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Modern View of Turbulence and Transport in Magnetized Plasmas
磁化プラズマの現代的描像について

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The modern view of turbulence has been established due to the discovery of structures drift-waves generate, such as zonal flows and streamers, providing a new framework for understanding turbulence-driven transport and structural formation in magnetized plasmas. This paper presents recent development of laboratory experiments to have advanced the understanding of plasma turbulence and transport, focusing on discoveries of mesoscale structures, such as zonal flows and streamers, the analyzing techniques to quantify the couplings between different scale structures, and physics of turbulence transport and barrier formation.

1. Introduction

Plasma is a state of matter extremely far from equilibrium, and is a fundamental element for understanding the phenomena of our surroundings (the sun, aurora, the ionosphere, dynamo, etc.) and for developing the modern technologies (nuclear fusion, display, plasma rocket, carbon nano-tube, etc.). Particularly, the plasma turbulence has been a key issue for nuclear fusion, and extensive studies of plasma turbulence over a half century have been carried out from its infancy [1,2].

Thanks to the intensive efforts, recently, a new framework has been established for understanding of the plasma turbulence. In the modern view, the plasma turbulence is regarded as a system of drift waves and structures that the drift-waves generate [3,4], while the plasma turbulence was simply recognized as a system of drift waves after the confirmation of the presence of drift waves in magnetically confined plasmas [5,6]. This paper introduces the modern view of the plasma turbulence and resultant transport, focusing on the experimental steps for accomplishing the modern concept of plasma turbulence by introducing recent examples of laboratory experiments.

2. Structures driven by drift-waves

At present it has been well recognized that the drift wave can generate mesoscale structures such as zonal flows, Geodesic Acoustic Modes (GAMs) and streamer, which have been predicted by theories and simulations. These structures have been identified in experiments to contribute to making the modern view of plasma turbulence. A few direct identifications of zonal flows have been performed in CHS [7] and others [8-10], while much more experimental results have been available for studies of GAMs [11] after their first identification [12,13]. As for streamers, a few experiments have shown the signature of their existence in toroidal experiments [14,15], while the complete identification has been done in a linear cylindrical device [16].

In addition to these mesoscale structures, another fluctuating structure driven by drift waves has been recently found in electron temperature fluctuation measurements in Large Helical Device (LHD) using electron cyclotron emission (ECE) [17]. The discovered structure shows a long radial correlation length comparable to the plasma minor radius, therefore, this observation shows that the drift waves should excite a linearly stable macroscopic structure as well as those in mesoscale.

3. Mutual Interactions between

Recent developments of computer technologies have made it easier to perform the analyses for extracting the elemental processes of turbulence [18-20]. The bicoherence analysis is often used to show the nonlinear couplings between turbulence generated structures (e.g., zonal flows, GAMs and others) and background waves in frequency domain [21,22]. The analysis have been extended to wavenumber space to confirm the wavenumber matching condition as well, i.e. $k_1 + k_2 = k_3$. In linear cylindrical devices, LMD-U [23] and VINETA [24], a 64-channel azimuthal probe array succeeded in resolving the nonlinear couplings including the wavenumber space. Recently, the similar technique using the wavelet was applied on temporal sequence of fast camera images in MIRABELLE, demonstrating the ability to study the temporal dynamics and spatial localization where the couplings occur [25].

Moreover, the energy transfer direction between the fluctuation components or structures can be deduced using the power transfer function (PTF) analysis that was applied originally in the edge of TEXT tokamak plasmas [26]. Nowadays, the analysis is extended to be applied on 2D probe data of the frequency and wavenumber space in TJ-K torsatron, demonstrating the nonlocal energy transfer from drift-waves to zonal flows [27]. The cross-bicoherence analysis implied that the energy exchange between zonal flows and local turbulence should have spatial (or radial) dependence in LMD-U [28]; the zonal flows lose their energy in the edge but gain the energy in the core.

4. Turbulence Transport in Modern View

These structures and drift-waves have their own contributions to plasma transport; the symmetric property of zonal flows causes no cross-field transport. Therefore, an increase in the zonal flows contributes to improving plasma confinement, and the energy partition between these elemental components in plasma turbulence should determine the transport. The hypothesis has been verified in biasing experiments performed in TJ-K stellarator [29] and TEXTOR tokamak [30]. The voltage is applied on the biasing electrode to induce the plasma flows and result in the confinement improvement in TJ-K and TEXTOR. The poloidally symmetric fractions of electrostatic component, *i.e.*, zonal flows, are suggested to increase in these experiments. In CHS the energy partition between the zonal flows and drift-waves is examined to conclude that the confinement is better in the case that the energy fraction of zonal flows is larger [31]. This observation demonstrates that the plasma transport is improved under the condition of enhancing the zonal flows. The laws of energy partition between the drift waves and their generating structures are important to be pursued.

5. Future Direction

The outstanding progress has been made in the study of plasma turbulence by the remarkable development of diagnostics [32]. According to the new paradigm, the plasma turbulence is maintained through the spatiotemporal interactions all over the whole plasma between the different scale fluctuations, *i.e.,* drift-waves (microscale), zonal flows and streamers (mesoscale) and macroscopic modes. For further understanding of the plasma turbulence and transport, full dimensional measurements, at least two-dimensional covering the wide region of plasma, should be necessary to clarify the spatial dynamics with extending the analysis into the wavenumber domain, which contributes to the first-principle understanding of unsolved problems such as nonlocal transport.

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