Symmetry-Breaking of Turbulence Structure and Position Identification in Toroidal Plasmas

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As a result of the progresses in the study of plasma turbulence, the picture of 'multiple-scale turbulence' is widely accepted, and the 'nonlinear excitation, nonlocal interaction, probabilistic transition' views have been developed. Along the paths of these progresses, importance of new problem, i.e., the symmetry-breaking of turbulence structure (such as up-down asymmetry, excitation of streamer, etc.) is gradually recognized. In this topical review article, we revisit these issues, and illuminate the possibilities that the new progresses (which will be brought about by studying the symmetry-breaking of turbulence) are expected. Examining theoretical predictions and preceding experimental achievements, new advancements, which will be realized, are explained. The experimental study of symmetry-breaking of turbulence structure ultimately requires to measure fluctuations (at all scales) over the whole plasma cross-section simultaneously. In addition, new type of demands can be imposed in measuring of fluctuations over the whole plasma cross-section simultaneously. One of such demands is the accuracy of the measurement position. Problems in this aspect are also discussed. This concise review is used to identify what will be discovered and how it will be reached in future experiments, in the subject of the symmetry-breaking of turbulence structure.

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1. Introduction

Turbulence and structure formation in high-temperature magnetized plasmas have attracted attentions. The research has been advanced substantially in the last decade [1–3]. Among various progresses, one may point out that the essential elements in these developments are the physics understanding of, such as, (i) the multiple-scale nonlinear interactions (including nonlinear instabilities) [4–25], (ii) bifurcation of the combined structure of turbulence and global inhomogeneity [26–38], and (iii) new aspect of the far-nonequilibrium feature of confined plasmas (i.e., the idea of 'heating heat turbulence', or 'fuelling fuels turbulence') [39, 40]. Another decisive progress is the advancement of the data-analysis method, which has enabled one to measure the magnitude of nonlinear interactions quantitatively [41–45], with examples of successful identifications of nonlinear excitations [46–51] and the identification of hysteresis in gradient-flux relation [52] (see reviews [53, 54]). Figure 1 illustrates the experimental confirmations of meso- and macroscopic perturbations in toroidal plasmas; spatiotemporal correlations of zonal flow (a), global fluctuation (b) and streamer (c), respectively. If one considers the cases of streamer [48, 55, 56] or the coexistence of vortex and zonal flow [51], one immediately recognizes that the microscopic turbulence and related nonlinear excitations are not homogeneous in the azimuthal direction. These are in contrast to the often-employed assumptions that microscopic fluctuations are (nearly) homogeneous in azimuthal direction. In order to highlight the importance of such newly-focused inhomogeneities of turbulence, we here use the concept 'symmetry braking of turbulence structure'. The new degrees of freedom in nonlinear interaction, which is caused by the symmetry-breaking of turbulence, is not limited to the streamer, as has been pointed out by many theoretical works [57–65]. In order to fully understand the multiple-scale turbulence, we must also investigate the issue of symmetry-breaking of turbulence structure.

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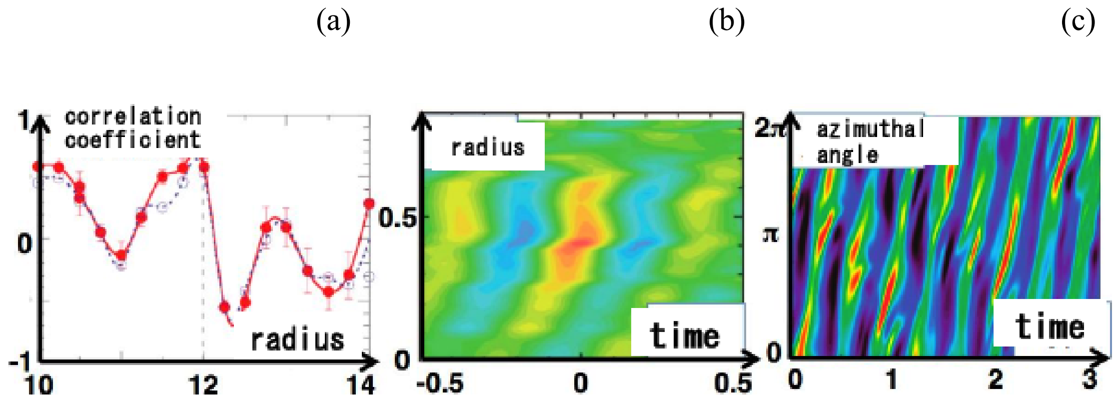

Fig. 1 Experimental confirmations of meso- and macroscopic perturbations in toroidal plasmas. Spatiotemporal correlations of zonal flow (a), global fluctuation (b) and streamer (c), respectively. Based on [46, 48, 50].

In the development of physics of plasma turbulence, the importance of symmetry-breaking of turbulence has been pointed out. In this short review article, we revisit the issues, and illuminate the possibilities that the new progresses are expected. This concise review might be used to identify what will be discovered and how will it be reached in future experiments. In addition, new type of demands can be imposed in measuring of fluctuations over the whole plasma cross-section simultaneously. One of such demands is the accuracy of the measurement position. Problems in this aspect are also discussed. One of fundamental elements in detecting the measurement position with high accuracy is the confirmation that different measurements are made on iso-magnetic surface. This problem is also discussed briefly.

This short review is constructed as follows. The physics issues are explained in chapter 2, and the required accuracy of measurement position is discussed in chapter 3. Possibility for identification of iso-magnetic surface is discussed shortly in chapter 4. Discussion is made in chapter 6.

2. Problem Definition in the "Symmetry Breaking of Turbulence"

In the beginning, we present a problem definition in conjunction of the symmetry-breaking of turbulence, for such a new device, in which the synthetic measurements of fluctuations of all scales are made simultaneosly, so that the new discovery of the dynamics of turbulence is pursued. In particular, one may challenge the issues, (one by one)

(i) the symmetry-breaking of turbulence structure,

(ii) distant nonlinear interaction of multiple-scale turbulence,

(iii) large-scale formation of vector fields from microscopic turbulence,

(iv) interactions and interferences between polar- and axial-vector-fields, including cross-talk/exchange between vector fields in different directions,

etc. will be investigated. One will also be able to study how the conservation relations impose constraints for structure formation of microscopic turbulence.

We here describe examples of physics processes, in which the localization of turbulence is essential. The issues are (1) previous studies on localization of turbulence or transport associated with in-out asymmetry, (2) dynamical interaction of axial vector field and turbulence, (3) updown asymmetry in the H-mode phenomena, (4) localized perturbation in the trigger of abrupt collapse events, (5) large-scale motion of turbulence clumps, (6) interaction of turbulence and magnetic islands, and (7) symmetry breaking that includes the impurity radiation. Based on these surveys, (8) the necessity to measure inhomogeneity of turbulence on magnetic surface is discussed.

The issues in this list are explained in the following.

2.1 Early studies on localizations of turbulence and transport

From the early days of fusion research, the in-and-out asymmetry (asymmetry in the high-field and low-field sides) of toroidal plasmas has been the central issue in the transport problem. Neoclassical processes are induced by this symmetry breaking [66], and many processes (e.g., Pfirsch-Schluter current [67], bootstrap current [68]) have been confirmed experimentally [69, 70]. The in-and-out asymmetry of collisionless toroidal plasma has been thought to influence the turbulence and turbulent transport via dynamics of trapped particles [71]. The trajectory of trapped particle depends on the shape of magnetic surfaces, thus the effect of the shape on turbulence has been discussed theoretically [72], as is illustrated in Fig. 2. Localization of fluctuations in the outside of torus has been observed [73]. A sample of experimental observation on the in-out asymmetry of fluctuations in tokamak is shown in Fig. 3.

