Towards an Emerging Understanding of Non-local Transport

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Abstract.

In this overview, recent progress on experimental analysis and theoretical models for non-local transport (non-Fickian fluxes in real space) is overviewed. The non-locality in the heat and momentum transport observed in the plasma, the departures from linear flux-gradient proportionality and spontaneously as well as externally triggered non-local transport phenomena will be described in both L-mode and improved-mode plasmas. We will report on ongoing evaluation of "fast front" and "intrinsically non-local" models, and their success in comparisons with experimental data.

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1. Introduction

One of the main goals of the study of turbulent transport in toroidal plasmas is to establish predictive capacity for the dynamics of burning plasmas. Indeed, considerable effect in the world magnetic fusion energy (MFE) research program is devoted to validation of simulation based transport models, with the aim of prediction. For this purpose, formulae for transport fluxes (of heat, particle, momentum, etc.), i.e., the expression of fluxes in terms of plasma parameters and mean electromagnetic fields, have been pursued (See [1] and references there in). More precise knowledge has been obtained concerning for the transport matrix, which describes the interaction between various gradients and fluxes (including an example of the momentum flux that is driven by the temperature gradient [2]). At the same time, experimental evidence has been accumulated about the breakdown of a "local expression" of the gradient-flux relation (which ties the fluxes to gradients of mean parameters and gradients at the same location) in TEXT, RTP, and LHD[3, 4, 5]. One example of such non locality phenomena is the spontaneous increase of core temperature associated with edge cooling by small impurity and hydrogen pellets which are observed both in tokamak and helical plasmas. This phenomena can be reproduced with the simultaneous decrease of thermal diffusively in the interior and the increase of thermal diffusivity in the outer region[3]. The shell mode is proposed to explain the decrease of thermal diffusivity interior region as a physics explanation[4]. In this model, the thermal diffusivity drops near the low order rational q surface and therefore a slight change of q profile causes a large decrease of thermal diffusivity averaged over the rational surfaces interior region where the magnetic shear is weak. In contrast, the phenomena of spontaneous core temperature rise is also observed in the helical plasma, where the q profile is determined by magnetic fields produced by external coil currents and the q profile is unchanged after the edge cooling by pellets[5]. The observation of non-local phenomena in LHD strongly suggests that the change in thermal diffusivity interior region is due to the change in temperature and temperature gradient in the outer region and not due to the change in the local magnetic shear. Simultaneous changes of thermal diffusivity both interior and outer region are considered to be due to the strong coupling of turbulence in the two locations, separated by more than the scale length of micro turbulence, which is called non-local transport. In general the feature of non-local transport is not identified in steady state, because the any radial profile of temperature can be reproduced with an arbitraly thermal diffusivity profile. Non-local transport is manifested in the transient phase as a "non-local phenomena". The contribution of the non-local transport can be dominant. The violation of the familiar local expression (local closure) compels us to explore new approaches to the predictive modeling for burning plasmas. We here use the word 'local expression' in a sense that the relation is given in terms of mean parameters at the local position in space and at the same time.

In particular, a successful transport model should be able to quantitatively predict *both* steady state *and* dynamical as perturbative transport phenomena. Thus, we claim that non-locality phenomena constitute a set of novel and interesting *validation challenges* for prospective models of turbulent transport. In this light, non-locality phenomena are central to the future development of transport modeling.

In the study of plasma confinement, two naive assumptions have often been employed: (1) First, a local expression of the gradient-flux relation is expected to hold, because the fluxes are induced by microscopic fluctuations, the correlation length of which is much shorter than the gradient of mean parameters; (2) second, if the local flux is induced by the local gradient, the response in transport would be diffusive. These viewpoints might be valid in some cases, but have several serious limitations. The conjecture (1) must be updated, because there are many kinds of fluctuations with mesoscale correlation lengths. Considering the recent progress on the study of meso-scale and macro-scale fluctuations (such as zonal flows [6, 7], geodesic acoustic modes (GAMs)[8, 9], streamers[10, 11, 12, 13], global fluctuations[14, 15], or possible synergy between nonlinear spreading and toroidal couplings[16], it is natural that the local expression of flux-gradient relations is not set by local mean parameters. Energetic particles are another origin for global perturbations, and naturally introduce nonlocal effects in the energy balance dynamics (see, e.g., reviews[17, 18], and references therein).

The local closure of the flux-gradient relation (that is, to relate the local heat flux in terms of the local mean plasma parameters) can be violated even by microscopic fluctuations (the Eulerian correlation length of which is microscopic e.g., ion gyro-radius). Turbulence spreading is predicted to appear in various circumstances[19, 20, 21]. In addition, the conjecture (2) must also be re-examined. The local gradient-flux relation can indeed induce ballistic response due to nonlinearity as is illustrated by an avalanche process related to the SOC models[22, 23, 24, 25]. Temporally-varying mean gradients in a "stationary state" have also been reported, and the relation with the avalanche process was discussed[26]. The understanding of "transient transport experiments" was assessed from these points of view[27]. Stimulated by these observations and studies of multiple-scale fluctuations, the research area of "non-local" transport problems has developed very rapidly. The objective of this article is to present a perspective for the present understanding of "non-local transport" problems from the viewpoint of the violation of the local closure of the transport relation.

We first survey observations of the violation of "local" gradient-flux relations, taking examples of recent studies such as the concave-convex transition[28, 29], tracer encapsulated Solid pellet (TESPEL) injections and supersonic molecular beam injection (SMBI)[30, 31]. The study of momentum flux in Alcator C-Mod is also illustrated in the light of violation of the local relationship. Through these investigations, it is shown that there are significant contributions of heat flux due to off-diagonal effects in the transport matrix (flux driven by local gradients of other parameters) and due to non-local transport, which are not included in the local framework. Evidence for the non-local transport contribution is provided by dynamic response experiments, and the relative importance of this effect is discussed. Transport with these effects also expands our view of the realizable profiles, from the "profile consistency[32]" or "local stiffness picture[33, 34]" to "selection of the global profile". Here the "local stiffness picture" is the concept that the heat flux is determined by the local temperature gradient and increases sharply when the gradient exceeds a critical value. This results in an apparent stiffness of the profile, so that the temperature profile does not change, regardless the heating profile or strength.

In contrast, "selection of the global profile" is the concept that the radial profile of temperature is not the results of an integrated temperature gradient determined by local transport, but is determined *globally*, by the strong and fast interaction between turbulence in the interior and outer region of the plasma. Please note that this is a broader concept than the original rather narrow "profile consistency" in the ohmic plasma, where the profile is determined by MHD activity sensitive to q-profile, not by the electro-static turbulences. We next discuss the detailed study of fluctuations in conjunction with the non-local problem in transport processes. Long-range fluctuations (coherent and transient), and rapid and long-distance dynamics of microscopic fluctuations are explained. We then illustrate theoretical progress. Theoretical considerations on the above-mentioned assumptions (1) and (2) are explained, and problem definitions for experimental identifications of essential processes are discussed. Thus, the efforts are accelerated to unite progress in experiment and theory. At the end, further challenging experimental observations are briefly explained. For clarity of argument, we stress the theme of 'violation of local closure' in this article. The motivation of this choice is to reduce ambiguities in the terminology of 'non-local phenomena' or 'transient transport problem', which are often used in describing experimental observations.

2. Heat and Momentum Transport

Let us take the radial heat flux driven by turbulence, $Q_{e,i}(r)$, which is the sum of a convection flux and a conductive flux expressed as $T_{e,i}(r)\langle\tilde{v}_r(r)\tilde{n}_e(r)\rangle$ and $n(r)\langle\tilde{v}_r(r)\tilde{T}_{e,i}(r)\rangle$, respectively. The conductive flux may be written using the local fluctuation intensity as $\langle\tilde{v}_r(r)\tilde{T}_{e,i}(r)\rangle \propto -Re\Big(\sum_{\vec{k}}\Big|\tilde{\Phi}_{\vec{k}}\Big|^2\tau_{c\vec{k}}\Big)\nabla T_{e,i}(r)$ where $\vec{k}$ is the wave number of the turbulence and $\langle\rangle$ denotes the magnetic flux surface average. The central issue in the problem (whether the flux is expressed in terms of the local global parameters or not) is thus formulated as whether the fluctuation intensities and phase are expressed in terms of the global parameters (at the same location and time) or not.

As a consequence of the mechanisms explained in the introduction, it has been considered that the relation between the flux and gradient can be given by an integral form (in space and time). If one explicitly writes the spatial integral effect in a form using a kernel

$$Q(r) = -\int \kappa(r,r')\nabla T(r')dr' \qquad (1)$$

A variety of approaches have been developed to model the kernel function (e.g., inductive[35], analytical or simulation approches[36, 37]. In the general case, the transport kernel structure may be characterized by a Levy distribution[36] , which can be approximated as a Lorentzian of width Δ [37].

$$\kappa(r, r') = \Lambda/[(r - r')^2 + \Delta^2] \tag{2}$$

The analyses related to the nonlocal kernel are explained in Chapter 5. The key is to identify the shape of the kernel function to the width of the interaction Δ, and the strength Λ.

As is stressed in the beginning of the introduction, recent developments of transport theory and simulation have demonstrated that (i) meso-scale and macro-scale fluctuations (which can violate local closure) exist, and that (ii) even microscopic fluctuations can induce mesoscale fronts and avalanches, which have a longer radial coherence length than the (Eulerian) correlation length of the consistent microscopic perturbations. If one quotes an example of dynamical equations for such microscopic turbulence and mean parameters (here, the temperature gradient is chosen as an example) from[21], the "diffusion equation" for the temperature gradient and the evolution equation for the fluctuation intensity I (which is normalized to the kinetic energy density at diamagnetic drift velocity v_{dia}) are given by

$$\frac{\partial}{\partial t} A = D_0 \frac{\partial^2}{\partial x^2}(IA) \tag{3}$$

and

$$\frac{\partial}{\partial t} I = \gamma_L(A) I - \gamma_{NL} I^2 + D_0 \frac{\partial}{\partial x} I \frac{\partial}{\partial x} I \tag{4}$$

where $A = \nabla T_a / T$ denotes the temperature gradient, $D_0 I$ is the 'diffusivity', γ and $\gamma_{NL} I$ are linear growth rate and nonlinear damping rate, respectively. One sees that this system of equations is fundamentally local, i.e., the right hand side (that induces temporal evolution) is described by the local values of parameters. Nevertheless, the one-to-one correspondence between fluctuation intensity and global plasma parameters does not hold, owing to propagating fronts. The expression of mean (i.e., long-time average) global flux cannot be closed by mean global plasma parameters at the same position and time. That is, even if the instantaneous (but course-grained with respect to microscopic fluctuations) flux is explicitly given by a function of instantaneous local parameters (that includes avalanche-like modifications), super-diffusive propagation of the profile modification is possible to occur[26]. So the Fickian model is invalidated. Based on these theoretical results, it is now urgent to examine experimentally whether or not a local relation between gradient and flux holds. In particular, observations of fluctuations are essential to propelling the understanding: If a violation of local closure is found, the essential point is to identify what properties of fluctuations induce it.

