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出版情報：Plasma Physics and Controlled Fusion. 53 (12), pp.124015(1)-124015(12), 2011-11-14. IOP Publishing
バージョン：

Experimental studies of mesoscale structure and its interactions with microscale waves in plasma turbulence

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Abstract. The modern view of plasma turbulence has been established due to the discovery of zonal flows and other structures drift-waves generate, and contribute to exploring new manners of understanding of transport and structural formation in magnetized plasmas and astronomic objects. This article presents recent development of laboratory experiments for plasma turbulence to have advanced its understanding and have made the paradigm shift. The topics include the discoveries of mesoscale structures, such as zonal flows and streamers, the recent development of analyzing techniques to quantify the couplings between different scale structures and methods to elucidate energy transfer direction, and turbulence transport and barrier formation. Finally, future experiments are suggested for establishing the first-principle laws of turbulence transport and structural formation.

1. Introduction

Plasma turbulence is a phenomenon ubiquitously observed in nature. Studies of plasma turbulence provides physically understanding of structural formation mechanism 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 the magnetic plasma confinement aiming at nuclear fusion. The turbulence determines the fusion performance, that is, basic plasma parameters; confinement time, density and temperature. Therefore, extensive studies of plasma turbulence over a half century have been vitally carried out in the fusion research from its infancy [1, 2].

The laboratory experiments in 1970's have elucidated that the plasma turbulence should be driven by drift waves whose existence was proven with with microwave scattering methods [3, 4]. Recent development in simulations and experiments has revealed the real image of plasma turbulence, indicating the capability of drift-waves to generate mesoscale structures, zonal flows, *e.g.,* geodesic acoustic modes (GAMs) and streamers. In fact, the discovery of zonal flows, *i.e.,* one of the mesoscale structures that the drift-wave generates, has made a paradigm shift of plasma turbulence. The present recognition is deviating from the old one that plasma turbulence is a system of drift-waves to the new paradigm [5, 6, 7, 8], giving a deep insight into unsolved issues in magnetized plasmas, such as transport barrier formation and nonlocal dynamics.

The physics of turbulence in magnetized plasmas should be common with astronomical and geophysical objects; such as the atmosphere of rotating planets, zonal flows in Jupiter, solar tachocline, geo-dynamo and galaxi-dynamo [9]. It has been pointed out that Hasegawa-Mima equation [10], which concisely describes the drift-wave turbulence, is equivalent to the one to describe the Rossby wave turbulence and phenomena observed in rotational planets [11, 12]; zonal flows [13] and red giant spot [14] in Jovian atmosphere. Therefore, the study of zonal flows and plasma turbulence in laboratory plasmas should give the fundamental understanding of processes occurring in the astronomical objects like the atmosphere of a rotating planet.

This article briefly reviews recent development in laboratory experiments to have made the paradigm shift of plasma turbulence, with the modern view that the plasma turbulence is regarded as a system of drift-waves and zonal flows (and other turbulence generating structures). After describing the discoveries of mesoscale structures, such as zonal flows and streamers, the article presents the recent development of analyzing techniques to quantify the nonlinear interactions between different scale structures and methods to elucidate energy transfer direction. The physical relation of zonal flows are discussed on turbulence transport and barrier formation in the modern view of plasma turbulence. Finally, the future experiments are suggested for advancing the physics of plasma turbulence

2. Discoveries of Structures Drift-Waves Generate

2.1. Identification of Zonal Flows and Magnetic Fields

Spatial diagnostics to measure plasma flows and electric field need to be developed for searching the mesoscale structures the drift-waves generate, although it may have been a difficult task. In the recent zonal flow experiments, heavy ion beam probe (HIBP) and beam emission spectroscopy (BES) have played an important role in identifying the zonal flows. Zonal flow is such a mesoscale structure linearly stable but nonlinearly driven by background drift-waves or turbulence. The major structural characteristics of the zonal flows are, i) zonal flows are symmetric around the magnetic axis ($m = n = 0$), ii) have a mesoscale wavelength ($\sim \sqrt{a\rho_s}$) in radial direction ($k_{\mathrm{r}} \neq 0$) [5, 6], where a and ρ represent plasma minor radius and Lamor radius at electron temperature, respectively.