It should be noted that these processes require care-

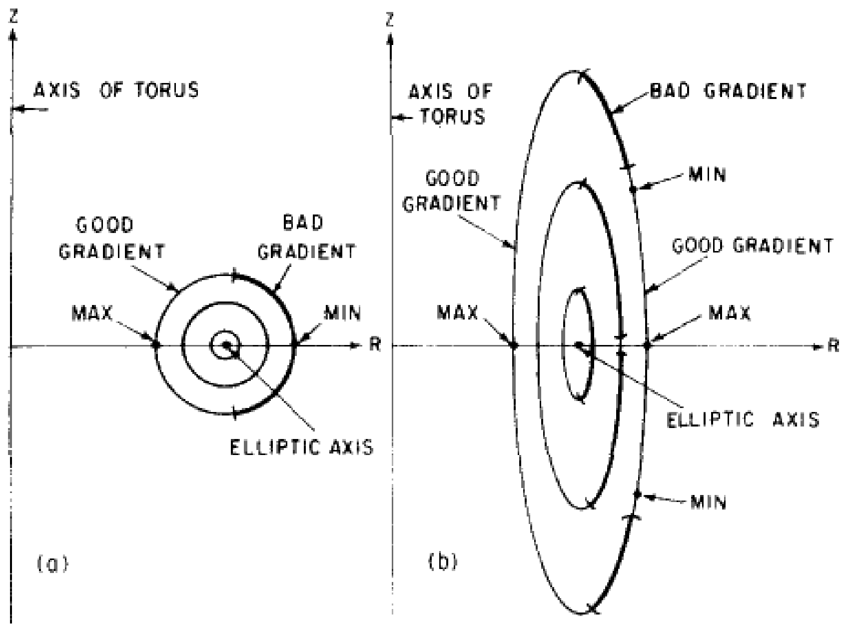

Fig. 2 Trapped particles and magnetic geometry. Shaping of magnetic surface can control distribution of trapped particles [72]. Effect of ellipticity on the instability. (a) circular tokamak and (b) elliptic tokamak. 'max' and 'min' denote the local extrema of B on the field line.

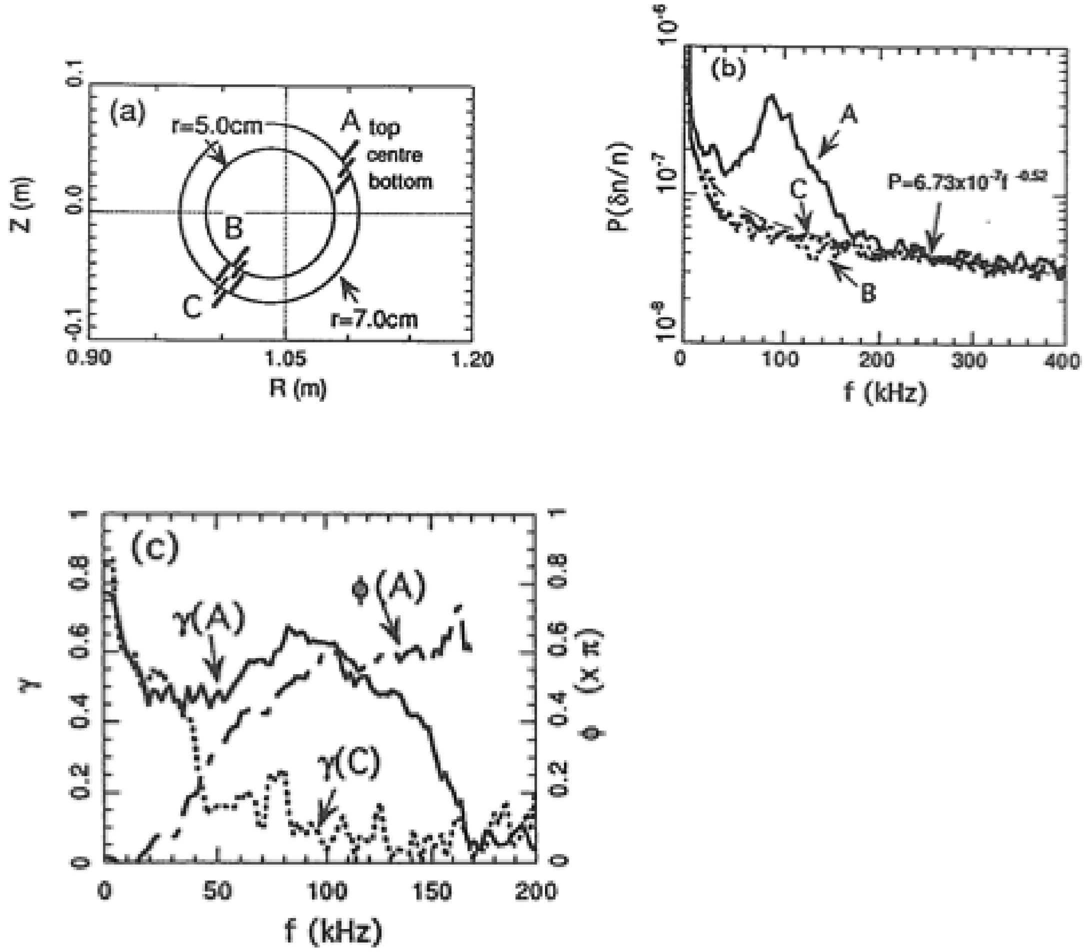

Fig. 3 Localization of turbulence intensity in the outside of torus. Measurements on the TEXT tokamak [73]. Poloidal asymmetry in density fluctuation spectra: (a) sample volume location, (b) power spectra, and (c) coherence between signals from two adjacent sample volumes and the phase difference on the low field side.

ful consideration on the conservation law. The process like bootstrap current indicates that the pressure gradient can induce toroidal current, i.e., the magnetic flux. One might wonder what happens in the conservation law of magnetic flux in high temperature plasmas. In axisymmetric magnetized plasmas, canonical angular momentum is conserved (not the angular momentum). Thus, the exchange between the particle angular momentum and magnetic flux function (vector potential) is allowed, satisfying the conservation law. The electron pressure gradient can drive the toroidal current, so that the interference between polar vector (gradient of scalar quantity) and axial vector can be induced. As is illustrated by this example, thought of conservation law is inevitable in considering the mechanisms discussed in the following sections.

2.2 Dynamical interaction of axial vector field and turbulence

The importance of symmetry-breaking of turbulence structure, which is associated with localization of turbulence, has attracted attentions recently. The pressure-gradient-driven turbulence can generate a global flow [24], and such a flow forms a doubly-connected flows in torus. Experimental identification of flow generation has been in progress [45, 58, 74], and a lot of fundamental mechanisms are known and wait experimental confirmations. For instance, the in-out and/or up-down asymmetry of turbulence has been known to play essential roles in the generation of poloidal and toroidal flows (axial vector field) from the turbulence which are driven by the density and/or temperature (scalar quantity).

2.2.1 Examples of predictions

Examples include following processes (a1)-(a7):

(a1) Stringer spin-up [75, 76], i.e., the rotation drive by the poloidal inhomogeneity of radial flux exists. Figure 4 denotes the essence of this spin-up mechanism. If there is an asymmetry of particle flux (localization at particular poloidal angle) in tokamaks, then there arises particle flux on a magnetic surface, which equilibrates particle supply on the magnetic surface. In conjunction with this, the difference of particle density on the magnetic surface is generated. Integrating the poloidal force on the magnetic surface, a net torque remains to drives poloidal rotation. The poloidal localization of radial particle flux should be related with the localization of turbulence on a magnetic surface. This phenomenon has not been experimentally studied.

(a2) The high dielectric constant of toroidal plasma at L-H transition which is induced by the dipole toroidal return flow [77, 78]. Toroidal return flow is illustrated in Fig. 5. Owing to the toroidicity, the poloidal flow is accompanied by divergence, which must be compensated by the secondary toroidal flow. The associated toroidal flow makes the total kinetic energy of poloidal rotation be enhanced. This is observed as an enhancement of effective mass in the acceleration of poloidal flow. This enhancement factor is known to be important in the experimental identification of the nonlinear driving mechanism of L-H transition [38, 79]. The secondary return flow has been partly observed [80], but the anti-symmetry with respect to poloidal angle has not yet been fully confirmed. Simultaneous measurements on both the inside and outside of torus are necessary.