Experiments	phenomenology	Physics oriented observation	
Issue / Subjects pursued	'nonlocality phenomena', that are not explained by diffusive process (and/or) Fick's law	violation of local closure, which relates the mean flux to the gradient of local mean parameters	
		Response in 'mean'	fluctuations
Core-edge coupling	Core temperature rise by Pellet and SMBI	Hysteresis in g-f relation; 'potential' for selection of state	Long range fluctuations
Concave-convex	Concave-convex transition in ITB	Role of curvature; Enhanced transport across barrier	
Momentum and energy	Flow reversal (IOC/ IOC?)	Residual stress	Changes ?
L-H transition LCO	Emergence of LCO	LCO in gradient and turb. intensity	ZF dynamics? Ballistic prop.?

Theory	Eq. for micro	Eq. for flux	Radial scale	Outcome
Local and stationary	Closed on each radius	Given by micro, & Closed on each radius	micro	grad-flux relation like $q = -\chi$ grad T
Avalanche	Not specified	Perturbed flux is related to perturbed T, on each radius	Length of avalanche (on-going)	Velocity of ballistic propagation, Super-diffusion
Fronts	With spreading, given on each radius	Given by micro, & closed on each radius	Length of front prop. (on-going)	Velocity of ballistic propagation, Super-diffusion
Meso & macro	Coupled with components with long radial coherence length	Given by micro (on each radius) plus that by meso-macro	coherence length of meso and macro; Front length	Nonlocal g-f relation, f can change before g changes

Table 1. Experimental observations and theoretical models of non-local transport

Momentum transport has been recognized to be much more complicated than heat transport in toroidal plasmas due to the "non-diffusive" terms. The toroidal Reynolds stress $\langle \tilde{v_r} \tilde{v_\phi} \rangle$ is often written as $-\mu_\perp \nabla v_\phi + V_{\text{pinch}} v_\phi + \Gamma_\phi^{RS}$ [38], the physics basis for which is fully explained in [39]. The first term is driven by the velocity gradient, while the second and third terms are independent of the velocity gradient, and are called "non-diffusive" terms. The second term, which is proportional to the velocity itself, is called the pinch term and changes its sign depending on the direction of rotation (co- or counter- rotation). In contrast, the third term is called the residual stress term, which does not explicitly depend on velocity shear or on the velocity. Some models categorize it as an off-diagonal term of the transport matrix[40, 41, 42] but the contribution of radial propagation of waves to this term has also been pointed out [39, 43]. The radial propagation of waves and turbulent acceleration[44, 45] could be the origins of the violation of local closure too. Considering the fact that the 'diffusion term' for heat flux is not always closed in a local form in terms of global parameters at the same position and same time, as is explained above, both the gradient-driven term as well as the residual term in the momentum flux can break the local closure. Keeping these in mind, we shall explain the experimental observations.

The survey of the issues in this chapter illustrates that the processes that are called *nonlocal* have various aspects and the adjunctive *nonlocal* has been used by various reasons. Thus, before going into the details to experimental observations and theoretical models, it might be useful to compare various approaches in a table, so that the readers can carry a map in visiting many complicated behaviors of plasmas (which are not understood within a conventional picture that the transport flux is determined by the local plasma parameter). Table 1 explains various approaches to the emerging understanding of nonlocality in plasma transport. Experimental observations are in one hand focused on the phenomenological observation, which tries to describe in what manner the local closure (i.e., the effort to relate the flux to the local mean plasma parameters) is violated. At the same time, efforts are made to identify the cause and mechanisms that induce the violation of local closure. When the contribution to these two physically-posed issues is not clear yet, one may use nonlocality (with citation mark). The phenomena, which are shown as examples, are the curvature transition, the fast core-temperature rise after edge-cooling, the flow-reversal phenomena, and the dynamics near L- to H-mode transition. Theoretical modelings are explained in later chapters. Depending on the models, descriptions of the microscopic fluctuations are different as is shown in Table 1. The origin that causes a long-range dynamics is also explained, and the outcome of the analysis is denoted. All of the avalanche model, front theory and the theory, which includes the meso- and macro-scales fluctuations, can explain some aspects of the violation of local closure. Each of models focuses upon selective issues, so as to explain physics processes that are related to the nonlinear mechanisms in the models. They illuminate many essential elements, which might induce the violation of local closure, are highlighted in the table.

3. Violation of local closure in transport

3.1. Transition between concave and convex ITBs

The spontaneous transition between two transport states in plasmas with internal transport barriers (ITBs) is observed during the steady state phase (constant q-profile) in JT-60U. These two states are distinguished by the change in sign of the second derivative of the ion temperature profiles (curvature); one has a concave shape and the other a convex shape. This curvature transition is clear evidence that the local closure of heat transport is broken, because were the heat flux determined by the local gradient and other local quantities, the curvature of the temperature profile should be unchanged in steady state.

Figure 1 shows the radial profiles of ion temperature in the ITB plasma with concave shape (t=6.06sec) and with convex shape(t=6.21sec) in JT-60U. The ITB plasmas with concave/convex shape are characterized by positive/negative second derivative (curvature) inside the ITB region. It should be noted that the ion temperature at

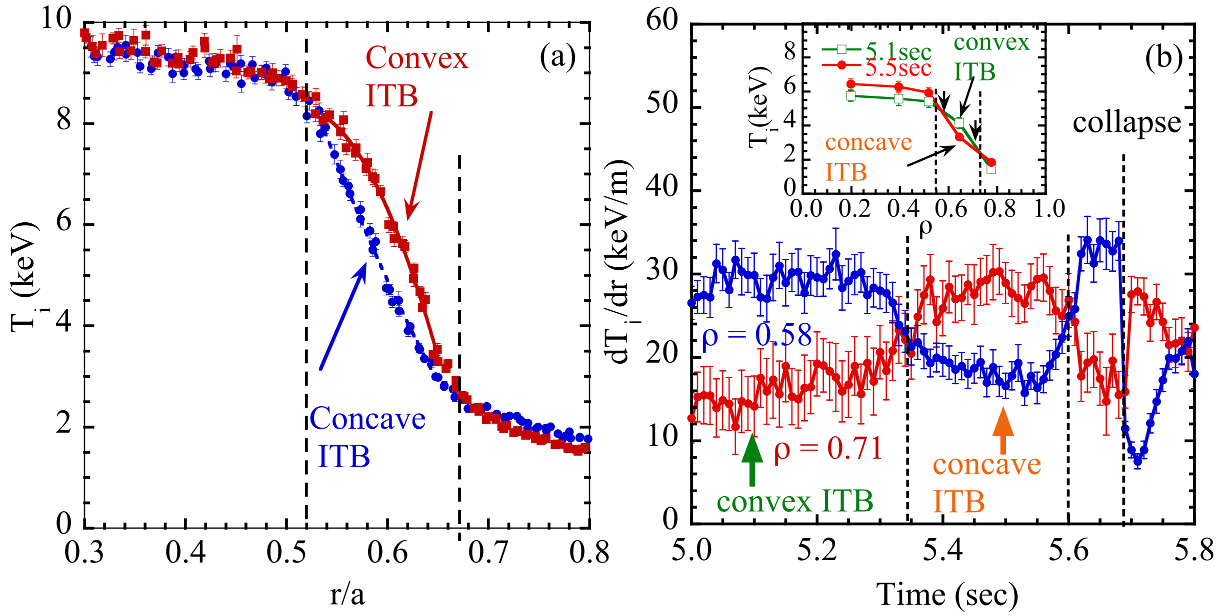

Figure 1. Radial profiles of (a) ion temperature in the ITB plasma with concave shape and with convex shape (in JT-60U. (b) Time evolution of ion temperature gradients at two locations inside ITB region ($\rho = 0.58$ and $\rho = 0.71$) , that are indicated with arrows in the radial profile in the ion temperature profile inserted.

the foot point and shoulder are almost unchanged. The transition of between two states of ITBs with concave shape and convex shape is called a curvature transition. In the curvature transition between the concave and convex ITB, a simultaneous increase and decrease of the temperature gradient nearby takes place, which suggests that the turbulence intensity is not determined by the local gradient, but rather the gradient nearby, inside the ITB region. The scale of curvature transition region is $0.15(r/a)$, which is 10 times of auto-correlation length of fluctuations[46]. The non-local contribution evaluated from the change in $\Delta(Q/n)$ during the curvature transition is 50% of the total heat flux[28]. When the turbulence intensity is determined locally, the transport can easily reach a steady state with a consistent temperature gradient, because the turbulence intensity increases as the gradient is increased, and larger turbulence intensity drives a reduction of the gradient for fixed heat flux. In contrast, when the turbulence intensity is determined by the nearby temperature gradient, both the heat flux driven by the turbulence and temperature gradient can oscillate in time, which is considered to be an instability of transport. The relation between the characteristic length of this transport coupling and the oscillation period should be studied in future.

The oscillation between concave and convex ion temperature profiles is observed, as shown in Fig.1(b). This oscillation may cause a severe collapse at t = 5.69 sec by an MHD instability due to too large a pressure gradient. The spontaneous transition between concave and convex ITBs is a good example of the violation of local closure in the transport, because (1) there are two metastable eigen-profiles of the ion temperature that are not determined by the local transport (flux-gradient relation) (2) and that the change of transport cannot be explained by the change of global plasma parameters. It should be noted that the experimental evidence for the existence of an "oscillation" between two states clearly shows that non-locality of heat transport can occur in space and time (as a memory effect). The temperature gradients at $\rho = 0.58$ and $\rho = 0.71$ at the end of concave state ($t = 5.55$s) are close to those at the beginning of the concave state ($t = 5.41$s), however, the behavior afterwards is completely different, as seen in Fig.1(b). This observation suggests that the transport is not solely determined by the present state of plasma parameter and implies that the transport during this curvature transition has a strong non-Markovian process feature.

In this paper, the transport where the local heat flux is not solely determined by the local mean plasma parameters is called "non-local" transport. The "non-local" transport play an important role in this oscillation in temperature gradient and heat flux and it causes the instability of heat transport, where the spontaneous rise and fall of the temperature gradient takes place even with constant heating power. Therefore understanding of the mechanism causing "non-local" transport is essential to control the plasma and achieve transport state. In fact, the minor collapse occurs at t = 5.68 s in this example when the ion temperature gradient at $\rho = 0.58$ reaches 32 keV/m. This is interesting ∇T_i oscillation (unstable transport) due to the "non-local" transport triggers the MHD instability by exceeding the threshold for pressure gradients. In order to achieve a stable plasma with ITBs, the amplitude of the ∇T_i oscillation should be reduced, because even if the ∇T_i value transiently exceeds the critical value for the MHD stability during this oscillation, a minor collapse takes place and the good performance of the discharge with ITBs is terminated. The stability of transport is a very important issue because high transport stability will be required in burning plasma, where the fraction of external heating power becomes small.

