Turbulence in edge and core transport barriers: new experimental results and modeling

journal or publication title	Nuclear Fusion
volume	57
number	2
page range	025001
year	2016-09-30
URL	http://hdl.handle.net/10655/00012645

doi: <https://doi.org/10.1088/0029-5515/57/2/025001>

Turbulence in edge and core transport barriers: new experimental results and modeling

T. Tokuzawa

National Institute for Fusion Science, Toki 509-5292, Japan

E-mail: tokuzawa@nifs.ac.jp

PACS; 52.35.Ra, 52.55.Fa, 52.55.Hc, 52.25.Fi

Abstract

In this paper, recent progressive study on experimental analysis and theoretical models for turbulence phenomena around the transport barriers in the high performance magnetic confined fusion plasma is reviewed. The linkage of radial electric field and turbulence, the importance of radial electric field curvature, and the observations of spatiotemporal turbulence structure are described with related theoretical models.

1. Introduction

The formations of the transport barrier in edge [1] and core [2] play a key role for highly confined magnetic fusion plasma devices. The understanding of the physical mechanism is in progress experimentally and theoretically. Several models, which are based on the suppression of the turbulence [3-5], the electric field bifurcation [6-7], the steep gradient of the electric field [8], the effect of ripple loss [9], and others, have been pointed out. The observations of these models also have been reported in many tokamak and helical/stellarator plasmas [10-22]. Nevertheless, there are still open questions about these nonlinear phenomena. These include what physics decide the threshold level, when the transition timing is, where the location is, how to control the limit cycle oscillations [8, 23, 24] or the edge localized modes[25], etc.

As for studying the behaviour of turbulence affecting the transport, in particular multi-scale interaction of turbulence between micro-, meso-, and macro-scale structure receives much attention [13, 23, 26-32] at present, since higher spatial and temporal resolution diagnostics have been developed and applied in several devices [33-37]. Some comparisons between the theoretical model and observation have led to new understandings.

It is suggested, for example, that the role of the curvature of the electric field is important for the relationship with the turbulence intensity [38].

In this paper, the current understanding of turbulence around the transport barriers is explained with a focus on the spatiotemporal dynamics of the plasma, and highlights areas in which more work is still needed. In section 2, at first, the causal relationship that includes the linkage of radial electric field E_r and turbulence intensity, and the treatment of the origin of E_r are discussed. Then, in section 3, the effect of E_r structure is discussed and the importance of E_r curvature is explained from the point of view of turbulence reduction in L-H transition. In section 4, several time-varying spatial structures of turbulence in recent observations with related theoretical models are reviewed, and the summary is provided in section 5.

2. Linkage of radial electric field and turbulence

When the L-H transition or the formation of internal transport barrier is formed, the reductions of turbulence intensity and also the correlation length have been observed in many devices. In such cases, the simultaneous change of poloidal flow and the radial electric field E_r has sometimes been observed. The typical observation example of L-H transition in DIII-D [39] is shown in figure 1. When the D_α signal drops, the turbulence intensity and E_r quickly respond. We can easily notice the linkage of turbulence and E_r and have discussed the causal relationship compared with some models. In the stationary phase, E_r is evaluated by the radial force balance equation. That is,

$$E_r = \frac{\nabla p_i}{Ze n_i} - V_\theta B_\phi + V_\phi B_\theta, \quad (1)$$

where ∇p_i is the ion pressure gradient, Z is the ion charge, e is the elementary charge, n_i is the ion density, V_θ and V_ϕ are the ion poloidal and toroidal velocities, and B_ϕ and B_θ are the toroidal and poloidal magnetic field strength, respectively. One is apt to misunderstand that the value of E_r is determined by the pressure gradient and the poloidal flow and toroidal flow as the causal relationship. This equation represents the relationship of the RHS and LHS and does not include the causality, because it does not express the time variance. Paying attention to the transition phase, we can identify the origin of E_r . The temporal change of E_r is expressed by the following,

$$\frac{dE_r}{dt} = -\frac{J_r}{\epsilon_0 \epsilon_\perp}. \quad (2)$$

Here, J_r is the radial current density, and ϵ_0 and $\epsilon_\perp$ indicate the dielectric constant for vacuum and the relative dielectric constant of toroidal plasma, respectively [40, 41]. Since the radial current can excite $J_r \times \mathbf{B}$ force and drive the poloidal flow, the identification and classification of J_r is important.