(a3) The up-down asymmetry of turbulence, which is driven by inhomogeneous radial electric field [81].

(a4) The dynamic shearing of turbulence (with up-down and in-out asymmetries) and excitation of GAMs [82].

(a5) The poloidal shock at L-H transition, which is associated with the jump of plasma parameters at particular poloidal angle [83, 84]. When the radial electric field be-

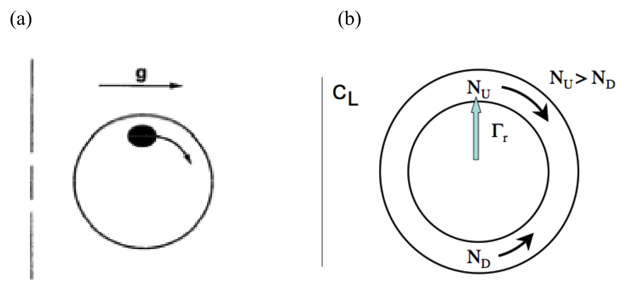

Fig. 4 Spin-up mechanism is explained in [76] as follows: (a) If a high density perturbation is produced in a localized region of upper-region, then the effective gravity would cause the density perturbation to swing clockwise. (b) If particle flux has up-down asymmetry, the density perturbation would have an up-down asymmetry. The density N_U (upper hemitorus) can be larger than N_D (lower hemitorus). This difference of density induces the poloidal rotation.

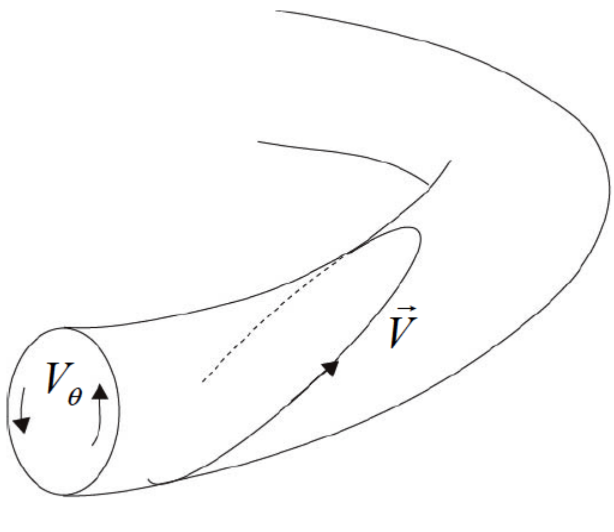

Fig. 5 Toroidal return flow is associate with the poloidal flow in the toroidal plasma [77].

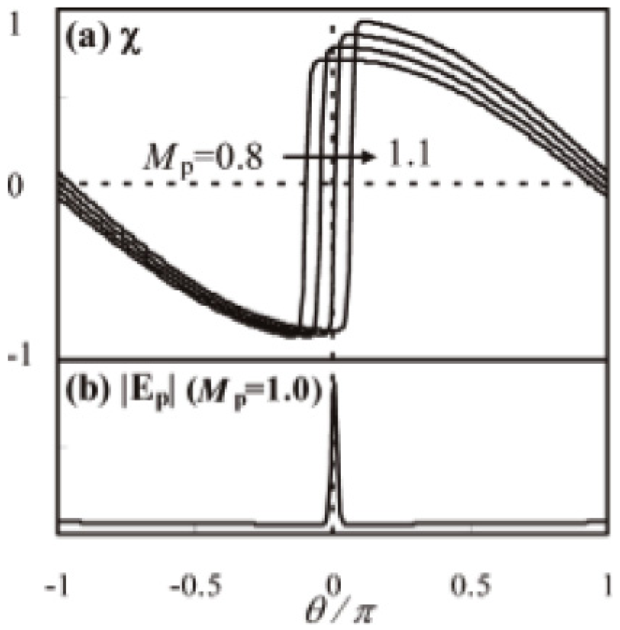

Fig. 6 Poloidal profile of normalized perturbed density (shown by natural log) (a) and magnitude of poloidal electric field for the case of $M_{\mathrm{p}} - 1$ (b), in the presence of strong radial electric field near plasma surface. The poloidal Mach number is close to unity. The poloidal shock is formed near $\theta \sim 0$ (low field side midplane) in the present case. (Quoted from [85].)

comes strong, the toroidal return flow, which is explained in the issue (a2), is enhanced as well. The speed of return flow varies along the magnetic field line, so that the shock is possible to occur. The poloidal shock, if it exists, is accompanied by the sudden change of plasma pressure (density) in poloidal direction across the shock. The steep change in the poloidal direction arises in the electrostatic potential of plasma, so that a strong *poloidal electric field* is generated at the shock. Figure 6 illustrates an example of poloidal shock [85]. The variation of density in the poloidal direction and the localized poloidal electric field are shown.

(a6) The toroidal flow generation by up-down asymmetry of turbulence [86].

(a7) The conversion and cross talk between toroidal and poloidal flows via phase space interaction [87] (Fig. 7) or via cross-ferroic turbulence [88, 89], etc.

2.2.2 Combined effect of symmetry breakings

These essential processes are related to the combined effects of symmetry breakings, which are induced by toroidicity and by inhomogeneous radial electric field. The deformation of fluctuating fields in cases (a3) and (a4) is illustrated in Fig. 8. In toroidal plasmas, in-out asymmetry appears as a ballooning effect on fluctuations, and the phase contour tends to be aligned in parallel to the midplane (majour radius direction) (Fig. 8 (a)). When the inhomogeneous rotation by radial electric field is imposed,

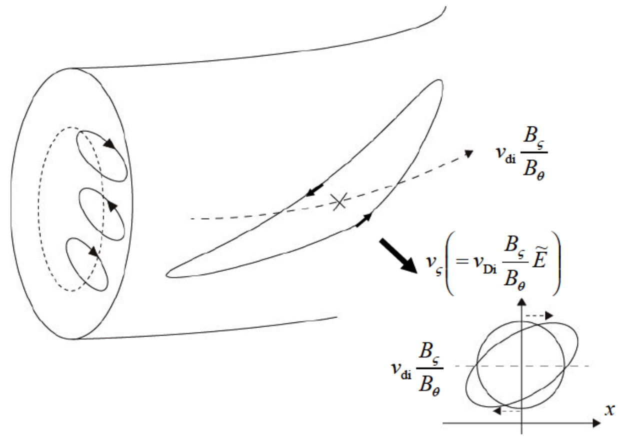

Fig. 7 Conversion of toroidal flow from poloidal flow. The precession of trapped particles is modified by the fluctuating electric field. A vortex in the phase space is inclined, so that the net toroidal torque remains [87]. This is compared with the conventional understanding of Reynolds stress, which is generated by the vortex in the real space.

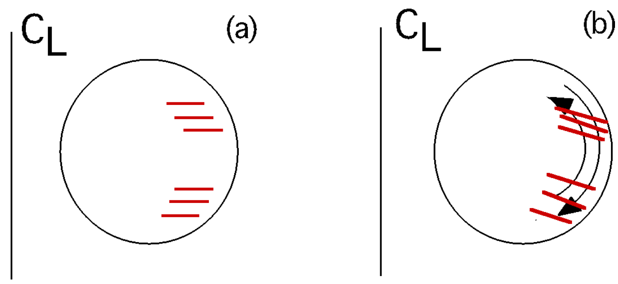

Fig. 8 Schematic illustration of dynamic shearing of ambient fluctuations by GAM. Contours of phases of toroidal fluctuations are shown by thick lines in (a). In the presence of poloidally-symmetric shearing motion, the phase contours are modified with up-down asymmetry. (Quoted from [82].)

the equi-phase contour is tilted. As a result, the phase contours show the up-and-down asymmetry. In the case of Fig. 8 (b), the equi-phase contour, along which plasmas are subject to drift, is close to minor-radial direction in the lower hemi-torus. The fluctuating radial motion (along the equi-phase contour) has longer radial wavelength than that in the upper one, so that the larger amount of energy is relaxed there by fluctuating convection for given fluctuation amplitude. In contrast, in the upper hemi-torus, the perpendicular wave number $k_\perp$ becomes higher, so that the energy relaxation is smaller (for given fluctuation amplitude). On the other hand, the Reynolds stress (for given fluctuation amplitude) is stronger in the upper hemi-torus, than in the lower hemi-torus. Thus, the fluctuation-driven transport of particle and energy are expected to be stronger on the bottom side (lower hemi-torus) in the case of Fig. 8 (b). If the sign of the radial electric field is reversed in Fig. 8 (b), the localization of fluctuations appears in the opposite up-down direction.