3.2. Appearance of violation of local closure by perturbations

In general, the flux gradient relation in transport $((Q/n)-(\nabla T))$ need not be determined by local parameters alone [1]. However, the violation of local closure in transport is not clearly identified in steady-state plasmas, except during the period of transition phenomenon. This is because even if the "non-local" contribution is as large as the others, the usually observed profile resilience (stiffness) introduces a collinearity between ∇T at different locations, so that the separation of the "non-local" term from the others becomes difficult in steady state. Perturbation experiments provide a useful approach to test local closure of the transport, because a Lissajous figure of $\Delta(Q/n)$ plotted as $\Delta(\nabla T)$ shows how the local closure is broken. When there are two heat fluxes for a given local temperature gradient, the results suggests that the local and linear transport is not valid. Although the "non-local" contribution may be evaluated from the hysteresis of $\Delta(Q/n)$ and is $10 \sim 30$ % of the total heat flux, it causes a change in the temperature which much faster than the diffusive process does.

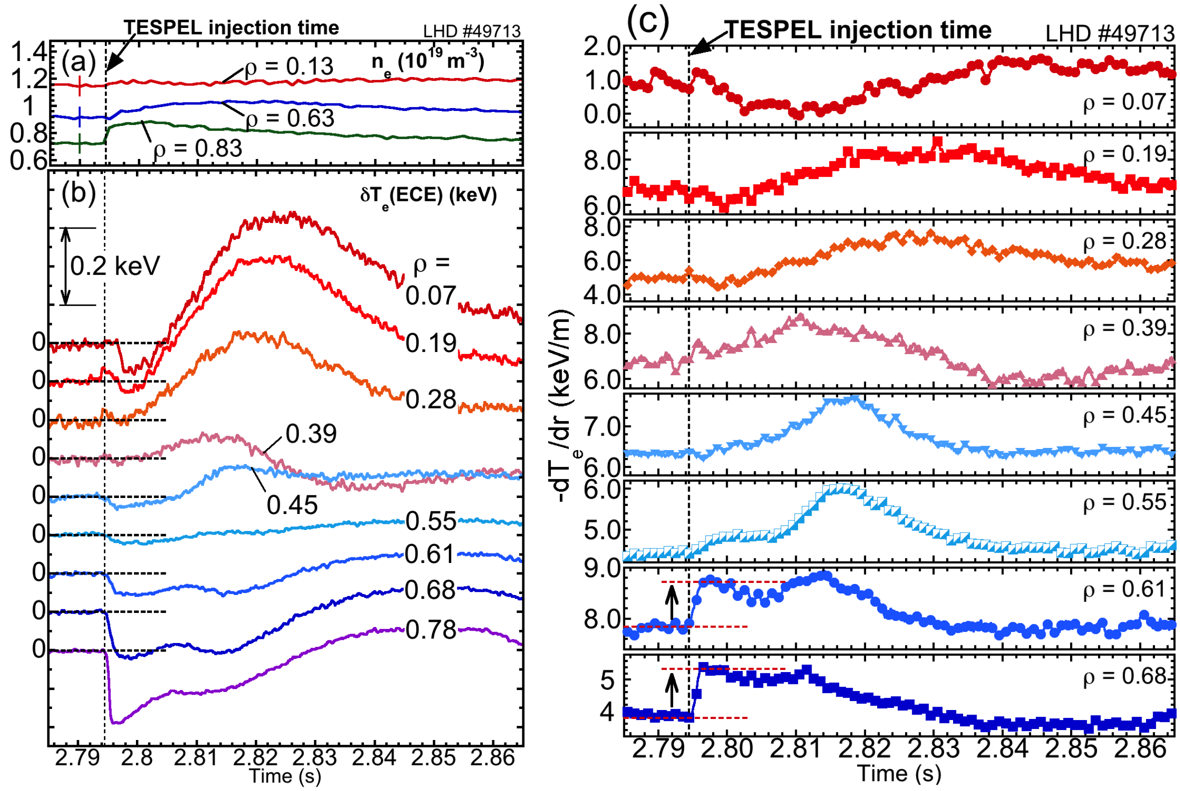

Figure 2. Time evolution of (a) electron density (n_e) and increment of electron temperature (δT_e) and (b) the electron temperature gradient ($\partial T_e/\partial r$) after tracer encapsulated solid pellet (TESPEL) injection in LHD.

Similar "non-local" transport phenomena was observed in helical plasma where there is no significant plasma current during experiments with tracer encapsulated solid pellet (TESPEL) [47]. Figure 2 shows the time evolution of electron density (n_e) and increment of electron temperature (δT_e) and electron temperature gradient ($\partial T_e/\partial r$) after TESPEL injection in LHD. The electron temperature decreases near the plasma periphery ($r/a > 0.6$), while an increase of electron temperature is observed in the core ($r/a < 0.5$), where the electron density is almost unchanged. Because of the simultaneous drop of the edge temperature and the rise of the core temperature, the temperature gradient increases transiently in the plasma. The time behavior of the core temperature gradient is quite different from that of the edge temperature. There are metastable states observed in the edge temperature gradient, but not in the core temperature gradient.

Recently the PDF of $\Delta(\nabla T)$ during "non-local" transport phenomena has been investigated in order to study the robustness of the transport flux landscape against the deformation, and to evaluate the level of non-locality in the transport[48, 49]. A large deformation from the steady-state value ($d\delta T_e/dr = 0$) indicates that the "non-

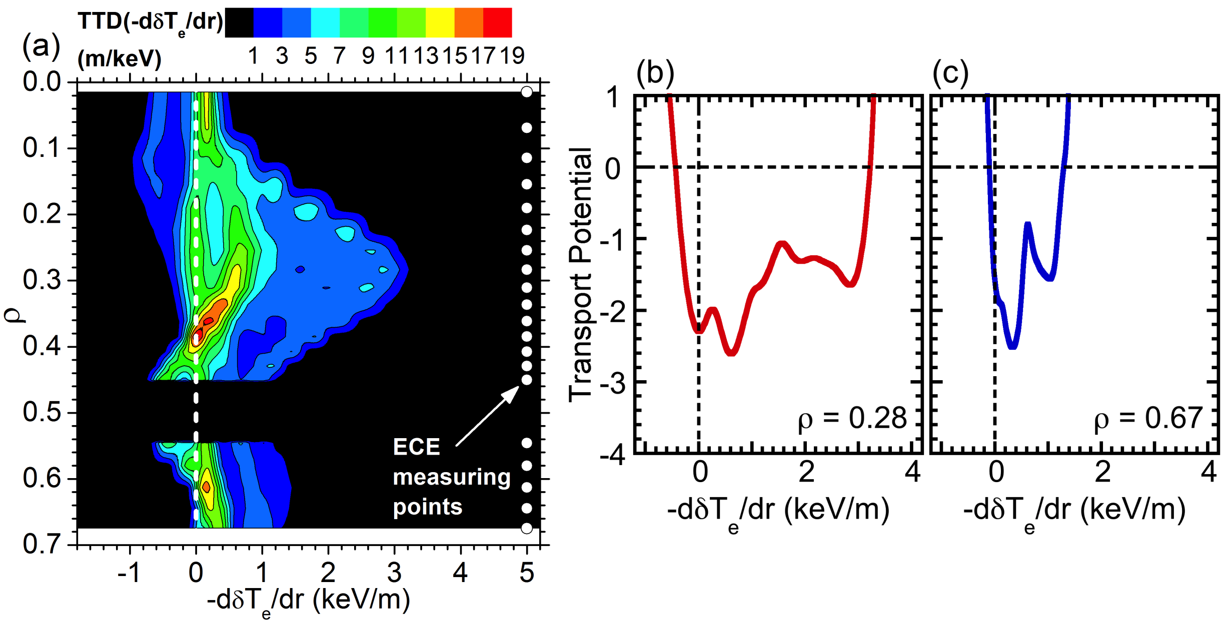

Figure 3. (a)Contour of the PDF in the space and temperature gradient, and transport potential, S, at (b)$\rho = 0.28$ and (c)$\rho = 0.67$ in LHD evaluated from the data in Fig.2.

local" transport becomes dominant. The radial structure of the level of non-locality of transport has been experimentally determined by the contours of the PDF in the parameter space of (r/a, $\Delta(\nabla T)$)[50]. Figure 3(a) shows a probability density function (PDF) of the displacement of the temperature gradients from the transport curve, $\delta(-\nabla T_e)$, during the transient phase after the TESPEL injection. When there is only one transport state in the plasma, the probability density function, $P(\delta(-\nabla T_e))$, has one peak at zero displacement because the plasma stays around the transport curve. On the other hand, two peaks of the probability density function, $P(\delta(-\nabla T_e))$, appear when there are metastable states of transport in the plasma. The transport potential, S, can be determined from the probability density function, P as $P(-\delta\nabla T_e) = \exp(-\mathrm{S})$, which is a good parameter to indicate how the plasma responds to the perturbation and to the robustness of the transport[49]. When the transport is robust, the transport potential becomes deep because the plasma goes back to the original transport curve quickly after the perturbation. In contrast, the transport potential has two wells when there is a metastable state near the edge ($\rho = 0.65$) or a shallow profile when the robustness of the transport is weakened in the core ($\rho = 0.31$) during the transient phase, as seen in Fig.3(b)(c).