The radial current J_r is modeled by use of the charge balance equation and indicated as [42]

$$J_r = J_i^{LC} + J_i^{BV} + J_i^{v\nabla v} - J_{e-i}^{WAVE} + (J_i^{NC(h)} - J_e^{NC(h)}) + J_i^{CX}, \quad (3)$$

where J_i^{LC} is the loss cone loss [6, 7], J_i^{BV} is the neoclassical bulk viscosity [7, 43], $J_i^{v\nabla v}$ is the Reynolds stress [44], J_{e-i}^{WAVE} is the wave convection loss [6], $(J_i^{NC(h)} - J_e^{NC(h)})$ is the other neoclassical component such as helical ripple loss [45], and J_i^{CX} is the charge exchange loss [40, 46]. It is considered that the origin of E_r is affected by those multiple mechanisms.

Among these mechanisms, the turbulence can affect directly via the Reynolds stress part. In order to study the E_r origin and the causal relationship with turbulence, the limit-cycle-oscillation (LCO) phenomenon is one of the good situations. The linkage of E_r and turbulence intensity is clearly observed in some devices by advanced diagnostics such as heavy ion beam probe (HIBP), Doppler reflectometry/back-scattering (DBS), beam emission spectroscopy (BES), Langmuir probes, etc. [13, 17, 19, 21, 22, 47]. In figure 2, two examples of the linkage between E_r and turbulence intensity are clearly shown.

The turbulence can affect E_r via the oscillatory $\mathbf{E} \times \mathbf{B}$ flow that is obtained in DIII-D and EAST, as shown in figure 3 [20]. The turbulence Reynolds stress $\Pi_{r,\theta} \equiv \langle \tilde{v}_r \tilde{v}_\theta \rangle = -\frac{1}{2B^2} k_r k_\theta S^2$ is evaluated and it shows the generation of the poloidal $\mathbf{E} \times \mathbf{B}$ flow. Here, k_r and k_θ denote radial and poloidal wavenumbers of the turbulence, S is the turbulence amplitude, and B is the magnetic field strength. The temporal behavior of turbulence intensity and the $\mathbf{E} \times \mathbf{B}$ flow connecting via Reynolds stress in LCO phase is explained by predator-prey model. The H-mode threshold power is also explained by the model in which the oscillatory flow becomes strong according to the increasing heating power and the turbulence energy transfers to the flow. These results show how important is turbulence driven E_r in LCO.

However, there are unlike experimental results obtained by studying the quantitative analysis in LCO plasma of JFT-2M [22] and HL-2A [48]. In the former research, the electrostatic potential fluctuation is measured by multi channel HIBP system. The turbulence driven $\mathbf{E} \times \mathbf{B}$ flow is estimated by $\Pi_{r,\theta}/L(2\pi f_{LCO})(1+2q^2) \sim 10$ m/s as shown in figure 4 and it is found to be quite different from the observed flow velocity of around 500 m/s. In the

latter case of HL-2A, the temporal behavior of E_r is obtained by Langmuir probes and it shows the continuous stable oscillatory waveform shown in Figure 5. It is found that the estimating amplitude of Reynolds stress driving flow is not responsible during the type-J LCO phase. Therefore, the turbulence driven E_r looks not to play a key role and is not necessarily important in both experimental results. In addition, the large separation of flow velocity between the estimation and observation values in JFT-2M is caused by the toroidal effects for dielectric constant $\varepsilon_{\perp} \sim 20$ not unity. As mentioned above, the origin of E_r is multi factor. The temporal trajectory (Lissajous) of an $E_r - J_r$ relationship helps to understand the identification of the essential terms. It is found that the observation in JFT-2M tokamak shows the good agreement with the contribution of $J_i^{LC} + J_i^{BV}$ during the L-H transition [49]. It is considered to be a quite useful expression for studying the causal relationship.

3. Importance of electric field curvature E_r''

Both the turbulence reduction and the radial electric field have some linkage in the transport barrier phenomena such as L-H transition, as discussed above. The spatial structures, however, remain under question, because some earlier fusion plasma experiments showed that the barrier location does not completely match with the E_r maximum location nor the maximum E_r shear location [33, 50]. The shear of radial electric field has been well understood to be important for turbulence reduction. The theoretical models indicate that the sheared electric field induces the stretching of eddy and the nonlinear decorrelation rate of fluctuations is enhanced [23] as:

$$\gamma_{NL} = \gamma_{NL,0} \left(1 + \tau_{dec}^2 \left(\frac{1}{B} \frac{dE_r}{dr} \right)^2 \right), \quad (4)$$

where $\gamma_{NL,0}$ is the nonlinear damping rate in the absence of the inhomogeneous electric field, τ_{dec} is the decorrelation rate of fluctuations, and B is the mean magnetic field strength. This nonlinear damping of drift wave fluctuations is considered the cause of fluctuation reduction via the energy transfer.