2.3 Up-down symmetry breaking in the H-mode phenomena

The issue of the up-down symmetry breaking must be studied in depth. Next example is related with the long-standing mystery of the L-H transition. It has been known that

(b1) the H-mode appears preferentially under the condition that the X-point of the magnetic surface is in the direction of the grad-B drift of ions [90].

A trial of experimental validation of the theories of L-H transition has been performed, based on the one-dimensional model and one-dimensional observations, and the origin of up-down asymmetry was not examined [91]. Semi quantitative confirmation has been reported, but still substantial difference was reported. Knowing the up-down asymmetry of the phenomenological observation on the L-H transition, the observations of the up-down asymmetry in physics quantities in the L-mode and in the L-H transition dynamics are necessary.

(b2) In addition, the so-called I-mode appears when the X-point is away from the grad-B drift of ions [92].

2.4 Localized perturbation in the trigger of abrupt collapse events

The localization of fluctuations on a magnetic surface is considered more and more important recently. A traditional approach to the abrupt collapses has been done as the search for a dominant 'mode' that is driven by instability. For instance, the '$m/n = 1/1$ mode' has attracted attentions in the study of sawtooth collapse (m and n are the poloidal and toroidal mode numbers, respectively).

However, the sudden excitation, which does not belong to the conventional 'modes', has been identified at the very onset of large-scale deformation recently. Nonlinear dynamics may play essential roles in trigger of collapse events [93]. New observations of event phenomena such as
(c1) 'tongue' in the onset of high-energy-particle driven bursts [94],
(c2) 'streamers' in the onset of type-III ELMs [95], and
(c3) 'fingers' in the onset of ELMs [96],
have been identified. Figure 9 shows the observation of 'tongue' phenomena, which appear in the trigger of high-energy-particle driven bursts in LHD [94]. The dependences of perturbation field on toroidal angle and poloidal angle are shown. The perturbed magnetic field is localized at particular toroidal and poloidal angles. The perturbation is, without doubt, strongly localized along the magnetic field. Such a strongly localized structure cannot be described by (small number of) principal modes that form helical pattern on torus. These perturbations can be captured by the simultaneous measurement of perturbations over a wide area of (or even whole) plasma. These observations, on the other hand, suggest the insufficiency of Fourier decomposition analysis, which is commonly employed, and stimulate the need for new way of data analysis.

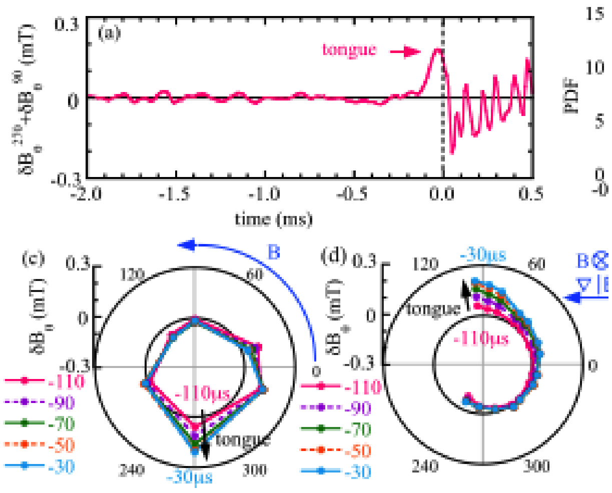

Fig. 9 'Tongue' in abrupt burst which was observed on LHD [111]. Time evolution of sum of magnetic field B_θ at ϕ = 90 and 270° in toroidal array. Polar plot of magnetic field perturbation B_θ of (c) toroidal array and (d) poloidal array during the 'tongue' event (t = −110, −90, −70, −50 and −30 μsec).

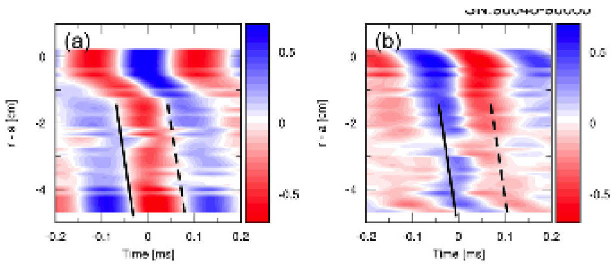

Fig. 10 Ballistic propagation of perturbation in turbulence amplitude near the edge of JFT-2M tokamak. Periodic modulation is induced by Limit Cycle Oscillation near plasma surface, and modulations of turbulence intensity and density gradient penetrate into the core plasma [79].

2.5 Large-scale motion of turbulence clumps

The fifth kind of problem, which demands the experimental study of global behaviour of fluctuation, has been pointed out. Theories have predicted
(d1) the ballistic motion of turbulence clump [97–100],
(d2) corrugations of mean profile [101, 102].
The experimental study on the ballistic motion of turbulence and/or spontaneous corrugation of mean profile requires the simultaneous observation of microscopic fluctuations in a global scale. The preceding theories [97–102] have studied the dynamics and structure in radial direction.

The large-scale ballistic motion of turbulence clump was partially measured experimentally as is illustrated in Fig. 10 [79]. Radial variation of the correlation length of fluctuations has been reported in [103] (Fig. 11). These initial observations motivate the experimental research of spatiotemporal dynamics of turbulence clumps in the core plasma. These can also have additional symmetry break-

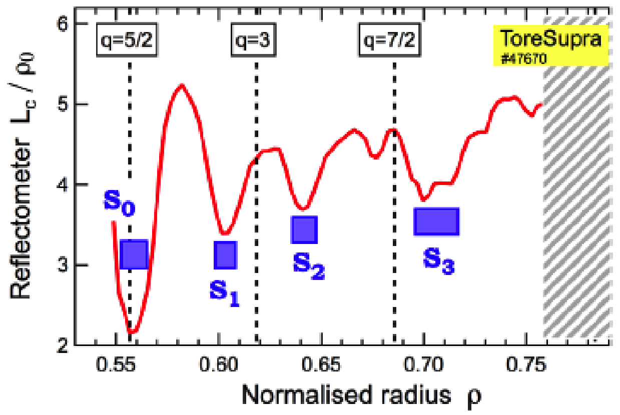

Fig. 11 Radial variation of the correlation length of fluctuations [103]. The reflectometer coherence length is plotted against radius (Tore Supra).

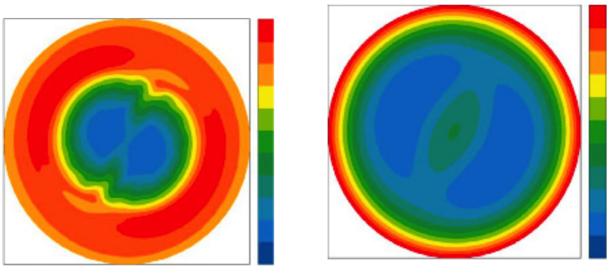

Fig. 12 Simulational prediction on turbulence intensity distribution, which is affected by the magnetic island [106]. Contour plots of fluctuating density (left) and helical flux function (right) at t = 5000.

ing. In the future, the simultaneous observations are required over the whole plasma column.