Figure 4 shows the time evolution of temperature or temperature gradient in a discharge with perturbation by supersonic molecular beam injection (SMBI)[30, 31] and density dependence of temperature rise after the SMBI. The core temperature increases,

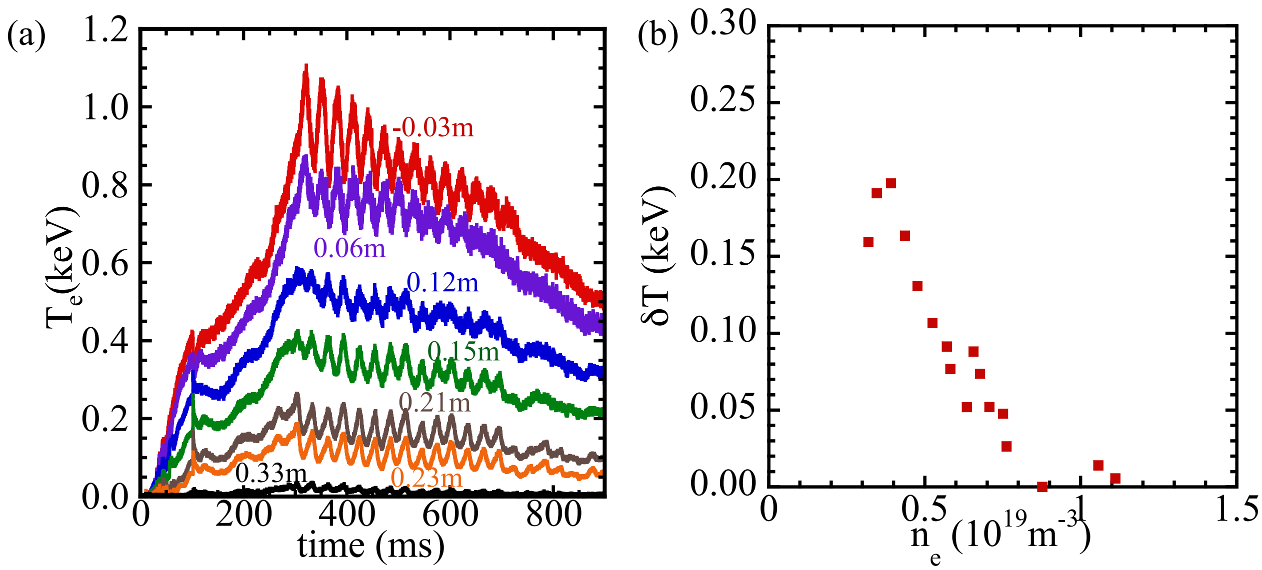

Figure 4. (a) Time evolution of electron temperature in a discharge with multiple SMBI and (b) increase of central electron temperature after the SMBI as a function of electron density in HL-2A.

associated with the drop of the edge temperature after the each SMBI, although the heat flux in the core even decreases. It should be noted that the core temperature increases can be sustained for many energy confinement time by applying multiple SMBI in the discharge. This phenomenon is observed clearly in the early phase where the electron density is low, and tends to disappear as the electron density increases. It should be noted that the decrease of temperature rise is larger than $1/n_e$ and there is no temperature rise above the critical electron density of 0.8×10^{19} m^{-3} as seen in Fig.2(b). The disappearance of the core temperature rise after the edge cooling at higher density (collisionality) is a common phenomenon in toroidal plasmas.

The "non-local" transport phenomena is also observed clearly in the ECH heated tokamak plasma at the event of the penetration of a large size carbon dust into the plasma in KSTAR[51, 52]. The central electron temperature increases transiently (Δt = 0.05 sec) associated with the cooling of the plasma edge by the dust. The increase of electron temperature (0.3 $\sim$ 0.5 keV) is observed only in the region near the magnetic axis. The flipping of temperature rise/drop is located near the plasma center ($\rho = 0.2 \sim 0.3$), which is in contrast to when the flipping location is middle of plasma minor radius of $\rho = 0.5$ in HL-2A and LHD. The mechanism which determines the flipping location is not well understood and should be studied in the future. This experiment suggest the importance of plasma-dust interaction even in core transport not just plasma edge - wall interaction.

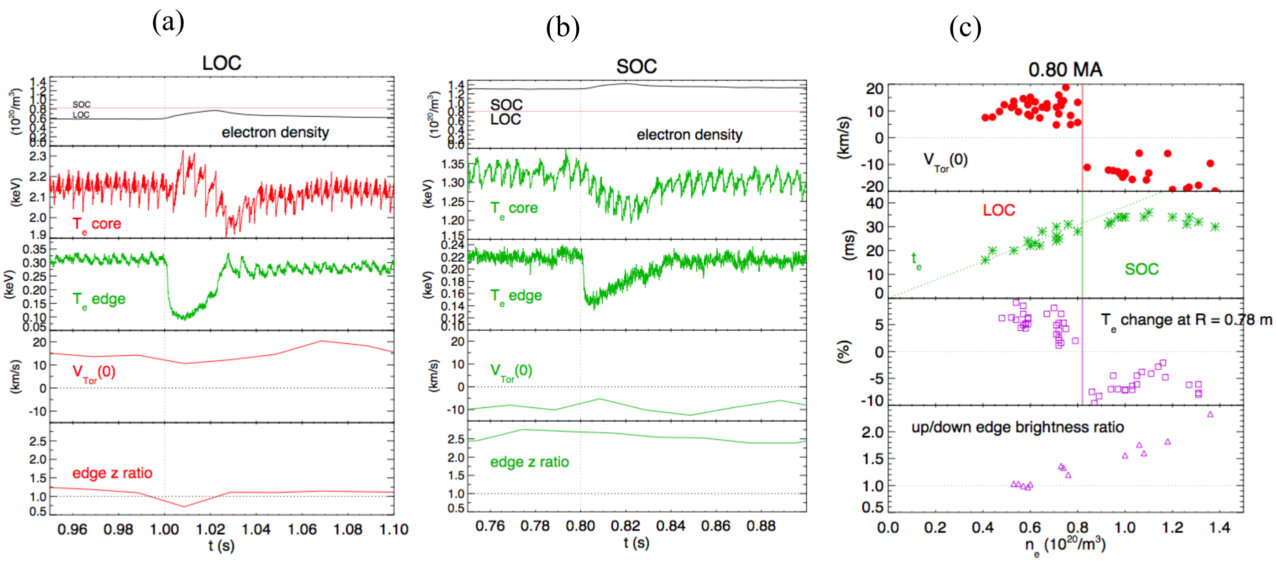

Figure 5. Time evolution of density, core and edge electron temperature, core intrinsic rotation and up/down impurity density asymmetry in response to cold pulses from Laser blow off for (a) LOC and (b) SOC plasmas. (c)Density dependence of the intrinsic rotation, global energy confinement time, change in electron temperature and up/down asymmetry of edge impurity emission in Alcator C-Mod.

3.3. Relation between energy and momentum flux

Momentum transport has been recognized to be much more complicated than heat transport in toroidal plasmas, due to the non-diffusive effects, which can cause intrinsic rotation in the plasma [38, 40, 53]. Since intrinsic rotation can be driven by temperature gradients[2, 54], there should also be a related non-locality of momentum transport in the plasma. In fact, the difference between momentum stiffness and heat transport stiffness, as well as momentum transport and heat transport between edge localized modes (ELMs) may be attributed to the differences in non-locality between momentum and heat transport. Recent experimental observations of the bifurcation of intrinsic rotation magnitude[55] shows that the momentum flux at one location is not uniquely determined by global parameters at that location, and implies the existence of a direct non-locality of momentum transport. Non-locality of both heat and momentum transport can be investigated from the detailed analysis during a transient phase, such as the L/H transition or ITB formation.

Because the "non-local" core temperature rise may be due to the change in the structure of turbulence in (k_θ, k_r) space, intrinsic rotation, which is due to the symmetry breaking of $k_\parallel$, should be correlated with "non-local" transport. Recently the relation between the confinement regime (linear ohmic confinement (LOC) and saturated ohmic confinement (SOC)), the response of "non-local" transport (core temperature rise or drop) and the direction of intrinsic rotation (co-rotation or counter-rotation) has been studied in Alcator C-Mod[56]. Figure 5 shows the time evolution of density, core and edge electron temperature,core intrinsic rotation and up/down impurity density asymmetry in discharges in the SOC and LOC regime. In the LOC regime ,the toroidal rotation is in the co-direction, while it is in the counter-direction in the SOC regime. Rises in the electron temperature are observed only in the LOC regime (lower density). At the higher electron density, the temperature rise (positive value) disappears and a temperature drop (negative values) is observed. The intrinsic rotation also changes sign from co-rotation (positive value) to counter-rotation (negative values). These observations clearly show that both the "non-local" response (T_e rise or drop) and sign of intrinsic rotation (co- or counter-rotation) are quite different between the confinement regimes (LOC and SOC), where the turbulence structure (turbulence mode) is different[43, 57, 58]. This experiment suggests a possible connection between the appearance/disappearance of "non-local" response and the direction of intrinsic rotation in the co-/counter-direction. However, further study is required to investigate whether this connection observed is a coincidence or there is a causal relationship between the "non-local" response and intrinsic rotation.

Similar flow reversal phenomena are observed in other tokamaks, however, the direction of the flow reversal is not common. For example, the direction reversals of intrinsic toroidal rotation during the density ramp up is from the co- to the counter-direction in Alcator C-Mod[57], while it is from the counter- to the co-direction in TCV[59]. The differences between these two experiments suggest that the direction of the intrinsic rotation may be sensitive to the boundary condition: limiter or diverter configurations[60]. (The plasma in C-Mod is diverted, while the plasma in TCV is limited.) More recently, double reversal (reversal from the co- to the counter-direction coincides with LOC-SOC transition and second reversal from the counter- to the co-direction in SOC) is observed in ASDEX upgrade[61]. The second reversal is interesting experimental observation, which clearly shows that the driving mechanism for the intrinsic rotation is not simply determined by the collisionality nor boundary condition because there are many important parameters affect the symmetry breaking of turbulence.

These experiments suggest that the non-linear coupling between the turbulence in $(k_r, k_\theta, k_\parallel)$ space would be the most important issue in "non-local" heat and non-diffusive momentum transport for an understanding of the "non-local" phenomena (curvature transition, core temperature rise) and intrinsic rotation in the plasma. It should be emphasized that "non-local" phenomena and intrinsic rotation are not always observed together. The mechanism causing these phenomena (non-linear coupling between the turbulence with different $\vec{k}$) always exists in the plasma and contributes to the dynamics of transport in $(t, r/a)$ space.

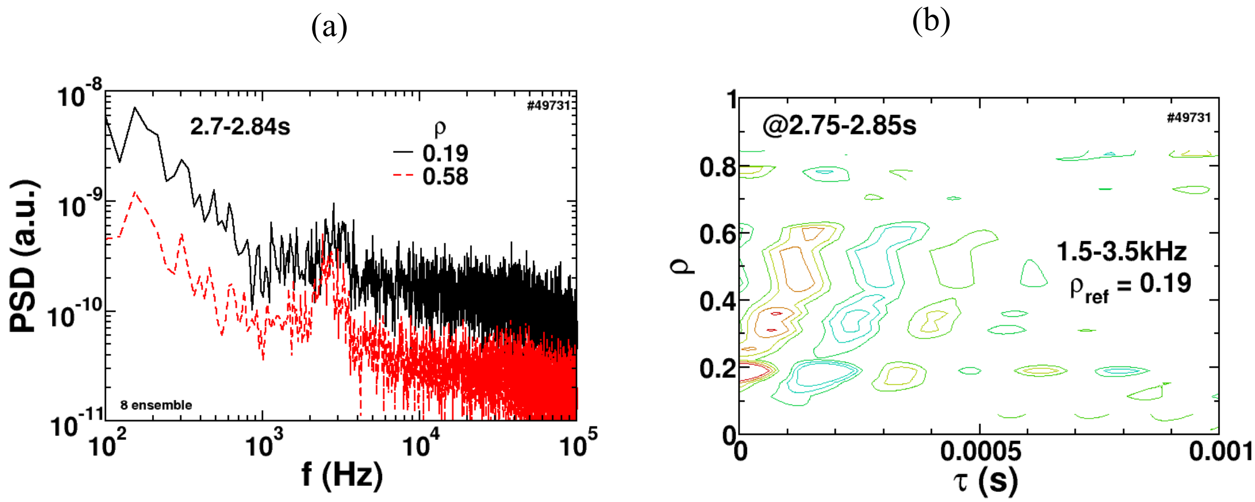

Figure 6. (a) Auto power spectrum of $\tilde{T}_e$ at $\rho = 0.19$ and 0.58 (from Ref [15]) and (b)Contour plot of the cross-correlation function of the low-frequency component (1.5 - 3.5 kHz) in LHD.