Figure 6 shows the example of the experimental observations which are the radial profiles of turbulence level, E_r , E_r shear (E_r'), and E_r curvature (E_r'') in DIII-D. Note that this figure is made to combine with Fig. 9(a) and 12 in Ref. [33]. Comparing two time slices of A and B, each value of E_r is almost the same and the absolute value of E_r' is also the same. However, the turbulence ratio between L-mode phase and H-mode phase is quite different. In

addition, the sign of E_r' does not influence according to equation (4). Therefore, it is found that E_r' is not a key player in the physics mechanism in this situation.

A new theoretical model including the effect of E_r curvature is presented [23]. It is based upon the view that the force of the divergence of turbulence Reynolds stress is proportional to E_r'' , and the work done by the inner product of force and velocity is proportional to $E_r \nabla \cdot E_r''$. Here, $E_r \nabla = E_r - B_0 V_\phi$ is the poloidal motion component of $\mathbf{E} \times \mathbf{B}$ velocity [38]. The evolution equation of fluctuation intensity is written as [42]

$$\frac{d}{dt}I = \left(\gamma_L - \gamma_{NL,0} \left(1 + k^{-2} \left(\frac{1}{v_d B} \frac{dE_r}{dr} \right)^2 + k^{-2} \left(\frac{1}{v_d B} E_r \nabla \right) \left(\frac{1}{v_d B} \frac{d^2 E_r}{dr^2} \right) \right) \right) I. \quad (5)$$

Here, I is the turbulence intensity, γ is the growth rate, k is the wave number, and v_d is the drift velocity. According to this expectation, not only the E_r' but also the sign of $-E_r \nabla E_r''$ are important for the turbulence growth and/or suppression.

From this point of view, simultaneous observation of both E_r and turbulence intensity at the same position is demanded. Recently, in LHD seven radial channel Doppler reflectometer has been installed and measures the radial profile of turbulence intensity and the related E_r values in the electrode biasing experiment [35]. Controlling the $\mathbf{J}_r \times \mathbf{B}$ driving force by the biasing electrode, a poloidal plasma rotation is changed and the bifurcation phenomenon of transition is occurred. The spatio-temporal behavior of turbulence intensity, which is evaluated the summation of high frequency (>100 kHz) components, is shown by the contour map in figure 7(a). During the transition period, the turbulence intensity seems to be localized in around $r_{\text{eff}} = 0.51$. Figure 7(e) shows the calculated value of E_r'' at the time slice of $t = 4.33$ s. It seems that the turbulence is suppressed in the region of $-E_r E_r'' > 0$ (region A) and that the turbulence is concentrated in the region of $-E_r E_r'' < 0$ (region B). This result does not conflict with the theoretical hypothesis which states that “turbulence reduction/concentration is trapping a through or summit according to the sign of E_r'' ”. The previous DIII-D experimental result is also explained by this hypothesis, and another example of the JT-60U experimental results show the similar feature [36].

This may lead to a question: which parameter is the key to reducing the turbulence? Now we consider that it depends on the turbulence scale size. When the scale size of turbulence is much smaller than that of E_r structure, the eddy stretching and nonlinear damping effect will appear strongly. On the other hand, when the turbulence scale is similar with the E_r scale, the so-called meso-scale mean flow may play an important role.

4. Spatiotemporal structure of turbulence

As presented above, the observation of the turbulence spatiotemporal structure is extremely important for studying the turbulent plasma phenomena. At present, good spatiotemporal diagnostics have been applied in many devices and give us new information regarding turbulence-related physics such as the peculiar relationship of the scale size, nonlocal coupling, rapid propagation, fine structure, etc. In this section, these interesting phenomena are discussed below.

4.1 Effect of fluctuation scale

The radial cross-correlation profile of $\mathbf{E} \times \mathbf{B}$ flow in DIII-D plasma is measured by the Doppler back scattering technique as shown in figure 8 [19]. The observation is carried out in I-phase of LCO. The color map shows that the strong correlation appears in different positions separated by about more than 4 cm and that this flow has the feature of the zonal flow. Also, the radial wavelength of this flow structure is found to be about 9 cm. This scale size is much larger than the pedestal barrier width of about 2 cm which is estimated by the typical electron density profiles in L-mode and H-mode shown in figure 8(b). This might be evidence of the long range interaction phenomena in the L-H transition.

Another example, shown in figure 9, was obtained by the gas puff imaging technique in TEXTOR [51]. The 2D image of drift wave turbulence near the last closed flux surface (LCFS) is observed in the biasing induced H-mode plasma. The stretching eddy is clearly observed just outside of LCFS in the SOL region. The size of this region is estimated to be about 3 cm. The inhomogeneous profile of radial electric field controlled by the bias voltage is also shown in figure 9(a). The eddy stretched region is well consistent with the large gradient region of E_r . It is found that the scale size of turbulence is almost the same as the E_r structure.