Electric field measurements with twin HIBPs confirmed the existence of the zonal flow in CHS, as is shown in Fig. 1 [15]. In magnetically confined plasmas, the perpendicular flow to the confinement magnetic field is equivalent to $E \times B$-drift, hence the measurement of radial electric field is equivalent to that of the perpendicular flows. The fluctuations in the lower frequency ($\sim$ 1 kHz) were found to satisfy the above conditions, and were identified as zonal flows [15, 16]. A combined method of time-delay-estimate with BES for 2D plasma flow measurement succeeded in detecting the stationary zonal flows in the core of the L-mode plasma in DIII-D tokamak [17]. Using Langmuir probe arrays, experiments for the stationary zonal flows have been carried out so far to identify the zonal flows both in linear plasma devices [19, 20] and the plasma edge of toroidal devices [18].

In toroidal plasmas, the poloidal asymmetry in magnetic field configuration gives birth to another type of zonal flows, so called geodesic acoustic modes (GAMs), *i.e.*, an oscillatory branch of zonal flows. The GAMs can be detected in density fluctuations, in contrast to the stationary zonal flows. The properties of GAMs make many diagnostics possible to detect their presence, therefore, the investigations of GAMs have been performed in a number of toroidal plasmas [21, 22, 23, 24], after the GAM identification in the H1-heliac [28, 25, 27].

Several theories have been proposed to predict the existence of zonal magnetic field generated from the turbulence [29, 30, 31]. The zonal magnetic field generation due to turbulence was confirmed by developing the capability of the HIBPs in CHS to measure magnetic field, showing quite similar spatio-temporal characteristics to the zonal flows [16, 32], as is shown in Fig. 1(c). The phenomenon is associated with the historical physical problem, the dynamo field generation universally observed in astronomical objects, rotating planets and galaxies. The observation should be the first direct experimental evidence that the turbulence really generates a global and structured magnetic field [33, 34, 35].

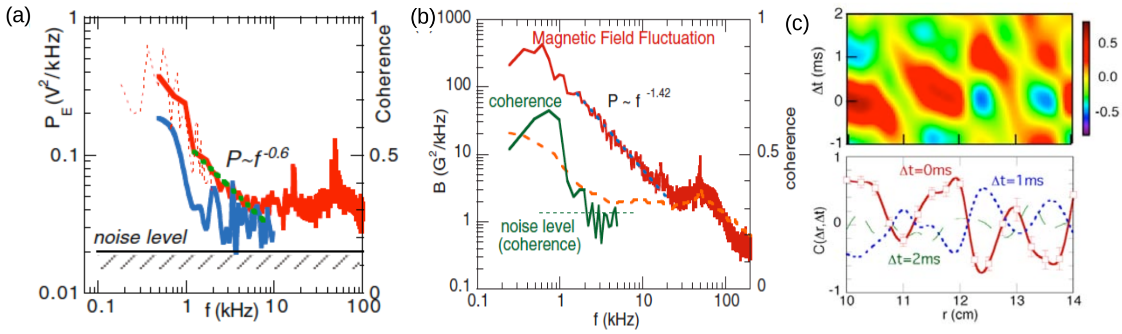

Figure 1. Zonal flows and fields. (a) Electric field fluctuation spectrum, with correlation in the toroidal direction. (b) Magnetic field fluctuation with correlation in the toroidal direction. (c) Spatio-temporal (radial) correlation between electric field at two distant position.