4. Fluctuations associated with "non-local" response

4.1. Long-range fluctuations

The experimental observations discussed above (curvature transition, strong correlation between core heat flux and the temperature gradient at half of the plasma minor radius, existence of a metastable state after perturbations) strongly suggest there should be some "agent" to couple the micro scale turbulence at different radii separated by a distance greater than the scale length of the turbulence. Coupling between the micro scale turbulence determining the transport and meso-scale fluctuations and/or zonal flows has been proposed as one of the candidates for the "agent" [7, 37, 62]. The energy exchange between zonal flows and micro-scale turbulence or between micro-scale turbulence and meso-scale turbulence (high k and low k turbulence) has been found in experiments [6, 63]. Recently, coupling between micro- and meso-scale turbulence with long-range correlation[15, 64] has been observed experimentally, and this turbulence with long-range correlation can be another candidate for the "agent" to explain "non-local" transport. Turbulence with a long-range correlation is identified in the electron temperature measured with ECE.

As seen in the auto-power spectrum of temperature fluctuations in Fig.6, a clear peak is observed at 2.5 kHz, with a bandwidth of 1 kHz in LHD plasmas. This peak is mode significant at mid radius of $\rho = 0.58$, while the peak becomes small near the plasma center of $\rho = 0.19$. The auto-power spectrum at the higher frequency, above 8 kHz, is contaminated by the thermal noise of the ECE signal. Figure 6 (b) shows the contour plot of the cross-correlation function of the low-frequency turbulence (1.5

- 3.5 kHz). The radial propagation of low-frequency turbulence is due to the phase propagation of spiral turbulence structure. The spiral structures observed have a long range correlation both in the poloidal ($m = 1$) and radial directions, which differ from the zonal flow ($k_\theta = 0, m = 0$) and MHD mode (localized at fixed ρ).

A possible candidate of this fluctuation has been discussed. Plasma parameters are in the banana regime for ions, $\omega_{b,i} > \epsilon^{-1}\nu_i$, ($\omega_{b,i}$: bounce frequency of trapped ions, ν_i: ion collision frequency and $\epsilon = r/R$). For this observed perturbation, the phase velocity is larger than ion thermal velocity $v_{th,i}$, and the frequency is higher than the ion bounce frequency. That is the relation $|k_\parallel v_{th,i}| < \omega < \omega_{b,i}$ is satisfied for the fluctuation of interest ($k_\parallel$: parallel wavenumber, and ω : angular frequency of wave). Thus, the observed fluctuation is conjectured to be linearly stable dissipative trapped-ion mode (DTIM). The dispersion relation was given for DTIM as $\omega_{DTIM} = \sqrt{\epsilon/2}\omega_*$ and $\gamma = \epsilon^2\nu_e^{-1}\omega_*^2/4 - \epsilon^{-1}\nu_i$ [65]. Considering the positive mean electrostatic potential (which is of the order of T_e), a Doppler shift of $\omega_{E\times B} \sim m \times 10^4 s^{-1}$ occurs (m: poloidal mode number). Thus, the dispersion relation in the laboratory frame for DTIM is $\omega_{Lab} = \omega_{DTIM} + \omega_{E\times B} \sim -(1 + \sqrt{\epsilon/2})m \times 10^4 s^{-1}$. The observed frequency is close to ω_{Lab}, and the spectral width of excited fluctuations is close to damping rate $-\gamma$. Based on these analyses, DTIM has been proposed as a possible candidate. However, the DTIM is linearly stable. Therefore a possible candidate of excitation of linearly stable DTIM is the coupling between this mode and microscopic drift wave turbulence[66]. Future studies will be conducted for the identification of the mode for understanding its excitation mechanism.

4.2. Fast changes of turbulence spectra

By assuming that the Doppler frequency of this mode is dominated by the $E \times B$ rigid rotation, the structure of this low frequency turbulence (1.5 - 3.5 kHz) can be reconstructed[67]. Figure 7 shows time evolution of electron temperature and envelop of temperature of low-frequency turbulence (1.5 - 3.5 kHz) and reconstructed image plot of low-frequency turbulence structure on the poloidal cross-section (c) before and (d) after the TESPEL injection in LHD. After the TESPEL injection at t = 2.845s, the electron temperature in the core region of $\rho < 0.5$ starts to increase, while the temperature near the periphery drops due to the radiation of injected impurity. The envelop of temperature of low-frequency turbulence (1.5 - 3.5 kHz) shows the oscillation due to the $E \times B$ rigid rotation. The envelop starts to decrease after the TESPEL injection (t = 2.845s) with finite delay of 5 ms. Before the TESPEL injection, the spiral structure extends from the plasma center to the half radius. After the TESPEL injection, the radial correlation of low-frequency turbulence becomes shorter and this spiral structure becomes less pronounced and turbulence becomes more localized at the half radius. Turbulence with this spiral structure is a strong candidate for connecting the turbulence intensity at separated locations in the plasma.

As seen in the contour plot of the cross-correlation function of the low-frequency

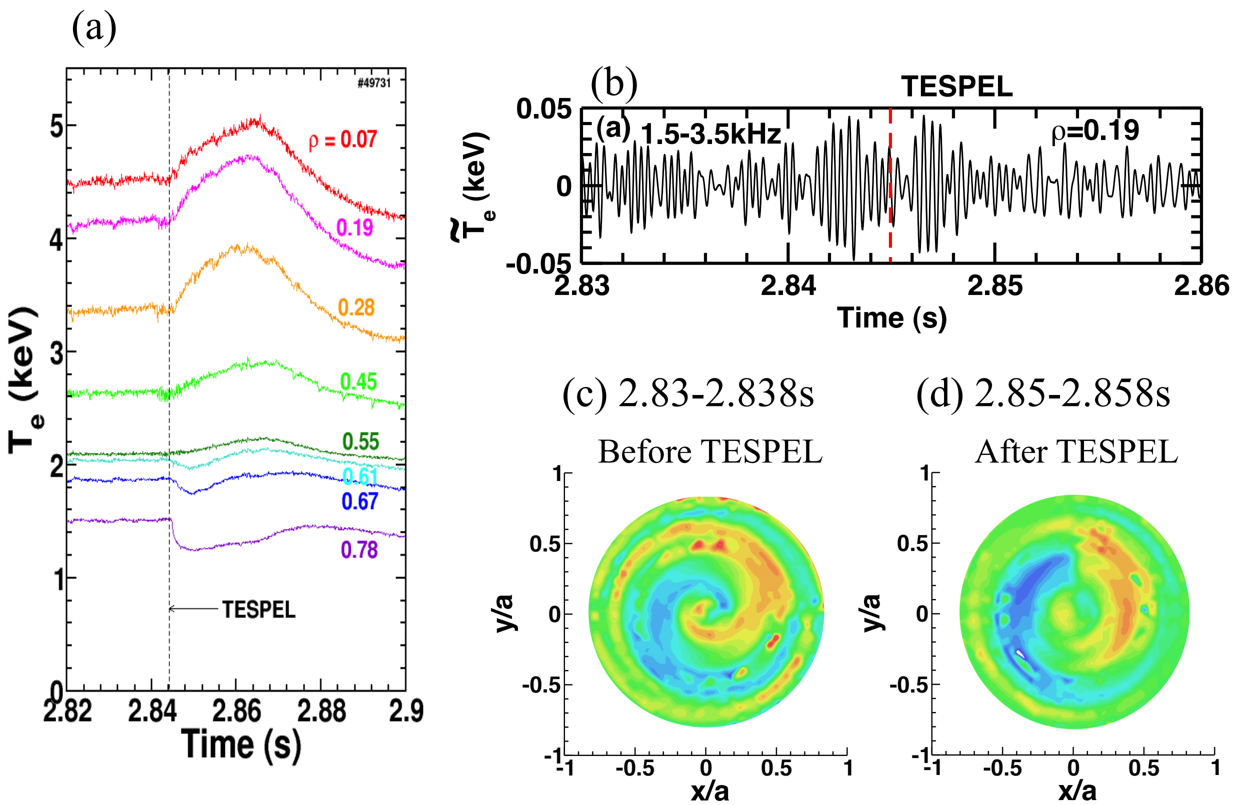

Figure 7. Time evolution of (a) electron temperature and (b) envelop of temperature of low-frequency turbulence (1.5 - 3.5 kHz) and reconstructed image plot of low-frequency turbulence structure on the poloidal cross-section (c) before and (d) after the TESPEL injection in LHD.

component in Fig.7(c)(d), the radial correlation changes during the transient phase where the temperature gradient increases after the TESPEL injection[67]. Before the TESPEL injection, the radial correlation is quite long and turbulence at the plasma center and at half of the plasma minor radius are connected to each other. However, the radial correlation becomes shorter during the transient phase, after the TESPEL injection, where the core temperature increases. The working hypothesis of that the micro turbulence intensity is modulated by this low k turbulence through modulational coupling has been proposed[66]. This experiment clearly shows that during this transient phase, modifications occur in the phase relationship of this turbulence between the center and half radii and in the radial wavenumber of fluctuations, k_r.