These two experimental results lead to a peculiar relationship in which the meso-scale flow structure is larger than the macro-scale structure in the former DIII-D case and the micro-scale turbulence structure is similar to the meso-scale in the latter TEXTOR case. Of course, these observations are obtained in different devices and different plasma conditions, but for the consistent understanding of turbulence physics, it is suggested that nonlocal or nonlinear treatment is necessary. In addition, in the case of TEXTOR GPI image, the stretching of eddy is observed only in the outside of LCFS but is not observed in the inner side where the absolute value of E_r shear is nevertheless almost the same. This suggests the importance of geometrical treatment of symmetry.

4.2 Bi-coherence analysis for the verification of multi-scale coupling

A multi-scale coupling phenomenon is one of the important issues for the turbulence study. A local coupling with meso- and micro-scale turbulence is now routinely observed in many devices, such as DIII-D [52], Alcator C-mod [53], JFT-2M [54], ATF [55], ASDEX upgrade [56], etc. It has been obvious that the multi-scale coupling occurs in fusion plasma locally and the turbulence energy transfer to the others by the bi-coherence analysis. Figure 10 shows the wavelet bi-coherence spectrum of potential fluctuation at the pedestal in H-mode EAST plasma [57]. Here, the local bi-coherence $b_{Local}(f_1, f_2)$ and the summed bi-coherence spectrum $B_{Local}(f_3)$ are expressed as:

$$b_{Local}^2(f_1, f_2) = \frac{\left| \left\langle X(f_1)X(f_2)X^*(f_3) \right\rangle \right|^2}{\left\langle |X(f_1)X(f_2)|^2 \right\rangle \left\langle |X(f_3)X^*(f_3)|^2 \right\rangle}, \quad (6)$$

$$B_{Local}^2(f_3) = \sum_{f_3=f_1 \pm f_2} b^2(f_1, f_2), \quad (7)$$

where $f_3 = f_1 \pm f_2$, $\langle \rangle$ means the ensemble average, the asterisk represents complex conjugate, and X is the fluctuation component. Clear coupling between three frequency ranges that are around 3, 30, and 300 kHz is observed in the local analysis.

Recently, the simultaneous multi-point measurements are able to be carried out and nonlocal turbulence coupling has been studied [58]. In order to observe a nonlinear coupling between micro-turbulence and macro-scale oscillation (such as the long range mode) directly, the bi-coherence analysis of fluctuations at different radial locations, i.e., the nonlocal bi-coherence analysis, is performed with the following modification as

$$b_{non-Local}^2(\rho, f_1, f_2) = \frac{\left| \left\langle X(f_1, \rho)X(f_2, \rho)X^*(f_3, \rho_0) \right\rangle \right|^2}{\left\langle |X(f_1, \rho)X(f_2, \rho)|^2 \right\rangle \left\langle |X(f_3, \rho_0)|^2 \right\rangle}, \quad (8)$$

$$B_{non-Local}^2(\rho, f_3) = \sum_{f_3=f_1 \pm f_2} b^2(\rho, f_1, f_2). \quad (9)$$

The summed nonlocal bi-coherence $B_{non-Local}(\rho, f_3)$ of the low frequency fluctuation ($f = 2.75$ kHz) at $\rho = 0.63$ and the high-frequency fluctuations at $\rho = 0.88$ is shown in figure 11. This indicates the total impact of high-frequency fluctuations at $\rho = 0.88$ on the low frequency perturbation of $f_3 = 2.75$ kHz at $\rho = 0.63$. There is a peak of $B_{non-Local}$ at $f = 2.75$ kHz. It is shown that the nonlocal bi-coherence remains finite unambiguously, in the case of low frequency fluctuations ($f_3 = 2.75$ kHz), and f_1 and f_2 satisfies $f_1 + f_2 = f_3$ for high-frequency turbulence fluctuations. That is, the turbulence at $\rho = 0.88$ has nonlinear interaction at the

fluctuation at $\rho = 0.63$. This indicates the nonlinear interaction between fluctuations at different radii clearly.

4.3 Dynamic propagations of turbulence

The theoretical models are exploited for the explanation of the anomalous response phenomena such as nonlinear, non-diffusive, and nonlocal nature. Although the transport barrier is generated at a limited region in the plasma edge, a global and rapid improvement of confinement, that is nonlocal improvement, is observed just after the transition in many devices. The ballistic propagation of pulse front is predicted [59-61]. Recently, high spatial and temporal resolution diagnostics are used to measure the spatio-temporal behavior of turbulence. Here, the following three examples of rapid propagation of the electron temperature, the electric potential, and the electron density fluctuation are explained.