2.2. Identification of Streamers

Streamer is a short-lived mesoscale structure radially elongated and localized in poloidal direction in mesoscale width, *i.e.,* $k_r = 0$ and $k_\theta \neq 0$, and streamer is nonlinearly generated from drift-waves, as is similar to zonal flows [36]. The existence of streamers has been predicted in a number of simulations [37, 38]. In toroidal plasma experiments, however, there have been only a few observations to hint streamer formation [39, 40]. On the other hand, streamer was identified with a combination use of multi-channel probes in a linear cylindrical plasma, LMD-U [41, 42]. The azimuthal probe array found that poloidally localized structures were generated quasi-periodically from nonlinear couplings between elemental drift-wave components of radially elongated structures. Figure 2 shows an example of density (ion saturation current) fluctuations, detected with a 64 ch. probe array, to demonstrate the presence of streamers as quasi-periodical bursts localized in a narrow poloidal region.

2.3. Identification of Macroscopic Fluctuating Structure

Another fluctuating structure driven by background turbulence has been found in electron temperature fluctuation measurements in LHD using electron cyclotron emission (ECE) [43]. As is shown in Fig. 3, the discovered structure has a maximum amplitude at the half radius with a long radial correlation length comparable to the plasma minor radius, and with $n = 1$ periodicity in toroidal direction. The fluctuation frequency of the structure is in a few kHz range, which corresponds to the range of dissipative trapped ion modes (DTIM) [44]. The coupling of the fluctuating structure with the background turbulence is confirmed with bicoherence analysis (see the next section), therefore, the fluctuating structure is assumed to be the stable DTIMs that are destabilized by the background turbulence.

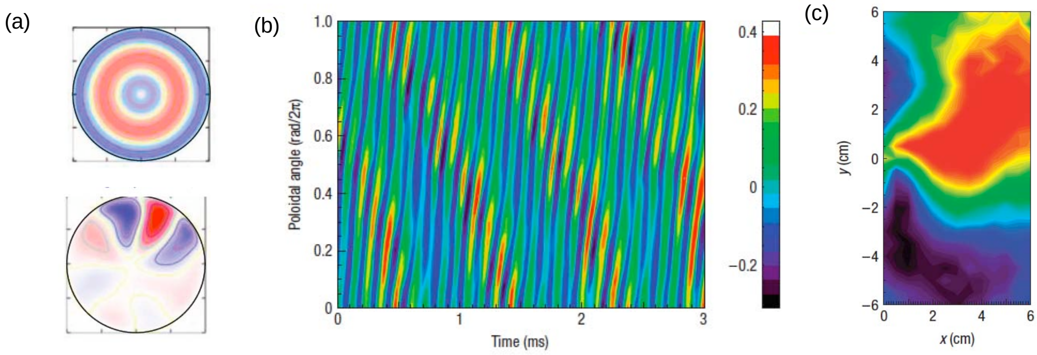

Figure 2. Identification of streamers in a linear cylindrical plasma. (a) Cartoons of structures of zonal flows and streamers. (b) Simultaneous measurement of the spatiotemporal behaviour of the ion saturation-current fluctuations by a 64 ch. azimuthal probe array. (c) Real parts of cross-spectrum pattern showing that the elementary component constituting the streamers is radially elongated.

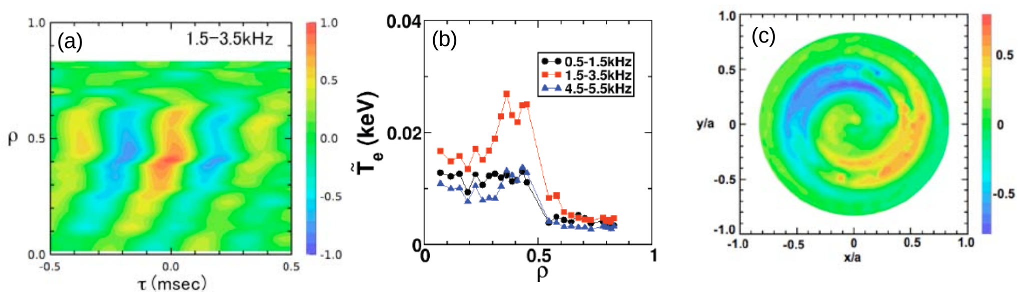

Figure 3. Macroscopic fluctuating structure discovered in Electron Cyclotron Emission measurement in LHD. (a) Radial correlation function of macroscopic fluctuating structure. (b) The radial amplitude profile of macroscopic fluctuating structure. (c) Reconstructed image of the fluctuating structure.