Figure 8 shows the time evolution of electron temperature and power spectra of fluctuations before and after the SMBI in the discharge without and with significant core temperature rise in HL-2A. In the discharge plotted in Fig.8(a), there is no significant temperature rise associated with the SMBI, while the significant increase of temperature rise is observed in the discharge plotted in Fig.8(b). Microwave reflectometry studies

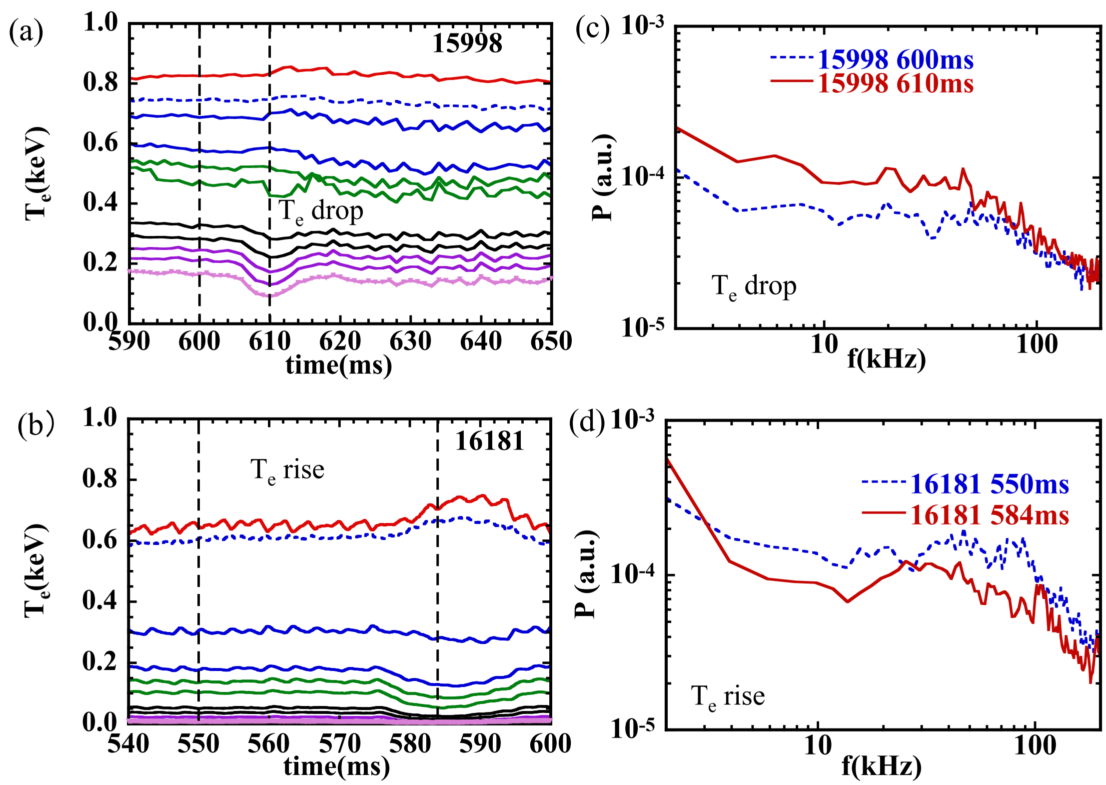

Figure 8. (a)(b) Time evolution of electron temperature and (c) (b) Power spectra of fluctuations before and after the SMBI in the discharge (a)(c) without and (b)(d) with significant core temperature rise in HL-2A.

of the core density fluctuation turbulence show the dynamical response after SMBI. Initial observations suggest the alternation between small and large scale fluctuations. This requires further investigation of the role of multi-scale interactions in non-locality. Figure 8(c) shows the power spectra density turbulence measured with reflectometers (35 GHz) at $r/a = 0.9$ before (t = 600 ms) and after (t = 610 ms) the SMBI. The core electron temperature increases transiently after the each SMBI associated with the drop of the edge temperature. The micro-scale turbulence (high frequency component of density fluctuations) is suppressed transiently after the SMBI, which is well correlated to the core temperature behavior. When the amplitude of the micro-turbulence starts to increase again, the central temperature starts to decrease. In contrast, the meso-scale turbulence (low frequency component of density fluctuations) shows a slight increase, while the micro-scale turbulence is suppressed. It is more important to investigate how the structure of low k turbulence in (k_θ, k_r) space changes during the suppression phase. Although the radial cross-correlation function (CCF) of the meso-scale turbulence at $r/a = 0.9$ is almost unchanged during this phase, the poloidal CCF of the meso-scale turbulence shows a significant increase during the suppression phase of micro-scale turbulence (t = 550 - 584 ms). The maximum poloidal CCF increases from 0.1 to 0.2, while the maximum radial CCF increases from 0.13 to 0.18 after the SMBI pulse

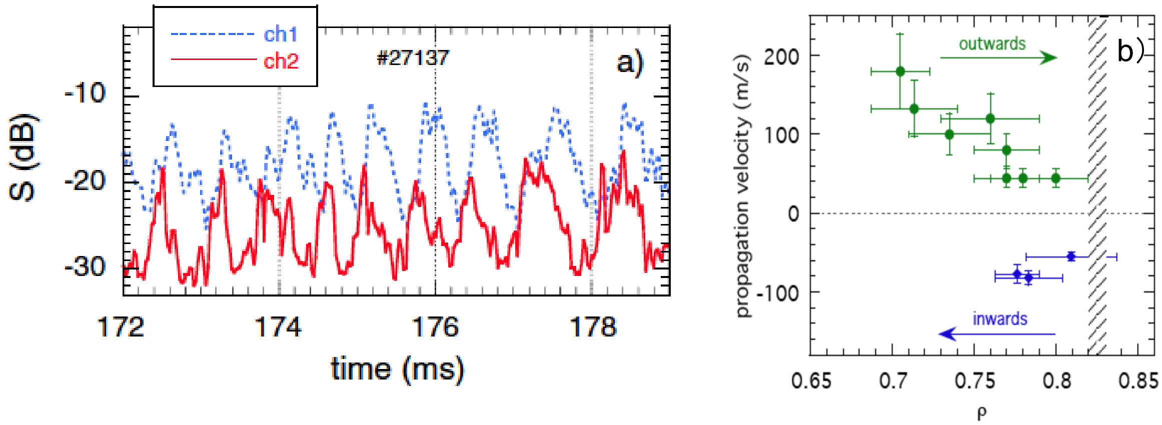

Figure 9. (a) Time evolution of density fluctuation level at $\rho = 0.8$ (ch1) and $\rho = 0.75$ (ch2) and (b) radial profiles of radial propagation velocity in TJ-II. Inward propagation velocities (negative values) are represented using small symbols. The striped area indicates the radial location of the E_r shear. (from Ref [82])

as seen in Fig.8(d). The clear increase of the poloidal CCF suggests the turbulent low frequency structures are poloidally elongated during the suppression of micro-scale turbulence. The relation between the poloidal elongation of the eddy and the $E \times B$ shear should be investigated in future. Therefore the core temperature rise triggered by the cold pulse is categorized to a transient formation of the internal transport barrier (ITB) based on the non-locality of transport.

4.3. Modulation of micro-scale turbulence with meso-scale fluctuations

There are several possible mechanisms for the modulation of micro-scale turbulence. Zonal flows constitute one of the candidates to modulate the micro-scale turbulence in time and space. The energy exchange between zonal flows and drift wave turbulence which modulate the micro-scale turbulence level in time has been experimentally observed. Moreover the roles of mean electric field and zonal flows at the L- to H-mode transition has been investigated both in experiment and theory[68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81]

Recently the spatio-temporal evolution of turbulence has been investigated both in experiments and with theoretical modeling. Figure 9 shows the time evolution of the fluctuation level measured simultaneously at two radial positions in TJ-II[82, 83]. The fluctuation level shows clear oscillations associated with the oscillation of the radial electric field E_r near the plasma edge. Therefore, it is possible to obtain information on the radial propagation characteristics (propagation direction and velocity) from the spatio-temporal pattern of fluctuations. The outward propagation velocity (positive values) decreases as the E_r shear location (at $\rho = 0.82$) is approached. This outward propagation is found in all the oscillation patterns measured at line densities between

$2-2.5\times10^{19}$ m^{-3}. At densities above 3×10^{19} m^{-3}, in some cases the propagation direction eventually reverses after a short time period without oscillations. These data clearly show that the fluctuation levels at radii separated by $\delta\rho = 0.05$ are correlated each other. This experiment indicated that the heat flux is strongly affected by the fluctuation and temperature gradient at radii separated by $\delta\rho = 0.05$. This strongly indicates that a local closure (that is, to relate the local heat flux in terms of the local mean plasma parameters) is violated. There are two possible mechanisms for this propagation. One is a radial spreading of the plasma turbulence from the plasma core to the edge barrier[80], and the other is modulation of the fluctuation levels by the oscillating zonal flows with the scale lengths comparable to the separation of the measurements[84].

Simultaneous measurements of temperature gradient, heat flux, and micro turbulence intensity during the modulation electron cyclotron heating (MECH) in LHD show that the temperature gradient responds to the heating power on the time scale of a few tens of milliseconds[85]. This is in contrast to that both heat flux and micro turbulence intensity respond to the change in heating power within a few milliseconds, which is much faster than that of mean plasma parameters such as temperature gradient. This is a clear experimental evidence that the turbulence intensity and heat flux drive are directly influenced by the heating power in addition to the temperature gradient.

5. Relevant Theoretical Approaches

5.1. Introductory note

The theory of "non-local" transport phenomena is still developing. In this section we briefly survey theoretical approaches in the context of the phenomenology discussed in the preceding sections. This article classifies "non-local" phenomena from the viewpoint of the violation of the local closure (in space and time) in the transport relation. This recognition of transport properties (violation of local closure) is assessed in the following way: i) global transport property in the formation of transport barriers, as an introduction for the universality of local closure violation, ii) perturbation induced 'anomalous response' in energy transport, iii.) generalization including momentum transport, and iv.) observations of multi-scale phenomena in fluctuations.

Recent development in the theory of plasma turbulence has focused on the multiple-scale nonlinear and statistical dynamics of turbulence. Various processes are schematically shown in Fig.10. In understanding the "non-local" transport problems, theoretical approaches might loosely be classified, starting from microscopic fluctuations, as: a.) avalanches, non-diffusive (ballistic) pulse and front propagation models, b.) flux-driven residual stress and intrinsic torque density models, c.) barrier formation and propagation models, d.) modulational multi-scale models, e.) statistical transport models with local closure violation. Rather clearly, one can see a correspondence of these approaches to the experimental observations. The problems associated with front

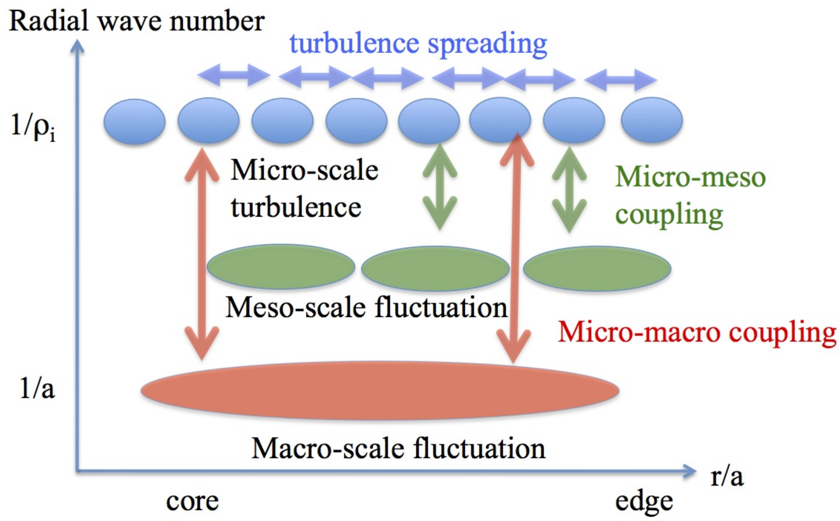

Figure 10. Illustration of elementary processes in multiple-scale turbulence.

propagation are mainly explained in this article, because this is a prototypical example that local dynamics can induce a violation of local closure. It should be noted that the avalanche dynamics, which is in common with front propagation in the local diffusion model, can induce a violation of local closure and produce "non-local" phenomena. The theory has been developed but the experiments have not yet been fully studied. Then a few comments are made on topics in conjunction with macro and meso-scale fluctuations and barrier formation problems.