A single avalanche event of electron temperature fluctuation is observed in DIII-D [62]. The radial speed of the avalanches is calculated by the cross correlation between ECE channels at different radial locations. Figure 12(a) shows the pairwise cross correlation of each ECE channel. The position of maximum cross correlation to larger lag is moving outward and the effective velocity is approximately constant at ~ 100 m/s.

The rapid propagation of the turbulence suppression front is clearly obtained by HIBP measurements during the L-H transition in JFT-2M shown as figure 12(b) [37]. The time axis is normalized as $(t - t_{\text{LH}})/\Delta t_{\text{LH}}$, where t_{LH} and Δt_{LH} show the beginning time and typical duration of the L-H transition, respectively. The turbulence suppression front starts from the edge region where the transport barrier is created, and propagates toward the core with ~ 400 m/s.

Radial propagation of micro-scale turbulence has been observed by the DBS in LHD plasmas with ELM events [35]. When the ELM occurs, the pivot point appears near the LCFS and the electron density well inside of the LCFS (about 10 cm) is also dropping, simultaneously. The high frequency density fluctuation amplitude, which has over 100 kHz frequency components, is evaluated and its temporal change is shown as a contour map of figure 12(c). Here, 146 ELM events are ensemble-averaged. Just after the ELM onset, rapid increase of turbulence amplitude at 2 cm inside the pivot point is observed. Then, the turbulence front appears to propagate inward direction with a speed ~ 100 m/s.

In these cases, the propagation time scales are faster than the diffusive transit time scales and these observations are crucial to explore the plasma non-locality along with the theoretical prediction [59].

4.4 Flow pattern observation

Another interesting coupling phenomena between the meso-scale and larger scales are predicted as $E \times B$ staircase [63]. The structure of $E \times B$ staircase is a quasi-regular pattern of thin $E \times B$ shear layers and related pressure profile corrugations, interspersed between regions of strong turbulent avalanche activity. Because the mean gradient is not smooth in radius caused by the nonlinear interaction between the turbulence and turbulence-driven $E \times B$ flow, the spatial profiles have shown a staircase structure in simulation study. Recently, the observation of the fast frequency-sweeping microwave reflectometer shows the evidence of this staircase-like structure in Tore Supra [64]. The reflectometer frequency sweeping is fast enough (3 μ s) to effectively freeze the staircase dynamics, and the instantaneous radial profile of turbulent fluctuations can be obtained. Figure 13 shows the radial profile of the correlation length L_c of the turbulent density fluctuations. A quasi-periodic structure not correlated with low- q resonances is observed.

The more small-scale fine structure of flows is observed around 5 cm at LCFS in LHD by the frequency comb Doppler reflectometer [65]. The non-homogeneous structure of turbulence is also observed and the correspondence to the flow structure is studied.

The discussion as to how these structures generate is ongoing and has several interesting features including the scale-mixing concept in turbulence transport.

5. Summary

In this article, recent developments in research on plasma turbulence in magnetic confinement devices are presented. In the issue of the causal relationship between the radial electric field E_r and turbulence, it is important that the time derivative dE_r/dt with toroidal effect on the dielectric constant should be considered for studying the origin of E_r . The poloidal Reynolds stress that consisted in a part of J_r components is discussed. The turbulence driven E_r is found to be largely different from the conceived value in the cases of JFT-2M and HL-2A experimental results. In the topics about the effects of the turbulence suppression or generation, the importance of electric field curvature E_r'' in addition to the effect of shear E_r' is pointed out. Some experimental observations show the relation that is turbulence is suppressed at $-E_r E_r'' > 0$ and trapped at $-E_r E_r'' < 0$. Recent new diagnostics with high temporal and spatial resolution show some interesting phenomena that are the peculiar relationships between the turbulence scale size and plasma structure, the local / nonlocal turbulence couplings, the turbulence rapid propagations, and the generating flow structures. These observations will lead to more fruitful discussions with some predicted and/or new theories and models for studying turbulence transport physics.

Acknowledgements

The author wishes to thank Profs. K. Ida, K. Itoh, S. Inagaki, and Dr. T. Kobayashi for useful discussion and contributions to this work. This work was partially supported in part by KAKENHI (Nos. 26630474 and 25289342), by a budgetary Grant-in-Aid of NIFS LHD project under the auspices of the NIFS Collaboration Research program and of the RIAM of Kyushu University. Also, this work was partially supported by Japan / U.S. Cooperation in Fusion Research and Development.