3. Developments of Analyzing Methods to Quantify Nonlinear Interactions

3.1. Bicoherence for Quantifying Three Wave Coupllings

Nonlinear interactions between background waves and meso- and macroscale structures are the major processes to realize the final state of turbulence. Therefore, methods to elucidate such nonlinear processes are necessary for understanding of the turbulence formation mechanism. The bicoherence is a method to quantify three-wave couplings in turbulence [45, 46, 47]. Recent developments of computer technologies have made it easier to perform the bicoherence analysis for extracting the elemental processes of turbulence both in toroidal and cylindrical linear plasmas [48, 49].

A number of bicoherence analysis have been done to show the nonlinear couplings between GAMs and background waves [28, 50, 51]. Figure 4a shows, for example, a bicoherence diagram obtained for potential fluctuations measured with a Langmuir probe at the plasma edge in JFT tokamak. The bicoherence diagram clearly shows the presence of two bright lines [51, 52, 53]. It was shown that the third frequency, $f_3 = f_1 + f_2$, of a constant value was agreed with the GAM frequency in the plasma. The two bright lines show that the nonlinear couplings are strong between the GAM and the background turbulence.

The couplings between component waves in turbulence could be intermittent, as the intermittency is one of the well-known characteristics with turbulence. The wavelet bicoherence analysis was invented to investigate dynamics of nonlinear couplings [54, 55]. It is really confirmed, as is shown in Fig. 4b, that the properties of the couplings are really changed due to the background structure of turbulence, *i.e.,* zonal flows. Consequently, the nonlinear interaction between component waves can be influenced with the condition of the stationary zonal flows, through the mechanisms such as the zonal flow shearing, the wave scattering, the wave trapping, and so on [5].

These bicoherence analyses have been usually performed in frequency domain. However, in strict sense, the matching condition in frequency is just a necessary condition for three wave couplings, consequently, the analysis needs to be extended to wavenumber space to confirm the wavenumber matching condition as well, *i.e.,* $\vec{k}_1 + \vec{k}_2 = \vec{k}_3$. In linear cylindrical devices, LMD-U [56] and VINETA [57], a 64 channel azimuthal probe array succeeded in resolving the nonlinear couplings including the wavenumber space. In VINETA the wavelet analysis was adopted to resolve the temporal couplings in 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 [58].

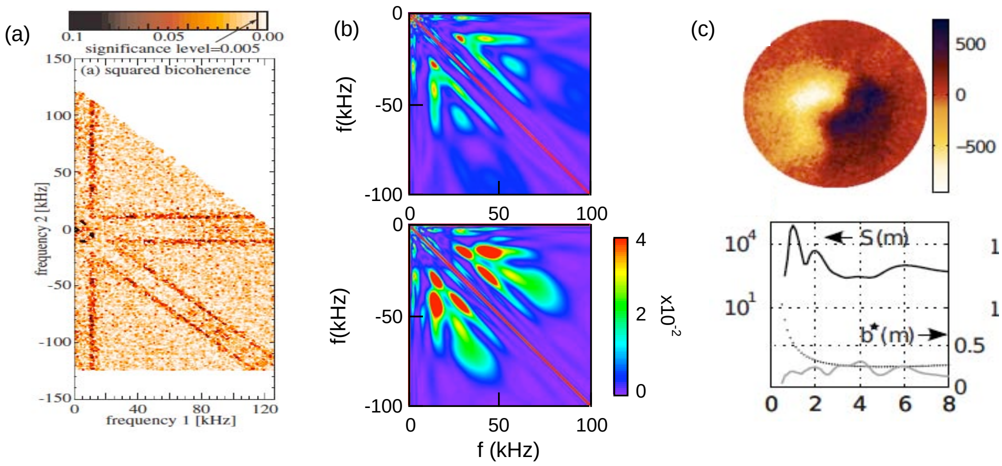

Figure 4. Bicoherence analyses. (a) Bicoherence diagram showing the couplings between GAM and turbulence. (b) Wavelet bicoherence diagrams showing the change of the couplings dependent on the phase of zonal flows. (top) The one for the phase of zonal flows orienting to the direction of the bulk flow, and (bottom) the one for the opposite. (c) A fast camera image (top), and temporal wavelet spectrum and summed wavelet bicoherence showing temporal couplings in wavenumber space (bottom).