5.2. Local mechanisms that induce "non-local" responses

Avalanche models and the pulse and front models exploit the natural formulation of dynamical, 'anomalous response' phenomena as a set of coupled, highly non-linear reaction diffusion equations. Such systems have the property of exhibiting non-diffusive solutions in what naively appear to be diffusion equations. Classic examples of this are Fisher fronts, nonlinear diffusion-convection for turbulence spreading, and nonlinear wave packets. Studying this problem has two illustrative important examples in the transport phenomena. First, this is a prototypical example to demonstrate why local closure of the flux-gradient relation is violated, although turbulent transport is usually expressed in terms of 'local fluctuations'. Second, though very simplified, it introduces general guideline for the 'radial velocity' of super-diffusion propagation of response. The nonlinear damping process, which often arises from the cascade in wavenumber space (i.e., the transfer of energy via nonlinearity to highly stable components causes damping of the fluctuations of interest), causes the real-space diffusion of I. Due to this reason, $D_0 \frac{\partial}{\partial x} I \frac{\partial}{\partial x} I$ has similar properties to $\gamma_{NL} l^2$, where l is a characteristic spatial

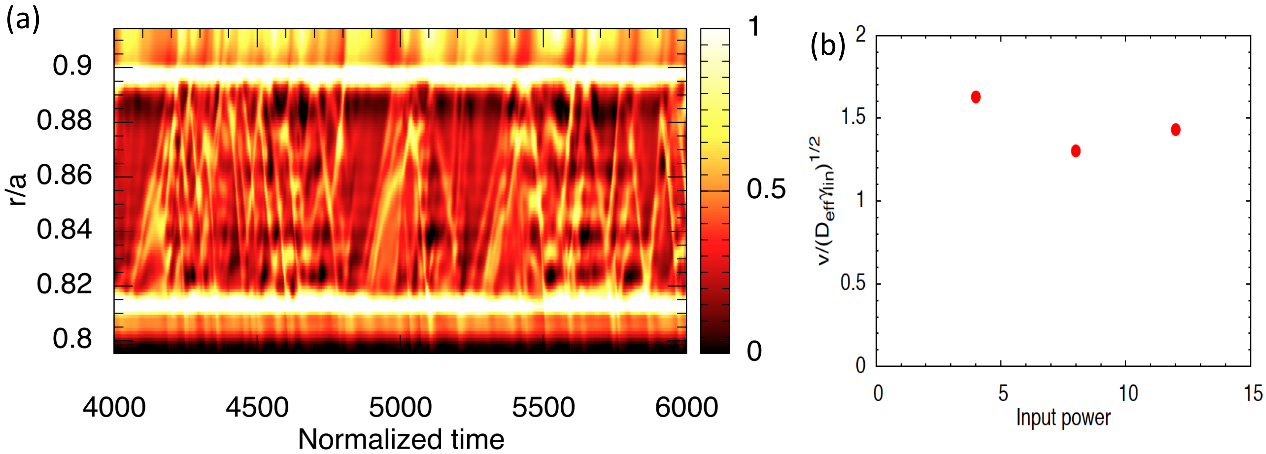

Figure 11. (a) Spatiotemporal turbulence intensity calculated with three dimensional edge turbulence simulation and (b) the ratio of Fisher front velocity in the turbulence simulation to the that with theoretical formula as a function of input power.

scale of fluctuations. (See [19, 20] for details.) Although this equation (2) is given in terms of the 'local' equation, i.e., all terms are given by local parameters, solutions of such systems represent ballistic (non-diffusive) response. Pulses have been shown to propagate in constant speeds (Fisher front velocity), $v_r \sim \sqrt{\gamma D_0}$, where γ is a linear growth rate, which gives an order- of-magnitude estimate as $v_r \sim v_{dia}$ for drift wave turbulence.

This is a prototypical example to understand 'super-diffusive response' in diffusive systems. The basic formulation of this class of models is local but highly nonlinear. One can find a variety of work in this direction of thought. Recent simulations have shown that the relation of $v_r \sim \sqrt{\gamma D_0}$ gives a good approximation for a statistical average of a large number of excited pulses and fronts as seen in Fig.11. (The detailed description of the simulation is given in [86].) The radial correlation length of these ballistic pulses was also studied, and the Lagrangian correlation length is a few times longer than the local correlation length[87]. The convergence to the long-time average has also been studied in detail by use of the Hasegawa-Wakatani model[88]. The deviation from the long time average converges following the scaling law $1/\sqrt{N}$, where N is the number of events. The events last a significant fraction of the confinement time. The typical event duration is thus in the range of 5 correlation times, a ratio also reported in gyrokinetic flux driven simulations[37].

Momentum transport has the property that it is sensitive to stresses, which are not simply proportional to velocity or its shear. These contributions, called 'residual stress' convert radial inhomogeneity into intrinsic torque density and flow drive by symmetry breaking. Developments in this issue are discussed in depth in the overview[39], where aspects of avalanche dynamics as well as long correlations are illuminated, and readers are referred to [39] for detailed arguments. A example of this process is taken from the cases of the co-intrinsic torque exerted by the ETB in H-mode, which is formed from the Reynolds stress $\langle \tilde{v}_r \tilde{v}_{\parallel} \rangle$. An interesting property of residual stress is that it may be viewed as an effective, heat flux driven internal source in the momentum balance. No counterpart in heat transport for such internal sources has been pointed out. (Nevertheless, it is worth pointing out that the anomalous coupling/transfer between different plasma species has such properties (i.e., if one looks at the electron energy balance, a turbulence-driven source/sink appears), though it is not the divergence of a flux[89]. In [89], the nonlocal nature in the interaction between different species has also been discussed.) Thus, for example, counter-NBI deposited on axis in H-mode plasmas must work against the intrinsic co-torque in the pedestal. In one experiment, these two effects canceled, leaving a state of zero rotation[90]. Such internal sources, say at the edge, thus have been shown to affect profoundly the momentum transport in the core, giving the flavor of a 'tail wags the dog' effect. Interestingly, here apparently "non-local" phenomena emerge from a fundamentally local (through non-diffusive) model.

The dynamics which is related with the fronts and avalanche have been shown in flux-driven simulations. Flux-driven fluid[23, 25, 91, 92] and gyrokinetic[93, 94, 95] systems are now in common use and have increasingly been reporting deviations from the local and diffusive paradigm, either confirming the ideas of avalanching and spreading or the characterization of non-local, non-diffusive behavior[16, 19, 20, 22, 27, 37, 88, 35, 96, 97, 98, 99]. Since in flux-driven systems the only constraint is to ensure a balance, on average only, between the sources and the sinks, computations have shown that probability distribution functions (PDFs) of the particle flux[88] or of the heat and momentum flux[100, 101] display heavy tails towards the large positive values, that the effective flux is essentially sustained by the heavy tail part of the PDF. This property is typical of avalanche-like behavior[22, 91, 92, 93, 94, 102, 103, 104] and 1/f frequency spectra[22, 94, 102, 105, 106] are observed. Flux-driven gyrokinetics confirms this result as avalanche-like heat propagation has been shown to be still significant even though the mean field scaling are considered to be close to the familiar gyro-Bohm scaling [37, 107, 108, 109]. This observation indicates that the dimensional similarity of the mean heat flux to the gyro-Bohm scaling does not necessarily means that the mean heat flux (at any radius) is given in terms of the local mean plasma parameters (at the same radius).

This issue could be investigated by studying the dynamic response in simulations. The convergence towards a statistical average scales with $1/\sqrt{N}$[88], N being the number of events which contribute most to the PDF of the particle flux, which is indicative of the difficulty in obtaining sufficient statistics to determine with precision the steady state regime. It is also a strong indication that an accurate modeling of the transport processes up to the confinement time seems crucial to characterising the transport processes. Indeed, tracing the large flux events and determining their dynamics, there are indications that these events behave like fronts or avalanches such that the microscopic transport is close to ballistic[22, 37, 88, 106, 110], in marked difference with that assumed when considering the Brownian motion-based local paradigm. The

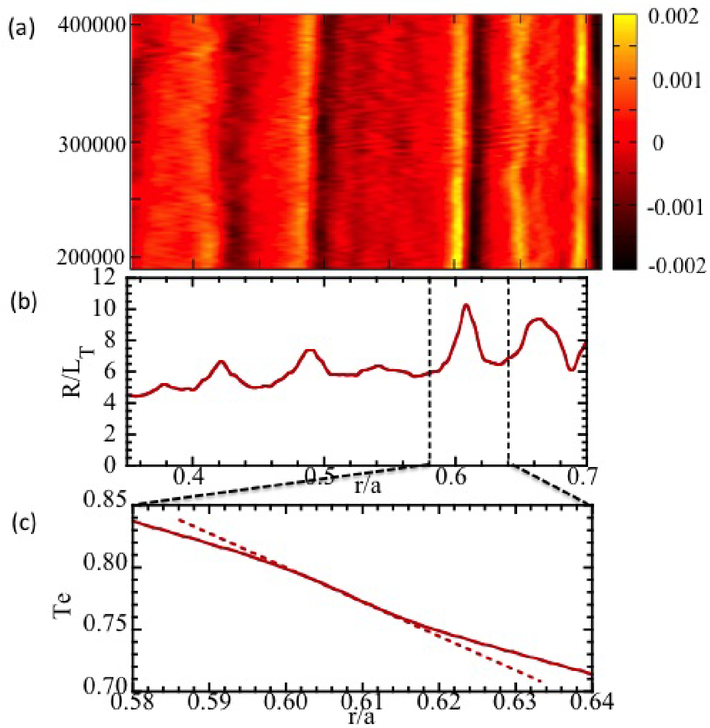

Figure 12. (a)Contour of radial electric field shear and radial profile of (b)temperature gradient (R/L_T. where R is major radius and L_T is scale length of temperature and (c) electron temperature calculated, which shows multiple-scale dynamics and formation of "staircase" in gradient.

fine details of the profile dynamics thus seem important for explaining these results. There is indeed mounting evidence which shows the importance of non-local interactions in plasma profile evolution which is related to meso-scale structure formation, should it occurs through zonal flow pattern formation[37] or through the fluctuation of the intensity envelope[111, 112]. Both approaches are different sides of the same coin as the intensity profile is related to spatial structure of the Reynolds stress, which is manifested through avalanching and pattern formation in the meso-scale range.