2.6 Interaction of turbulence and magnetic islands

Sixth, the issue of influence of the topology/configuration of magnetic surfaces on turbulence demands further experimental research. In particular, the interaction of turbulence and magnetic island is another issue, which merits detailed experimental studies. Turbulence drives/accelerates the growth of tearing mode [104–107]. The topology of magnetic island can affect the turbulence intensity. Figure 12 illustrates a simulational prediction on turbulence intensity distribution, which is affected by the magnetic island [106]. The onset condition of neoclassical tearing mode depends on the turbulent transport near the magnetic separatrix [108–110]. Mutual interactions between islands and turbulence induce nontrivial dynamics, such as the intermittent transmission of heat pulse across the magnetic island [111] (Fig. 13). Initial report has been given about the inhomogeneity of turbulence intensity on the magnetic island, i.e., the localization of turbulence intensity near the X-point [112]. The global measurement of turbulence will illuminate the interaction in the dynamics

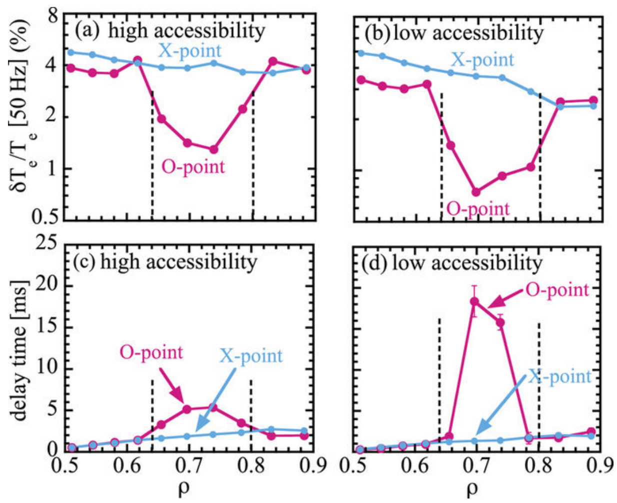

Fig. 13 Delay time of the heat pulse propagation in the magnetic island was observed. The transition between two states (fast and slow propagations into island, (a) and (b)) are observed [111]. Radial profiles of modulation amplitude with fundamental frequency (50 Hz) for the (a) a high accessibility state (high accessibility magnetic island) and (b) a low accessibility state (low accessibility magnetic island) and the radial profile of delay time of heat pulse with fundamental frequency (50 Hz) for the (c) a high accessibility state (high accessibility magnetic island) and (d) a low accessibility state (low accessibility magnetic island).

of turbulence and magnetic island.

2.7 Symmetry-breaking associated with impurity radiation

Radiation of photon from plasmas is also coupled with the turbulence and turbulent transport. The radiation loss by impurities has complex dependence on temperature, which has been thought to be one of reasons of density limit. An example of the experimental observation on the temperature dependence of radiation loss is shown in Fig. 14 [113]. The nonlinearity in the temperature dependence has been known to introduce nonlinear structure formation, such as detachment event, MARFE, and etc.

Here, we briefly revisit MARFE, because it is a phenomenon that shows strong asymmetry. The MARFE is a phenomenon, in which the localized radiation (nearly symmetric in toroidal direction) appears in the inside of toroidal plasma (in-out asymmetry) near the plasma surface [114] (Fig. 15 (a)). The peak of radiation density often shows weak-up-down asymmetry. A qualitative explanation of the onset of MARFE has been given as a thermal instability on a magnetic surface: If one considers the situation that the energy transport (from the core plasma) preferentially takes place in the low-field-side of torus, one expects that the electron temperature is not constant on the magnetic surface, but is higher in the outside (i.e., lower in the inside). (See, Fig. 15 (b).) This difference of electron temperature induces the poloidal inhomogeneity of impu-

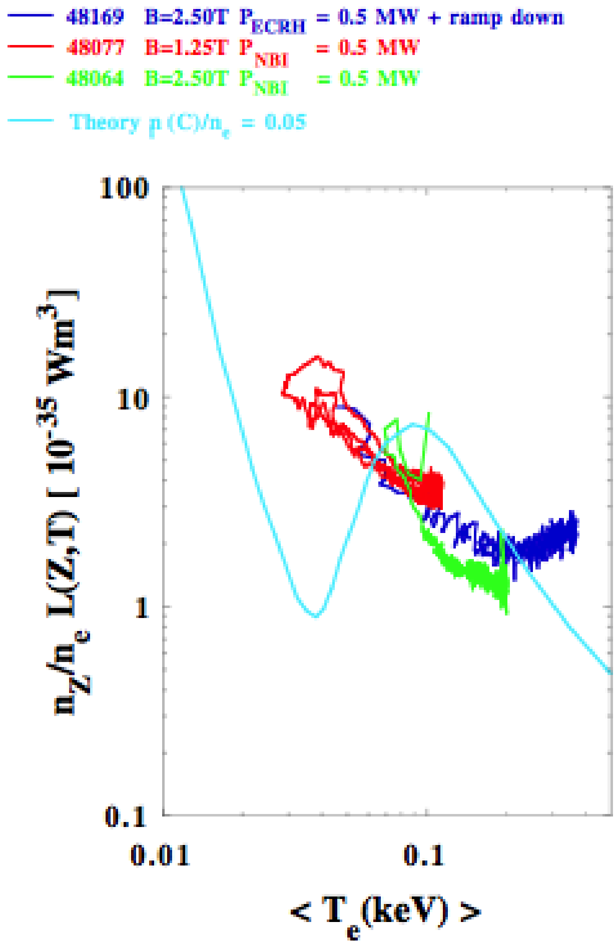

Fig. 14 Comparison of experimental cooling curves (Total radiation power divided by mean electron density, as a function of averaged electron temperature) in discharges with P_{NBI} or $P_{\mathrm{ECRH}} = 0.5\,\mathrm{MW}$ at a rotational transform, ι, of 0.34. For comparison the cooling curve of carbon (as a function of local temperature) with a 5% relative concentration is shown. The presentation of the measurements in this form allows a simple but rapid comparison of the impurity content of the different discharges. (Quoted from [113].)

rity radiation. Even if the impurity density is constant on the magnetic surface, the impurity radiation P_{rad} is stronger in the inside of torus (in the regime of temperature where $\mathrm{d}P_{\mathrm{rad}}/\mathrm{d}T < 0$), so that the impurity radiation tends to make the temperature (in the inside) lower. This temperature dependence of P_{rad} enhances the temperature inhomogeneity on the magnetic surface. On the other hand, the electron heat flux along the magnetic field line reduces the temperature inhomogeneity on the magnetic surface. Thus, if the impurity radiation exceeds a threshold, the role of impurity radiation to enhance temperature inhomogeneity overcomes the counter effect due to electron parallel heat flux. Once the radiation instability takes place, then the radiation loss may be localized at particular poloidal angle.

The origin of MARFE is considered to be connected with the poloidal inhomogeneity of heat flux. Thus, the localizations of turbulence and turbulent transport play the key role for it. In addition to it, the poloidal inhomogeneity of impurity density, if it exists, may play another essential role in the MARFE problem. Moreover, once the radiation inhomogeneity becomes unstable and starts to grow, this could influence the turbulence and turbulent transport. Experiment on ALCATOR-C has shown that strong high-frequency fluctuation arises when the MARFE starts, as is illustrated in Fig. 16 [114]. This phenomenon has been studied in conjunction with the density limit problem.

When the radiation loss is localized at particular posi-

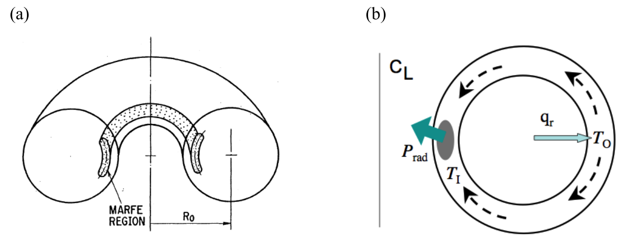

Fig. 15 MARFE Phenomenology; the spatial localization of radiation density is denoted by hatched region in (a). The preferential turbulent heat flux at the outside (low-field side) of torus, can induce the temperature inhomogeneity on a magnetic surface (higher at low-field side, and lower at the high-field side of torus, $T_O > T_I$) (b). If temperature T_I is low enough, the lower temperature (at high-field side of torus) induces an enhanced radiation loss there. The electron heat flux along the field line (the poloidal projection of which is illustrated by thick dotted line in (b)) tends to equalize the electron temperature. However, if the localized radiation exceeds a threshold, the equalization by parallel heat flux becomes insufficient. The localized radiation loss and temperature differences are enhanced simultaneously. (The conceptual illustration (a) is quoted from [115].)