3.2. Evaluation of Internal Energy Transfer

The power transfer function (PTF) analysis have been developed to elucidate not only the presence of the nonlinear couplings but also energy transfer direction between different scale fluctuations or structures, since method based on Hasegawa-Mima equation [10] was proposed [60, 61, 62, 63, 64]. The analysis successfully deduced the essential parameters, such as the growth rate γ_f and the PTF, $T(k_1, k_2)$, to demonstrate the presence of energy exchange between component waves, according to the following formula,

$$\frac{\partial P_k}{\partial t} = 2\gamma_k P_k + \sum T(k_1, k_2).$$

The PTF analysis is extended and applied on two dimensional (2D) probe data, which provides the turbulence information in the wavenumber space, in TJ-K torsatron. The energy transfer is evaluated in the two-dimensional wavenumber space, demonstrating that dual cascade feature, which means the inverse and forward cascade in potential and density fluctuations, respectively [65].

Many other methods has been proposed to infer the energy transfer direction. For example, two-field model [66, 67] includes the contribution of density fluctuations neglected in the single-field models based on electrostatic potential, and has been applied on the experimental data in TJ-K [68] and in CSDX [69]. The most recent work carried out in TJ-K along the above line succeeded in proving the nonlocal energy transfer from drift-waves to zonal flows [70], as is shown in Fig. 5a. The cross-bicoherence analyses were used to demonstrate the energy transfer mediated via GAM convection between density fluctuations in DIII-D [71]. The cross-bicoherence analysis implied that the energy exchange between zonal flows and local turbulence should have spatial (or radial) dependence in LMD-U [72]; the zonal flows lose their energy in the edge but gain the energy in the core, as is shown in Fig. 5b.

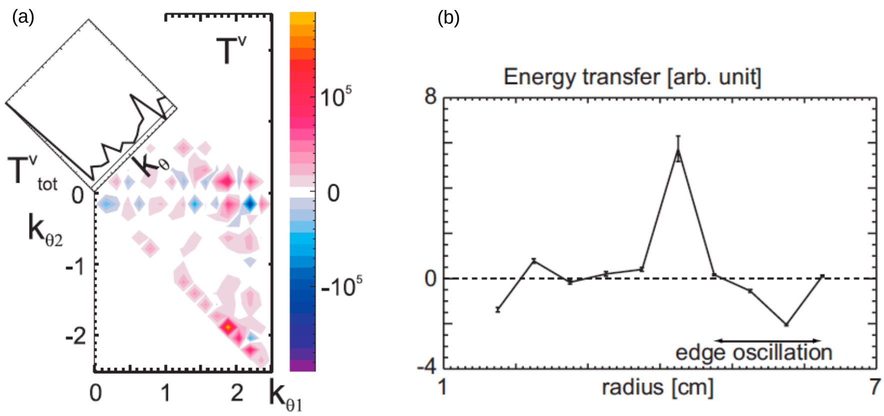

Figure 5. Energy Transfer Analysis. (a) Energy transfer analysis in the wavenumber space in TJ-K. (b) Energy transfer analysis based on cross-bicoherence analysis showing the nonlocal energy exchange between zonal flows and local turbulence in LMD.