References

- [1] Wagner F. *et al* 1982 *Phys Rev. Lett.* **49** 1408
- [2] Koide K. *et al* 1994 *Phys. Rev. Lett.* **72** 3662
- [3] Biglari H. *et al* 1990 *Phys. Fluids B* **2** 1
- [4] Itoh S.-I. and Itoh K. 1990 *J. Phys. Soc. Jpn.* **59** 3815
- [5] Hinton F. L. *et al* 1994 *Plasma Phys. Control. Fusion* **36** A273
- [6] Itoh S.-I. and Itoh K. 1988 *Phys. Rev. Lett.* **60** 2276
- [7] Shaing K.C. *et al* 1989 *Phys. Rev. Lett.* **63** 2369
- [8] Itoh S.-I. *et al* 1991 *Phys. Rev. Lett.* **67** 2485
- [9] Kovrizhnykh L. M. 1984 *Nucl. Fusion* **24** 851
- [10] Groebner R. J. *et al* 1990 *Phys. Rev. Lett.* **64** 3015
- [11] Ida K. *et al* 1990 *Phys. Rev. Lett.* **65** 1364
- [12] Burrell K. H. 2001 *Rev. Sci. Instrum.* **72** 906
- [13] Fujisawa A. 2009 *Nucl. Fusion* **49** 013001
- [14] Zohm H. 1994 *Phys. Rev. Lett.* **72** 222
- [15] Colchin R. J. *et al* 2002 *Phys. Rev. Lett.* **88** 255002
- [16] Schirmer J. *et al* 2006 *Nucl. Fusion* **46** S780
- [17] Conway G. D. *et al* 2011 *Phys. Rev. Lett.* **106** 065001
- [18] Xu G. S. *et al* 2011 *Phys. Rev. Lett.* **107** 125001
- [19] Schmitz L. *et al* 2012 *Phys. Rev. Lett.* **108** 155002
- [20] Tynan G. R. *et al* 2013 *Nucl. Fusion* **53** 073053
- [21] Cheng J. *et al* 2013 *Phys. Rev. Lett.* **110** 265002
- [22] Kobayashi T. *et al* 2013 *Phys. Rev. Lett.* **111** 035002
- [23] Diamond P. H. *et al* 2005 *Plasma Phys. Control. Fusion* **47** R35
- [24] Kim E.J. and Diamond P.H. 2003 *Phys. Rev. Lett.* **90** 185006
- [25] Leonard A.W. 2014 *Phys. Plasmas* **21** 090501
- [26] Fujisawa A. *et al* 2004 *Phys. Rev. Lett.* **93** 165002
- [27] Nagashima Y. *et al* 2007 *Plasma Phys. Control. Fusion* **49** 1611
- [28] Hallatschek K. and Biskamp D. 2001 *Phys. Rev. Lett.* **86** 1223
- [29] Yamada T. *et al* 2008 *Nature Phys.* **4** 721
- [30] Drake J.F. *et al* 1995 *Phys. Rev. Lett.* **75** 4222
- [31] Champeaux S. and Diamond P. 2001 *Phys. Lett. A* **288** 214
- [32] Ding W. X. *et al* 2007 *Phys. Rev. Lett.* **99** 055004
- [33] Moyer R. A. *et al* 1995 *Phys. Plasmas* **2** 2397
- [34] Kamiya K. *et al* 2010 *Phys. Rev. Lett.* **105** 045004

- [35] Tokuzawa T. *et al* 2014 *Phys. Plasmas* **21** 055904
- [36] Kamiya K. *et al* 2014 *Phys. Plasmas* **21** 122517
- [37] Kobayashi T. *et al* 2015 *Nucl. Fusion* **55** 063009
- [38] Itoh K. *et al* 2015 *Plasma Phys. Control. Fusion* **57** 075008
- [39] Doyle E.J. *et al* 1991 *Phys. Fluids B* **3** 2300
- [40] Itoh K. and Itoh S.-I. 1996 *Plasma Phys. Control. Fusion* **38** 1
- [41] Fujisawa A. *et al* 1997 *Phys. Rev. Lett.* **79** 1054
- [42] Itoh K. *et al* 2015 Paper presented at 15 th Int. Workshop on H-mode Physics and Transport Barriers (Garching, Germany, 2015) and submitted to *Nucl. Fusion*.
- [43] Stringer T. E. 1993 *Nucl. Fusion* **33** 1249
- [44] Diamond P. H. *et al* 1991 *Phys. Fluids B* **3** 1626
- [45] Kovrizhnykh L. M. 1984 *Nucl. Fusion* **24** 851
- [46] Itoh K. and Itoh S.-I. 1995 *Plasma Phys. Control. Fusion* **37** 491
- [47] Estrada T. *et al* 2011 *Phys. Rev. Lett.* **107** 245004
- [48] Cheng J. 2014 *Nucl. Fusion* **54** 114004
- [49] Kobayashi T. *et al* 2015 5th Asia Pacific Transport Working Group (APTWG) (Darlian, China, 2015)
- [50] Kamiya K. *et al* 2011 *Nucl. Fusion* **51** 053009
- [51] Shesterikov I. *et al* 2013 *Phys. Rev. Lett.* **111** 055006
- [52] Hillesheim J. *et al* 2012 *Phys. Plasmas* **19** 022301
- [53] Cziegler I. *et al* 2013 *Phys. Plasmas* **20** 055904
- [54] Nagashima Y. *et al* 2005 *Phys. Rev. Lett.* **95** 095002
- [55] Hidalgo C. *et al* 1993 *Phys. Rev. Lett.* **71** 3127
- [56] Manz P. *et al* 2015 *Nucl. Fusion* **55** 083004
- [57] Wang H.Q. *et al* 2014 *Nucl. Fusion* **53** 043014
- [58] Inagaki S. *et al* 2014 *Nucl. Fusion* **54** 114014
- [59] Hahm T.S. *et al* 2004 *Plasma Phys. Control. Fusion* **46** A323
- [60] Gu'rcan O' .D. *et al* 2005 *Phys. Plasmas* **12** 032303
- [61] Garbet X. *et al* 2007 *Phys. Plasmas* **14** 122305
- [62] Politzer P.A. *et al* 2000 *Phys. Rev. Lett.* **84** 1192
- [63] Dif-Pradalier G. *et al* 2010 *Phys. Rev. E* **82** 25401
- [64] Dif-Pradalier G. *et al* 2015 *Phys. Rev. Lett.* **114** 085004
- [65] Inagaki S. *et al* 2015 Paper presented at 15 th Int. Workshop on H-mode Physics and Transport Barriers (Garching, Germany, 2015)