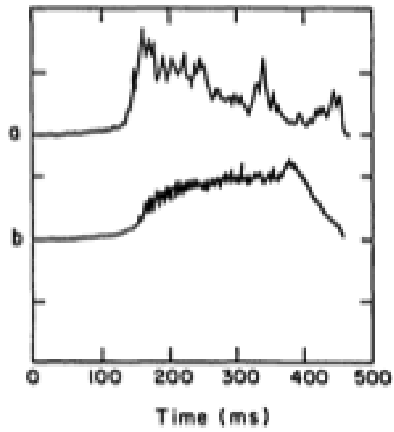

Fig. 16 Enhanced fluctuation at the onset of MARFE was observed on ALCATOR-C [80]. In this figure, line (a) indicates the line-averaged value of square of microscopic density fluctuation, which was measured by single-beam CO_2 laser scattering. In this discharge the MARFE begins at 150 ms. It was reported that increase over two orders of magnitude in scattered power was observed when the scattering volume intersects the MARFE region. (Quoted from [114].)

tion on the magnetic surface, the electron pressure shows a local dint (if density is less influenced than temperature), and the electron pressure is not constant along the magnetic field line. Then, the force balance of electrons along the magnetic field line requires that the parallel electric field increases so as to balance with the electron pressure gradient. Assume that the electron pressure is low in the region of localized radiation; in this case, the electrostatic potential also shows a minimum there. The local minimum of electric potential induces a convection motion of plasmas around the radiation domain. Such a macroscopic eddy influences the turbulence and particle balance as well.

2.8 Measurement of inhomogeneity of turbulence on magnetic surface

The measurement of large-scale turbulence structure and the evaluation of nonlinear interaction across long-distance must be performed. In particular, the *inhomogeneity of turbulence on the magnetic surface* is essential. The nonlinear interaction will be quantified, by observing the cross-bispectra [116] at different locations. The experimental device, which will measure fluctuations on a whole cross-section of the plasma, will enable such a measurement, and will open a new path for experiments that challenge these un-attacked problems.

The measurements are a *terra incognita* for experimentalists. This will impose a new demand for the success of experimental studies. One of the new requests is the high accuracy of the position of measurement. In other words, the method to identify that two observation points, which are separated by a long distance (say, in-and-out or top-and-bottom of torus) are on the same magnetic surface is required.

In the following two sections, we discuss the necessary accuracy and the method of identification. This analysis will be a basis for designing the position control of the experimental device, which will measure fluctuations on a whole cross-section of the plasma.

3. Tolerance in the Positioning Error

In order to achieve the above-mentioned experimental studies, the location of the measurement position must be identified (controlled) with very high spatial precision. ‘High’ means that it should be a scale of microscopic fluctuations, not that of macroscopic variable. The tolerance of the error in positioning is discussed here. The requested tolerance depends on the subject of research. In the following, demands are explained in the problems of (1) edge turbulence, (2) distant nonlinear interaction, (3) toroidal return flow and (4) turbulence stress.

3.1 Edge turbulence

The turbulence at plasma edge is strong in the L-mode, and is thought to play essential roles in the property of toroidal plasmas. It controls particle confinement time,

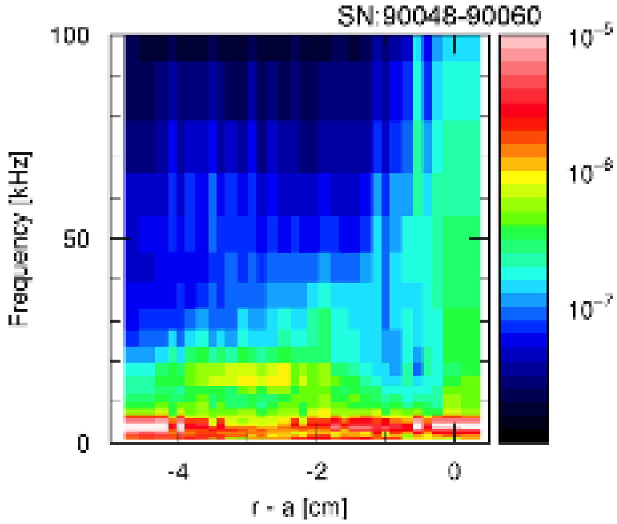

Fig. 17 Strong spatial inhomogeneity of turbulence near the plasma edge of the L-mode plasma in JFT-2M [119].

governs the conditions for L-H transition and edge transport barriers [77]. The edge turbulence contributes to the ‘intrinsic torque’, which is driven by turbulence [58, 74]. This turbulence might also be transported into core plasma. The measurement of edge turbulence, including the possible inhomogeneity on the magnetic surface, is therefore an important issue in the experiments on the experimental device, which will measure fluctuations on a whole cross-section of the plasma. The turbulence intensity and spectrum vary sharply in space [117–119]. High precision of spatial resolution is required if one tries to measure the poloidal inhomogeneity of turbulence. In the example of JFT-2M experiments [119], the wave number changes substantially in a radial distance of 5 mm - 1 cm. Figure 17 indicates the strong inhomogeneity of fluctuation properties near the plasma edge. Thus an identity of a magnetic surface must be confirmed with the spatial precision of a few mm, if one studies the inhomogeneity of turbulence on the magnetic surface.

3.2 Distant nonlinear interaction

The nonlinear interaction between global modes and microscopic fluctuation has been identified, so that the nonlinear interaction between microscopic fluctuations via global perturbation is possible to occur. This mechanism (*disparate scale interaction at far distance*) can also be an origin of non-locality in the transport relation. A trial to measure the nonlocal and nonlinear interactions has been initiated [120]. An example is quoted in Fig. 18. A microwave comb is one of possible methods for this purpose [121]. In order to quantify such nonlinear processes, the spatial position of microscopic fluctuation must be correctly measured. This is subject to the bicoherence (or tricoherence) analyses. If the errors of the phase of fluctuations are generated by the uncertainty of the measurement

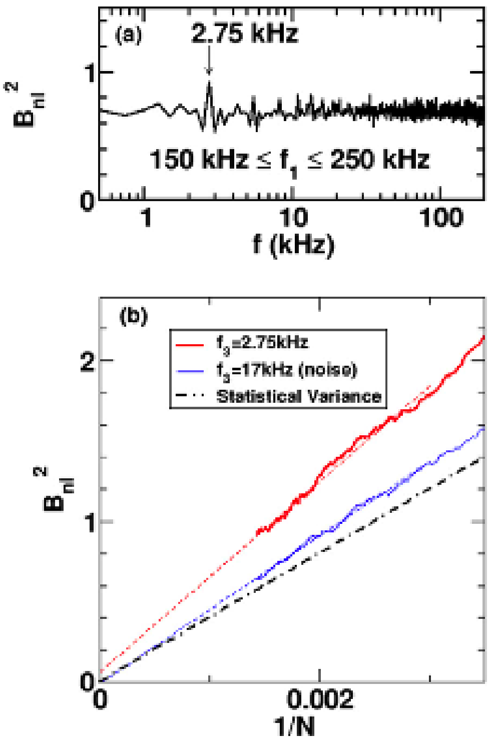

Fig. 18 An example of measurement of nonlinear interaction of microscopic turbulence at far distance. Quoted from [120]. Summed bi-coherence (which is a sum over the frequency range of 150 kHz < f_1 < 250 kHz). Signal at the frequency f_3 is obtained at $r/a = 0.63$, while those at f_1 and f_2 are measured at $r/a = 0.88$. (b) Convergence study for the summed bi-coherence.

location, the error in biphase is generated and could lead to misunderstanding of the causality.