4. Turbulence Transport in New Paradigm

4.1. Energy Partition and Transport

The symmetric pattern of the zonal flows causes no transport, thus, an increase in the zonal flows, owing to the energy transfer from the turbulence, contributes to improving plasma confinement. Therefore, the energy partition between zonal flows and drift-waves is a key to determine the level of transport. The hypothesis has been confirmed in several experiments, as is shown in Fig. 6. In biasing experiments performed in TJ-K stellarator [73] and TEXTOR tokamak [74], the voltage is applied on the biasing electrode to induce the plasma flow, then the confinement is found to be improved. Then, the poloidally symmetric fractions of electrostatic component, which can be regarded as zonal flows, are observed to increase in TJ-K, while a signature of zonal flows, *i.e.,* the long-range correlation, is found to increase in TEXTOR.

A direct evidence is obtained in CHS to show that the energy partition between zonal flows and drift-waves is a key factor for plasma confinement [75]. The energy partition between the zonal flows and drift-waves for the inside of the barrier is examined to conclude that the confinement is better in the case that the energy fraction of zonal flows is larger. This larger fraction of zonal flows can be ascribed to the low damping rate of flows after the strong positive electric field is realized according to the neoclassical bifurcation [76, 77]. This observation demonstrates that the plasma transport is improved in the condition of enhancing the zonal flows.

4.2. Zonal Flows and Barrier Formation

Roles of the zonal flow on transport barrier formation are needed to be clarified. In the state with a barrier in CHS, the zonal flows fraction is found larger than in the state of no barrier at the barrier position. As is shown in Fig. 7a, the zonal flow fraction clearly decreases with an increase in the microscale fluctuations, *simultaneously*, at the time when the internal transport barrier is broken. Similarly in H1-heliac, the enhancement of zonal flow fraction was observed with the reduction of background turbulence after H-mode transition [78]. In TJ-II experiment, in the H-mode transition, the zonal flow fraction is observed to increase with the reduction of turbulence (see Fig. 7b) [79]. After this increase of zonal flow fraction, the mean electric field shear is observed to be developed. This observation could suggest that the increase in zonal flows should be the triggering mechanism to induce the H-mode transition. Although it has been a well-known long-standing problem whether the generation of mean shear flows or flow bifurcation is the cause for transport barrier formation, the third element, zonal flows, comes up to the causality question of transport barrier formation. Recently, a significant nonlinear interaction between GAMs and turbulence during the L-H transition, for example, a limit cycle oscillation below threshold, has been observed in ASDEX-U tokamak [80] The causal relation between mean shear flow, zonal flows and background turbulence for barrier formation should be an intriguing question to be solved.