Figure captions

Figure 1. Typical time evolution of turbulence intensity and rotation flow signals at an L-H transition starting at 1859 ms in DIII-D. (a) D_α emission, (b) the integrated fluctuation power as monitored by a reflectometer near the separatrix, (c) V_θ , (d) E_r , and (e) ion temperature measured by the CER system, respectively. Based on [39].

Figure 2. Typical examples of the linkage between the E_r and turbulence intensity. (a) The time evolution of density fluctuation level (dotted line) and E_r (solid line) measured simultaneously at two radial positions in TJ-II. Based on [47]. (b) The smoothed E_r time trace and turbulence level S_D showing (1) rising turbulence, (2) threshold, and (4) turbulence suppression in ASDEX upgrade. Based on [17].

Figure 3. Example of turbulence driven Reynolds stress in DIII-D.

(a) D_α light modulations, (b) turbulent Reynolds stress and (c) turbulent energy, and (d) $(m, n) = 0$ $\mathbf{E} \times \mathbf{B}$ flow velocity. Data taken ~ 1 cm inside LCFS in DIII-D LCO regime. Based on [20].

Figure 4. Conditional averaged time evolutions of (a) fluctuation amplitude S , radial wavenumber k_r and poloidal wavenumber k_θ and (b) estimated Reynolds stress Π and E_r . The horizontal axis is the phase of the D_α LCO. Based on [22].

Figure 5. Temporal evolutions of (a) D_α emission, (b) inverse scale length of electron pressure gradient, (c) magnitude radial electronic field, (d) the Reynolds stress gradient, and (e) energy transfer production in the type-J LCO phase. Based on [48].

Figure 6. Radial profiles of (a) relative fluctuation amplitude, (b) E_r (solid line), (c) E_r shear, and (d) the estimated E_r curvature in DIII-D plasma. This figure combines the original figures 9 and 12 in [33].

Figure 7. Radial profiles of (a) contour map of time varying turbulence intensity, (b) relative turbulence intensity, (c) E_r , (d) E_r shear, and (e) E_r curvature in the transition phase of the electrode biasing experiment in LHD.

Figure 8. Radial profile of (a) velocity cross-correlation coefficient of zonal flow in I-phase; (b) electron density in L- and H-mode in DIII-D. Based on [19].

Figure 9. Radial profile of (a) E_r in the various electrode biased condition, (b) GPI image in the strong biased condition in TEXTOR. Based on [51].

Figure 10. Example of local bi-coherence of the potential fluctuation ϕ observed in EAST using complex Gaussian wavelet, and (b) integrated wavelet bi-coherence spectrum, and here the dashed curve shows the noise level. Based on [57].

Figure 11. Example of non-local bi-coherence analysis. Summed bi-coherence (which is a sum over the frequency range of $150 \text{ kHz} < f_1 < 250 \text{ kHz}$). Signal at the frequency f_3 is obtained at $\rho = 0.63$, while those at f_1 and f_2 are measured at $\rho = 0.88$. Based on [58].

Figure 12. Examples of rapid propagation of turbulence.

