-resolutions. These results shift the picture of plasma turbulence to the new one in which multi-scale fluctuations coexist and interact each other. This picture calls for a conceptual breakthrough for the control algorithm of plasma dynamics in future fusion reactors.

1. Introduction

In magnetized plasmas, micro-turbulence excited by the steep pressure gradient can drive fluxes of particle, heat and momentum across closed magnetic flux surfaces [1]. A local diffusive picture of transport in which the transport flux is expressed in terms of mean parameters and their spatial derivatives at the same location has been widely believed. For more than 20 years, however, dynamic behavior of magnetized plasma has indicated limitations of such diffusive picture [2]. The local closures of turbulence and transport (i.e., formulation in terms of local parameters) are not sufficient to describe turbulent transport. In the modern view of plasma turbulence, the couplings between different spatial-scale fluctuations could provide a possible link between turbulence at two distant radial positions in plasmas [3, 4]. Recently, the existence of macroscopic fluctuations coupling with micro-turbulence was discovered and considered to play important role on turbulence transport dynamics [5]. More recently, new global hysteresis in the flux-gradient relation was demonstrated [6]. The existence of hysteresis means that the heat flux is a multiple-valued function of gradient, so that the transport dynamics is quite far from that predicted by a simple diffusive transport, in which the heat flux is a single-valued function of gradient. These qualitative differences of transport picture have a critical impact on the predictive capability of temporal evolution of future burning plasmas and thus should be clarified.

We developed new analysis methods for a dynamic response of plasma by using of the linear plasma device PANTA. Then we applied these analysis methods extensively to LHD experiments and results made establish a research method of plasma turbulence transport. Furthermore, we developed a novel measurement tool for observation of the multi-scale plasma turbulence.

2. Correlation hunting

Identification of all the possible fluctuations and three-dimensional structure of them in confined plasmas remains an urgent issue. There are many experimental evidences for meso-scale and micro-scale fluctuations (e.g. zonal flows and drift waves, respectively). However, the knowledge of fluctuations, which have very long radial correlation lengths, was limited except in MHD modes. In addition, there are a few experimental observations concerning to two- or three-dimensional structure of turbulence. Correlation is very powerful tool to identify weak signals. In fact, the zonal flow is discovered by two-point two-time correlation analysis of dual HIBP signals. Here a cooperation of cross-correlation analyses by use of heterogeneous diagnostics (microwave reflectometer, array of magnetic probes and so on) is proposed to identify a hidden structure in turbulence. This approach is also valid for the evaluation of the two-dimensional turbulence structure. For example, a macro-scale fluctuation is discovered and the toroidal and poloidal mode numbers of it are measured by the cross correlation between a signal from ECE and magnetic probe arrays [6]. Correlation between the macro-fluctuation and the envelope of the micro-fluctuations is very useful to observe the non-linear parametric coupling between them. The cross-bi-coherence analysis also supports the existence of the disparate-scale coupling in the multi-scale turbulence.

3. Conditional averaging technique

Periodical and quasi-periodical changes of signals of interest can be extracted statistically by conditional averaging technique. If the signal of interest is some sort of incoherent wave, the envelope of wave is often used. In this technique, the periodical/quasi-periodical reference trigger is required. The signal is extracted for each time interval of trigger and averaged. This approach has been applied to turbulent plasmas in the LMD-U and PANTA device, and this has led to identification of large-amplitude solitary wave structures [7]. In the toroidal plasma experiments, the spike-like Hα signal during ELMs can be used to observe the H-mode transition dynamics. The spike-like blob signal in the SOL probe itself is frequently used to evaluate the spatiotemporal behavior of blobs. In the LHD, the spatiotemporal structure of heat pulse under modulated heating source is extracted precisely [6]. The averaged low-noise signals allow us to evaluate a temporal evolution of heat flux and an associated change of the micro-fluctuation amplitude. The difference in the time scales between responses in the gradients and the response in the heat flux to the heat source modulation clearly indicates that there is a hysteresis in the flux-gradient relation. On the other hand, the heat flux is proportional to the local micro-fluctuation intensity. This fact indicates that the turbulence intensity and heat flux are determined by the local temperature gradient only. The theoretical study proposed a new thermodynamical force in phase space and demonstrated the strong impact of it on the turbulence dynamics. The impact of structures in phase-space (phase-space turbulence) is a new area of theoretical and experimental study on turbulence.

4. Microwave frequency comb reflectometer

Global non-linear turbulence simulation codes predict that large-amplitude corrugations in the profile (e.g. ExB staircase) evolve dynamically [3,8,9]. To observe such corrugations, which can be essential to the dynamical response of turbulent plasmas, it is necessary to simultaneously measure the mean profile and its fluctuations precisely. Microwave frequency comb technique is accelerated over the past few years and this technique is applied to the reflectometry for core plasma diagnostic in fusion plasma. Microwave frequency comb reflectometer is a possible candidate to measure the density profile as a continuous function of radius with high temporal resolution. We used an ultra-high speed digital storage oscilloscope, which allow us to realize "digital mixer" for incident and reflect waves. We have developed a method to reconstruct the density profile as a continuous function of radius with a temporal resolution of 1 μs by using the conditional averaging technique. The new reflectometer is very promising for developing the physics of plasma turbulence and transport.

5. Summary

This study established experimental methods for generalization of (1) flux-gradient relation to replace Fick's law of diffusion and (2) non-local and non-linear coupling between multi-scale fluctuations. The resulting new picture of turbulence and turbulence transport will have deep impact on our predictability of evolution of turbulent plasmas, and provide a sophisticated controlling parameter of the burning plasmas, such as ITER.

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