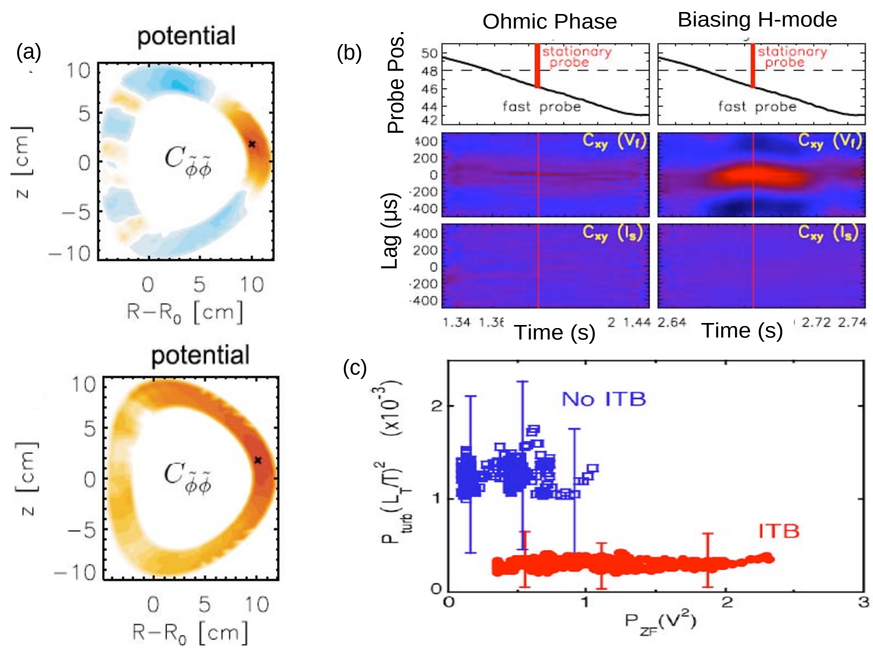

Figure 6. Transport barrier and Energy partition. (a) The change in the correlation between the potential fluctuation at two position before and after applying the voltage on the biasing electrode in TJ-K. (b) Changes in the correlation of potential and density before and after applying the biasing electrode in TEXTOR. (c) Two different states in energy partition between zonal flows and turbulence. The larger fraction of zonal flows results in better confinement.

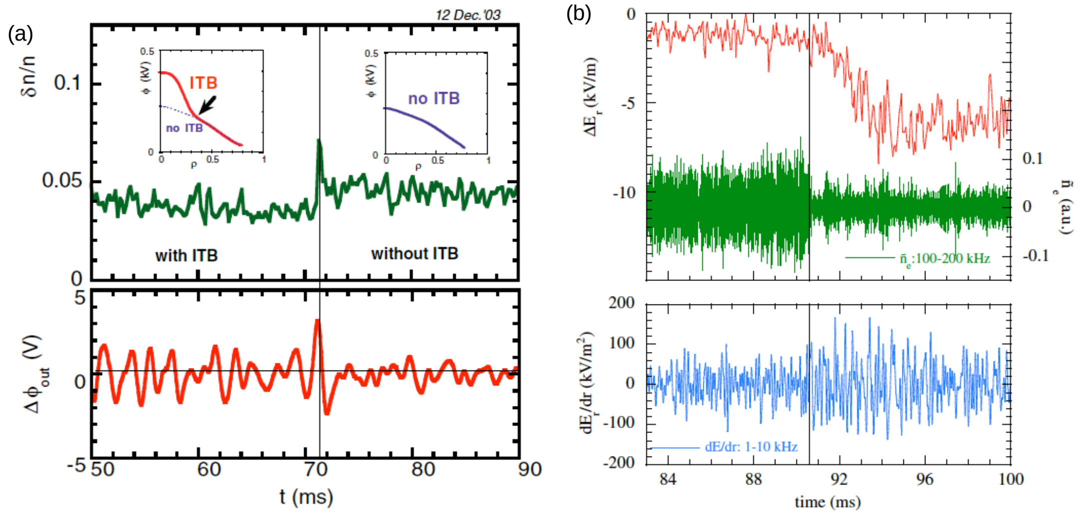

Figure 7. Zonal flows and transport barrier formation. (a) Change in turbulence and zonal flows before and after the internal transport barrier is broken down. (b) Changes in electric field shear, turbulence (top) and zonal flows after H-mode transition in TJ-II.

5. Future Issues for Plasma Turbulence Experiments

According to the new paradigm, the plasma turbulence is maintained through the spatio-temporal interactions all over the whole plasma between the different scale fluctuations or structures, drift-waves (microscale), zonal flows and streamers (mesoscale), and macroscopic modes. For further understanding of the plasma turbulence, full dimensional measurements, at least two dimensional, should be necessary to be developed. Two-dimensional measurements covering the wide region of plasma can clarify the spatial dynamics with extending the analysis into the wavenumber domain. Some of unsolved issues that can be addressed with such measurements are listed up as follows.

i) Interaction of background flows with drift-waves. The interaction between zonal flows and turbulence has been confirmed in single point or one-dimensional measurements, as is shown in Fig. 4(b) [81]. The amplitude of microscopic fluctuations is found to be modulated with the phase of zonal flows. Theories predict many possible causes of the modulation effects, e.g., shearing, trapping and so on. A single point or a narrow one-dimensional measurement, however, cannot resolve exact spatial dynamics accompanied with the modulation; for example, the annihilation/creation of the local turbulence cannot be discriminated from the spatial movement of a turbulence pattern.