5.3. Additional issues including non-local fluctuations and their impact

When the meso-scale and macro-scale fluctuations are excited, the transport which is caused by these fluctuations are non-local[16, 27, 37]. Thus, if the transport relation is closed in terms of global plasma parameters and their gradients, the local flux-gradient relation is replaced by a non-local, integral relation in space, and possibly in time. The kernel of the integral may have a divergent second moment, indicative of a Levy process. (Of course, such a divergent feature can arise even in the case where super-diffusive response is induced by the microscopic turbulence as explained in the preceding sections.)

The amplitude of the zonal flows is controlled by the integral of drive by microscopic fluctuations. Therefore, the back-interaction by zonal flows on the microscopic turbulence is not specified by local parameters, but influenced by fluctuations at a mesoscopically distant location (though within the coherence length of zonal flows). Thus, a non-local interaction like the "seesaw mechanism" can work [113]. There is another process, by which the meso-scale interaction can induce an intermittency of gradient. This coupling between small-scale turbulence and larger scales is done via meso-scale (mean) ExB flow shear which is seen through the spontaneous generation of meso-scale patterns of ExB flows called an ExB "staircase" as seen in Fig.12[37].

An $E \times B$ staircase is a quasi-periodic sequence of thin $E \times B$ shear layers and related profile corrugations, interleaved by regions of strong avalanche activity. The $E \times B$ staircase is the plasma analogize potential vorticity staircase well known and often observed in geophysical fluids[114]. Both the potential vorticity and $E \times B$ staircase are formed by (effective potential vorticity) mixing processes with a finite mixings scale. The interstep spacing of the staircase constitutes an emergent scale similar to the Rhines scale[115] familiar from geophysical fluids dynamics. The $E \times B$ staircase is remarkable in that it resolves the natural competition between flow shearing and avalanching by separating these into distinct spatial domains. $E \times B$ staircase are emergent phenomena, and are *not* trivial consequence of imprinting by the magnetic geometry. In particular the locations of the "step" in the core discussed in ref[37] are not correlated with low-q resonance. A particularly remarkable aspect of the $E \times B$ staircase is its quasi-periodic regularity amidst a background of stochastic avalanches. The discussion as to how these structures emerge is still ongoing yet it has already been shown that the existence of these structures has some interesting consequences on shear, poloidal rotation and turbulent transport.

The mean $E \times B$ flows are driven by the mean pressure gradient, turbulence and other mechanisms[116, 117, 118]. It may compete against zonal flow[73]. The staircase is a long-lived pattern of shear layers; in simulations where such structures exist the mean shear is reported to be dominant as compared to the zonal flows shear[102]. From a modeling perspective, mean flows are associated with meso-scale structures on the mean profiles; A systematic procedure has shown that Eqs. (1) and (2) are good fits to the turbulent heat flux Q. The size Δ of this kernel also coincides with both the typical step of the staircase and the typical avalanche size in the system. In-between the staircase steps, the transport is avalanche-dominated. How the stochastic avalanches may produce this quasi-regular flow pattern is under investigation. An analytic perspective is proposed by developing an analogy with the formation of Jams in traffic flux[119].

These studies in Sec.5.2 and Sec.5.3 give a basis to an inductive approach, in which the integral relation like Eq.(3) (in terms of the space- (and time) integral) with a test kernel[35, 96, 97, 98, 99, 120, 121] has been inductively obtained by fitting to the experimental observations. This approach has stimulated the importance of the study of violation of local closure. Balescu has stressed that the continuous time random walk (CTRW) model might be more relevant than the diffusion model [122]. A mathematical framework for the fractional kinetics has been developed[123], This line of inductive approach is complementary to the picture of multiple-scale turbulence, and might be unified in the future. The influence of higher-order derivative terms on the flux (e.g., [63, 124, 125, 126, 127, 128]) is also related to nonlocal closure. When the effect of curvature is as important as that of the gradient, the effects of much higher order derivatives should also be considered: that is, the study must be expanded to include the integral formulation of transport fluxes.

6. Discussion

The experimental study for the mechanism of violation of local closure will be an interesting topic for future work. In closing this article, some possible major impacts of this issue on future research are discussed: One is the identification of the mechanisms that introduce the (already-observed) violation of local closures. The other is that the validation of the direct simulation codes and transport models should include comparisons with studies of dynamical responses, in addition to those with stationary states. This is a crucial element of future studies of non locality phenomena. In identifying the physical mechanisms, two have been emphasized; one is the fast front propagation of micro-scale turbulence and the other is the coupling between micro scale and meso/macro-scale turbulence. Measurements of spatiotemporal micro-scale turbulence in experiment are essential to test these models. The former process appears as an incoherent propagation of micro-scale turbulence, for which new experimental observations are emerging. For instance, D-III D has reported possible avalanches in the core plasma[26]. In addition, spatio-temporal dynamics of turbulence and gradient in the limit cycle oscillation near edge plasma of JFT-2M plasma are compared to front propagation dynamics [80, 129, 130, 131]. Observations on TJ-II, which are produced as Fig.9(b), might also be studied along this line of thought. The latter appears as a coherent propagation of micro-scale turbulence regulated by the frequency of meso/macro scale turbulence, some of which is noted in this article.

In LHD, the intensity of micro-scale turbulence is found to be modulated by the frequency of long-range fluctuations ($\sim$ 2.5kHz) and the transport driven by microscopic turbulence is reduced by the appearance of long-range fluctuations. The reduction of high-frequency fluctuations occurs in conjunction with the long-range fluctuations[66], while the long-range fluctuation (note that $n \neq 0$ and $m \neq 0$ that differ from the zonal flow) itself induces additional transport. Comparing these two competing processes, the net transport is reduced by the appearance of these long-range fluctuations near the threshold condition of instability.

More recently the direct influence of central heating on turbulent transport at two thirds of the plasma minor radius has been identified in LHD[85]. Related observations have been historically reported[132, 133]. The hysteresis appears in the gradient-flux relation, as well as in the relation between gradient and fluctuation intensity. This issue must be studied in much wider circumstances. This phenomenon can be understood with the conjecture that the modulation of heating power at the center immediately influences the long range fluctuations which modulate higher frequency fluctuations at a far distance through their nonlinear couplings[134, 135].

The rapid progress in the experimental measurement of dynamics of turbulence will soon provide more quantitative information on the cause of violation of local closures for transport relations. It is a major challenge in experiment to measure the shape of non-local kernel, because it would be more definitic test of non-local transport model based on the different physics mechanism. The scale length of non-local kernel for the coupling micro- nd macro- turbulence is an auto-correlation length of the mcroscopic mode. On the other hand, the coupling length owing to the spreading was pointed out to be few times of correlation length of microscopic turbulence[136]. The former can be longer than the latter (few times of microscopic length), so that the non-local kernel for the coupling micro- and macro- turbulence can have much longer tail than that for turbulence spreading. It is also interesting test how the non-local transport changes when the MHD modes driven by energetic particles, because they can be also additional origin of global perturbations,

In the experimental observations, it may also be useful to note recent results of theory and simulations, in addition to fundamental elements explained in Chapter 5. Turbulence spreading can also contribute to the mesoscale dynamics via the formation of heat waves[136]. The fluctuating part of the temperature may indeed follow a wave-like equation to which a radial propagation speed is associated, which is in the ballpark of the observed radial propagation speed of the turbulence. Turbulence spreading might be mediated by GAMs[137] as GAMs have a radial group velocity[138] and are amplified in the edge via the beach effect[136]. In these respects, recent flux-driven gyrokinetic simulations of energetic GAMs (EGAMs)[139] have been performed in the presence of turbulence, which show that the presence of EGAMs is found to impact the mean temperature profile, therefore impacting the turbulence through a possible coupling between EGAMs and mean $E \times B$ flows[140]. The excitation of GAMs by energetic particles and the energy channeling to bulk ions[141] has been observed by experiments[142]. Thus, coupling of transport processes in wider circumstances, including velocity space non-locality (e.g., [143]), will be studied in the future.

The finding of non-local transport in experiment has a strong impact for the local transport model and simulation based on the turbulence determined by the local quantity. Comparison of simulation results with the experiments have been done in the steady state profiles not in the dynamics in the transient phase. The reproducing the non-local phenomena observed in experiment, where the transport at the locations separated is correlated each other, is a big challenge for simulation, because this is the definite test of validity of transport model. The comparison in the steady state profiles between the experiment and simulation is not enough, because the non-local transport feature can be identified only in the dynamics of transport not in the steady state transport. In fact there is no simulation which can reproduce the ITB radial propagation in the steady state configuration (for example q - profile) observed in experiment[144, 145]. A preliminary report has been made on the global nonlinear simulation, which has examined the dynamics response against the periodic modulation of heating, has been made, where the violation of the local closure was demonstrated[146]. The dynamic transport simulation which can reproduce the non-local dynamics in experiment is desirable to understand the non-local transport.

The importance of non-locality phenomena to the critical task of transport model validation *cannot* be over-emphasized. The escalating costs of ITER and DEMO drive us to demand a prediction model. However, the effectiveness of the validation challenges confronted so far - mostly cares from steady state ion heated L-mode plasmas - is quite limited. Moreover, the validation domain of these exercises has been all *inside* familiar territory. Even then, results have not been satisfactory, in that the "$\rho > 0.6$ shortfall problem" has been surfaced in local gyro kinetic models[147], the leading candidate. This problem night arguably be said to constitute a re-statement of the familiar 25+ year old observation that local drift wave theories tend to fail as ρ increases, while temperature drops. Non-locality phenomena are significant here, in that i) they offer a novel road forward for resolving the shortfall issue,by core-edge coupling phenomena such as avalanching, spreading, etc., ii) by their transient, multi-scale character, they constitute far more rigorous test of transport model. In particulars, the relation between fluctuations, and transport and spatio-temporal dynamics over a wide range of space *and* time scale must be successfully predicted in order to declare victory in the modeling of such phenomena. iii) They constitute a kind of "terra nova" for validation studies - i.e. in this context, models can be forced to actually *predict* the outcome of *new* experiment, and can not so easily be tuned to obtain a previously known "right answer". Points i) - iii) above all support the important role non-locality studies can and indeed *must* play in the world wide program of transport model validation for the development of magnetic fusion energy. Non-locality phenomena are *central issue* and not some peripheral .exotica, as claimed by some. We look forward to future contributions to model validation by non locality studies with great interest.

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