3.3 Toroidal return flow

Toroidal return flow, which is associated with the poloidal flow (e.g., zonal flow), has the parity like Pfirsch-Schluter current. (See Fig. 5.) It depends on the poloidal angle like $\cos\theta$ (θ being the poloidal angle). This is a typical example that introduces inhomogeneity on a magnetic surface. This return flow is essential in determining the enhanced toroidal dielectric constant, and is influential on the L-H transition. The typical radial width of the toroidal return flow can be a few times of poloidal ion gyroradius. The possibility of the poloidal shock has also been pointed out. Therefore, the accuracy for the radial position of measurement must be, at least, of the order of poloidal ion gyroradius. Even in the absence of poloidal shocks (i.e., the flow changes in poloidal direction with the typical scale length of plasma minor radius), it varies in radial direction within the scale length of poloidal ion gyroradius. The confirmation that two measurement positions (which are separated by the distance of plasma radius) are on the same magnetic surface must be obtained with the accuracy (in radial direction) better than poloidal ion gyroradius.

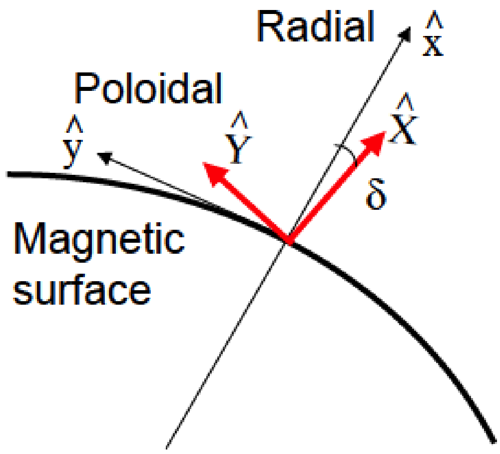

Fig. 19 Possible mis-alignment of Reynolds stress probe. The Cartesian coordinates on the probe array (X, Y) are inclined by the small angle δ, with respect to the radial-poloidal coordinates (x, y) on magnetic surface.

3.4 Turbulence stress

Turbulence Reynolds stress $\Pi_{\theta,r} = \langle \tilde{V}_r \tilde{V}_\theta \rangle$ is one of the key quantities in the study of plasma turbulence. For this purpose, Langmuir probe array is often used. If the angle of the probe array is inclined by an angle δ ($\delta \ll 1$) as is illustrated in Fig. 19, the data $\langle \tilde{V}_X \tilde{V}_Y \rangle$ measured by the inclined probe array has a relation $\langle \tilde{V}_X \tilde{V}_Y \rangle \sim \langle \tilde{V}_x \tilde{V}_y \rangle + \delta \langle \tilde{V}_x^2 - \tilde{V}_y^2 \rangle$, where the first order correction with respect to δ is kept. Since the drift wave turbulence can be anisotropic, the average $\langle \tilde{V}_x^2 - \tilde{V}_y^2 \rangle$ in the second term of the RHS can be of the order of $\langle \tilde{V}_x^2 \rangle$. The turbulence driven Reynolds stress is usually smaller than the diagonal element in the stress tensor, e.g., $\langle \tilde{V}_x^2 \rangle$. Thus, the erroneous inclination of the probe array with respect to the magnetic surface can easily introduce the error in the evaluation of Reynolds stress. This defines the possible tolerance of the misalignment of the Reynolds stress probe array.

Next is the transport of parallel momentum in radial direction, $\Pi_{//,r} = \langle \tilde{V}_{//} \tilde{V}_r \rangle$, which is analyzed by measuring the perturbation of the parallel flow velocity $\tilde{V}_{//}$. In the edge region, such quantity can be measured by the Mach probe. In the measurement of the fluctuation of the parallel ion velocity, $\tilde{V}_{//}$, the necessary accuracy of the probe position was found stringent [122, 123]. An example of the misalignment is illustrated in Fig. 20. The upper bound of tolerance is analyzed in [122, 123] and quoted here as $|\sin\delta| \ll 2.5(L_n/qR)(\rho_s/l)$, where l is the distance between two tips of the Mach probe, ρ_s is the ion gyroradius at the ion sound speed, and other notations are standard. If one makes mistake in the alignment, the phase of fluctuation Mach number becomes wrong, and the biphase measurement will be seriously polluted. The conclusion of the causality on the driving mechanism of the parallel flow can easily be misunderstood.

There is another requirement for the experimental research on the experimental device, which will measure

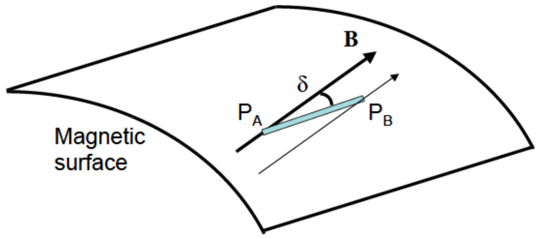

Fig. 20 Misalignment of the Mach probe. The probes at two ends of a Mach probe, P_A and P_B, are not on the same magnetic field line. Owing to the perpendicular wave number of fluctuations, the density fluctuation takes different values at P_A and P_B. This density difference is a source of error in the evaluation of the fluctuating Mach number.

fluctuations on a whole cross-section of the plasma. In the past, when $\Pi_{//,r}$ was measured, it was given at particular poloidal position. In the experimental device, which will measure fluctuations on a whole cross-section of the plasma, measurements of turbulence stresses are tried at all of poloidal angles, in order to identify the symmetry breaking of the turbulence structure. The setting of probe heads on a common magnetic field is possible only by knowing the direction of magnetic field line accurately at any poloidal angle.

4. On Identification of Iso-Magnetic Surface

The position of measurement of each diagnostic system will be calibrated, in order to confirm that measurements points are on a common magnetic surface. We here consider several possibilities that can provide a reference for calibration. The distance between measurement point and the device chamber is often used as the basis of calibration. However, they are not sufficient, from the viewpoint of the research objective of the experimental device, which will measure fluctuations on a whole cross-section of the plasma. This is because the location of the measurement position in the plasma frame (not only in the laboratory frame) is necessary. In particular, the identification of magnetic surface, on which the two (or more) diagnostic positions are placed, is inevitable, in order to measure the inhomogeneity of turbulence on a magnetic surface. For this purpose, a relative distance between the relevant magnetic surface (which is of interest from the experimental objective) and the device must be known at all poloidal angles. Such a calibration is required in the experiments on the experimental device, which will measure fluctuations on a whole cross-section of the plasma.

4.1 Use of GAM oscillations

One method for the identification of a particular magnetic surface is the observation of GAM oscillations. The GAM oscillation has the toroidal symmetry and has a short radial wavelength. It often shows a sharp frequency spectrum. In addition, the radial propagation pattern is strongly modified by the plasma surface. It was shown experimentally, that the plasma surface can be identified by observing the node of GAM oscillations [124]. Figure 21 illustrates the search of the node of GAM oscillations near the surface of JFT-2M plasma. The change of mean plasma parameters at the evaluated plasma surface is shown in Fig. 22. Radial profiles are shown for plasma parameters ((a) electron density and (b) electron temperature, respectively), which are obtained by current-voltage characteristic curves of a single Langmuir probe. Vertical lines indicate the position of plasma surface, which is estimated by cross points of the fitted asymptotic lines in the GAM amplitude profile.