(a) Cross correlation of ECE signals shows a single avalanche event of electron temperature fluctuation observed in DIII-D. Based on [62].

(b) Spatiotemporal evolutions of potential fluctuation measured by HIBP in JFT-2M. The time axis is normalized as $(t - t_{\text{LH}})/\Delta t_{\text{LH}}$, where t_{LH} and Δt_{LH} show the beginning time and typical duration of the L-H transition, respectively. Turbulence suppression front is propagated. Based on [37].

(c) Spatiotemporal evolutions of electron density fluctuation in ELMy plasma in LHD. Here, the ensemble averaged 146 events are shown. Turbulence front moves to core direction. Based on [35].

Figure 13. Observation of $\mathbf{E} \times \mathbf{B}$ staircase-like phenomena in Torre Supra. The reflectometer coherence length shows quasi-periodic structure at some locations. Based on [64].

Figure 1. Typical time evolution of turbulence intensity and rotation flow signals at an L-H transition starting at 1859 ms in DIII-D. (a) D_α emission, (b) the integrated fluctuation power as monitored by a reflectometer near the separatrix, (c) V_θ , (d) E_r , and (e) ion temperature measured by the CER system, respectively. Based on [39].

Figure 2. Typical examples of the linkage between the E_r and turbulence intensity. (a) The time evolution of density fluctuation level (dotted line) and E_r (solid line) measured simultaneously at two radial positions in TJ-II. Based on [47]. (b) The smoothed E_r time trace and turbulence level S_D showing (1) rising turbulence, (2) threshold, and (4) turbulence suppression in ASDEX upgrade. Based on [17].

Figure 3. Example of turbulence driven Reynolds stress in DIII-D.

(a) D_α light modulations, (b) turbulent Reynolds stress and (c) turbulent energy, and (d) $(m, n) = 0 \mathbf{E} \times \mathbf{B}$ flow velocity. Data taken ~ 1 cm inside LCFS in DIII-D LCO regime. Based on [20].

Figure 4. Conditional averaged time evolutions of (a) fluctuation amplitude S , radial wavenumber k_r and poloidal wavenumber k_θ and (b) estimated Reynolds stress Π and E_r . The horizontal axis is the phase of the D_α LCO. Based on [22].

Figure 5. Temporal evolutions of (a) D_α emission, (b) inverse scale length of electron pressure gradient, (c) magnitude radial electronic field, (d) the Reynolds stress gradient, and (e) energy transfer production in the type-J LCO phase. Based on [48].

Figure 6. Radial profiles of (a) relative fluctuation amplitude, (b) E_r (solid line), (c) E_r shear, and (d) the estimated E_r curvature in DIII-D plasma. This figure combines the original figures 9 and 12 in [33].

Figure 7. Radial profiles of (a) contour map of time varying turbulence intensity, (b) relative turbulence intensity, (c) E_r , (d) E_r shear, and (e) E_r curvature in the transition phase of the electrode biasing experiment in LHD.

Figure 8. Radial profile of (a) velocity cross-correlation coefficient of zonal flow in I-phase; (b) electron density in L- and H-mode in DIII-D. Based on [19].

Figure 9. Radial profile of (a) E_r in the various electrode biased condition, (b) GPI image in the strong biased condition in TEXTOR. Based on [51].

Figure 10. Example of local bi-coherence of the potential fluctuation ϕ observed in EAST using complex Gaussian wavelet, and (b) integrated wavelet bi-coherence spectrum, and here the dashed curve shows the noise level. Based on [57].

Figure 11. Example of non-local bi-coherence analysis. Summed bi-coherence (which is a sum over the frequency range of $150 \text{ kHz} < f_1 < 250 \text{ kHz}$). Signal at the frequency f_3 is obtained at $\rho = 0.63$, while those at f_1 and f_2 are measured at $\rho = 0.88$. Based on [58].

Figure 12. Examples of rapid propagation of turbulence.

(a) Cross correlation of ECE signals shows a single avalanche event of electron temperature fluctuation observed in DIII-D. Based on [62].

(b) Spatiotemporal evolutions of potential fluctuation measured by HIBP in JFT-2M. The time axis is normalized as $(t - t_{LH})/\Delta t_{LH}$, where t_{LH} and Δt_{LH} show the beginning time and typical duration of the L-H transition, respectively. Turbulence suppression front is propagated. Based on [37].

(c) Spatiotemporal evolutions of electron density fluctuation in ELMy plasma in LHD. Here, the ensemble averaged 146 events are shown. Turbulence front moves to core direction. Base on [35].

Figure 13. Observation of $\mathbf{E} \times \mathbf{B}$ staircase-like phenomena in Torre Supra. The reflectometer coherence length shows quasi-periodic structure at some locations. Based on [64].