ii) Competitions between fluctuating structures of different scales In plasma turbulence, co-existing fluctuations of different scales, *e.g.,* zonal flows, GAMs, streamers and drift-waves, compete with each other to determine the transport and plasma structure. The real observations of energy exchange or partitions between these elementary components are necessary to investigate the dynamic of plasma turbulence, moreover, to contribute to the first principle understanding.

iii) Fluctuation asymmetry and configuration geometric effects In toroidal plasmas, the poloidal asymmetry of fluctuation structure has been expected in theories and simulations, and confirmed in experiments [82, 83]. Therefore, the plasma turbulence and transport can be dependent on the magnetic field curvature or geodesic curvature. Moreover, even in a linear cylindrical plasma where configuration is azimuthally symmetric, the properties of azimuthally averaged turbulence-driven flux is found to be different from the local one [84]. Therefore, two-dimensional observations should be needed to reveal the dependence of plasma turbulence on local magnetic field structure and difference in local and global transport for establishing laws of transport and structural formation.

iv) Non-local dynamics and radial correlation Non-local transport, such as cold pulse propagation [85], simultaneous core transport change in H-mode transition [86], has been found in toroidal plasmas [87, 88, 89]. One of the possible explanations is ascribed to a long-distance radial correlation between local microscale fluctuations governing the local transport through the meso- or macroscale fluctuating structures, as is shown in Fig. 5. In other words, a change in microscale fluctuations at a point can alter the turbulence transport at distant positions through large scale fluctuations coupled with such microscale fluctuations [90]. The radial correlation length of zonal flows (see Fig. 1) could be sufficiently long over the whole plasma radius, and the recent found fluctuating structure could cover the whole plasma. Therefore, simultaneous measurements of different scale fluctuations are absolutely necessary to solve the long-standing mystery of the nonlocal transport.

6. Conclusion

The outstanding progress has been made in the experimental study of plasma turbulence. The remarkable development of diagnostics have revealed the existence of mesoscale structures which have made a paradigm shift of plasma turbulence. In this new paradigm the plasma turbulence is regarded as a system of drift-waves and drift wave generating structures, *i.e.*, zonal flows, streamers, and some other meso- and macro-scopic structures, and these elemental components nonlinearly interact with each other to realize plasma turbulence structure. The advanced techniques have been also developed to succeed in evaluating the nonlinear interactions, energy transfer and dynamics between these components.

These structures and drift-waves have their own effects on plasma transport; the symmetric property of zonal flows causes no cross-field transport. Therefore, it is absolutely necessary to clarify the mechanisms to determine the energy partition between these elemental components in plasma turbulence. Since these elemental structures are widely spread in the plasma, two dimensional measurement covering the whole plasma with full scale range of fluctuations is essential for further understanding of plasma turbulence. Such measurement should reveal the real spatio-temporal dynamics occurring between these elemental components in plasma turbulence, giving a decisive insight into the transport barrier formation and nonlocal dynamics that are still to be investigated in this field.

The future researches to finding the parameters to control the energy partition should contribute to establishing the laws of turbulence transport or of structural formation in turbulent plasmas. Finally, the phenomena associated with turbulence are ubiquitously observed in the universe. The laboratory experiments of plasma turbulence should give a deep understanding to not only to transport in magnetized plasmas but also to the transport phenomena and structural formation in the universe, the atmosphere dynamics in rotating planets, transport in accretion disks, and so on.

Acknowledgments

A special appreciation would be given to Profs. S-I. Itoh, K. Itoh, K. Matsuoka, H. Zushi, K. Hanada, K. Nakamura, S. Inagaki, Y. Nagashima, H. Idei, Drs. M. Sasaki, S. Oldenbüger, M. Hasegawa for their continuous supports. This work is partly supported by the Grant-in-Aids for Scientific Research (No. 23246162) and the Grant-in-Aids for Scientific Research (No. 21224014). This paper is dedicated to 60th birthdays of Prof. S-I. Itoh and K. Itoh.

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