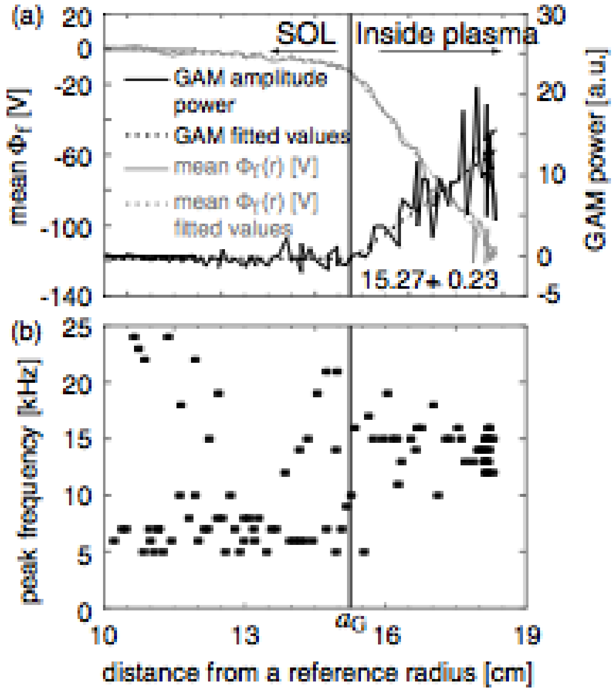

Fig. 21 Search of the node of GAM oscillations near the surface of JFT-2M plasma. (a) Profiles of GAM amplitude and mean electrostatic potential, ϕ_f. The thick solid line shows the measured amplitude of GAMs oscillation, and thick dashed lines indicate the fitting to hyperbolic curves, respectively. Thin (grey) lines denote the mean ϕ_f (solid: measurement, dashed: fitting). Vertical lines mean the cross points of the fitted asymptotic lines, and indicate the estimated radial position of the plasma surface. (b) A profile of auto-power peak frequency. (Quoted from [124].)

This node of GAM at the surface can be used as a reference for examining the relative difference of various diagnostics, which are located in the toroidal plasma. The search of the node of GAM can be performed either by using the Langmuir probe [124], or by HIBP [125]. Not only the node at plasma surface, but also the nodes inside the confined plasma, can also be used to identify the common magnetic surface (at different toroidal and

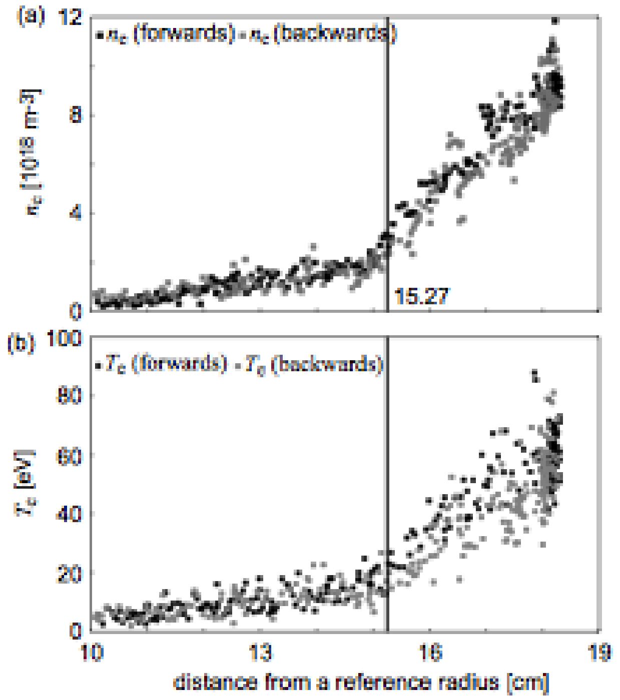

Fig. 22 Radial profiles of plasma parameters obtained by single Langmuir probe current-voltage Characteristic curves. (a) Electron density and (b) electron temperature, respectively. Plots during Forward and backward motions of the RLP are accompanied in both figures. Vertical lines indicate the position of plasma surface, which is estimated by cross points of the fitted asymptotic lines in the GAM amplitude profile. (Quoted from [124].)

poloidal locations). The application of GAM spectroscopy, that the waveform of GAM is searched for by observing the modulation of envelope of high-frequency perturbations [126, 127], is also useful for this purpose.

With this method, the relative accuracy, of the order of a few ion gyro-radius, can be achieved. This is because the GAM oscillation has a radial scale length of about ten times of ion gyro-radius [78].

4.2 Magnetic island

Next possibility is the observation of (either by instability-driven or externally-induced) magnetic islands. By applying the external helical resonant magnetic field, the magnetic islands are induced. By observing the islands, the mode-rational surface can be identified. The island by tearing mode instability appears in a limited kind of discharges. Nevertheless, once islands are generated, the particular magnetic surface (say, $q = 3$) is observed at any toroidal angle of plasma. The identification of X-point or O-point of magnetic island also serves as a reference for spatial locations of various diagnostics. If it is induced near the plasma surface, it can be observed by Langmuir probe as has been reported in [128]. By observing the magnetic island simultaneously at different locations (in toroidal and poloidal directions), the calibration of radial location can be performed. The identification of the radius of X-point can also be performed for the core plasma by the conditional average of ECE signals.

4.3 Adiabatic motion

The third is the use of slow adiabatic motion of plasma or that of diagnostic systems. By controlling the vertical magnetic field, the plasma position can be oscillated (slowly compared with the characteristic time of fluctuations) in time. Under this circumstance, by performing the measurement continuously, the relative position of measurement can be scanned continuously. By this method, very high resolution of spatial profile measurement can be realized. Examples include, e.g., the high-resolution in temperature measurement by CXRS, by which the curvature of electric field profile was measured with sufficient resolution for identifying the spatial structure of edge transport barrier [129]. The details of experimental procedures are reported in [130]. This approach was also applied in the search of corrugated radial profile of electron temperature.

5. Summary

In the development of physics of plasma turbulence, the importance of symmetry-breaking of turbulence has been now recognized widely. In this concise review article, we revisit the issues related with the symmetry-breaking of turbulence, and illuminate the possibilities that the new progresses are expected in near future experiments. This concise review might be used to identify what will be discovered and how will it be reached in future experiments. In addition, it is pointed out that new type of demands can be imposed in measuring of fluctuations over the whole plasma cross-section simultaneously. One of such demands is the accuracy of the measurement position. Problems in this aspect are also discussed. One of fundamental elements in detecting the measurement position with high accuracy is the confirmation that different measurements are made on iso-magnetic surface. This problem is also discussed briefly.

6. Discussion

Based on the recent progresses of plasma turbulence [131–133], a new initiative of the high temperature plasma physics has been launched [134, 135]. (This proposal has been selected in the 'Master Plan' by Science Council of Japan, and endorsed in the 'Road Map' by MEXT Japan [136, 137].) In this proposal, a tokamak, which allows the measurement of fluctuations over the whole plasma cross-section simultaneously, has been designed [138]. This is in some sense '*Kopernikanische Wende*' in the experimental approach in the plasma turbulence study: The new plan tries to realize a device that allows to measure 'what must be measured'. This is in contrast to efforts in the past, where 'what can be measured with given ports' was measured.

The realization of the proposal [134, 135] might need some time, but the chance to challenge this idea (i.e., measurement of fluctuations over the whole plasma cross-section simultaneously) was approved. The Specially-Promoted-Research (in FY 2017-2021, Principal Investigator is A. Fujisawa) was granted, and a proof-of-principle device for the vision above, named "PLAsma Turbulence Observatory" (PLATO), is now under construction [139]. This tokamak device is equipped with the ports and diagnostics that allow simultaneous measurements of fluctuations over the whole cross-section, such as super-tomography [140, 141].

The two dimensional profile of emission of photons from the plasma is observed by use of this super tomography. Necessity of information on the neutral dynamics will be revealed, in addition to the measurements on plasma density, temperature and potential. Up-down asymmetry of neutral particles was predicted to influence the penetration of impurities into the core plasma [142]. Considering the importance of the role of neutral particles in inducing the plasma turbulence near plasma edge [40], the new information about the neutral particle dynamics (including neutral fluctuations) will open another new field of turbulence studies. It is expected that new arena of research of turbulence will be developed in a near future. This article would be useful as an interface between the problem definition (in conjunction with the symmetry-breaking of turbulence) and manufacturing of device and measurement system.

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