Edge-Core Interaction Revealed with Dynamic Transport Experiment in LHD

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Abstract. Large scale coherent structures in electron heat transport of both core and edge plasmas are clearly found in plasma with a nonlocal transport phenomenon (NTP, a core electron temperature rise in response to an edge cooling) on Large Helical Device (LHD). At the onset of the NTP, a first order transition of the electron heat transport, which is characterized by a discontinuity of electron temperature gradient, is found to take place over a wide region (at least 6 cm wide) in the periphery of the plasma. At about the same time, over a wide region (about 10 cm wide) of the plasma core, a second order transition of the electron heat transport, which is characterized by a discontinuity of the time derivative of the electron temperature gradient, appears. The both large scale coherent structures are of a scale larger than a typical micro-turbulent eddy size (a few mm in this case). In order to assess dynamic characteristics of the electron heat transport state in the core region during the NTP, a transit time distribution analysis is applied to the temporal behaviors of the electron temperature gradient. The analysis results more clearly show the existence of the large coherent structures in electron heat transport. Thus the NTP observed in LHD is considered to be invoked by the interaction of those structures.

1. Introduction

The importance of nonlocality (Here, it means a spatial interaction between two distant points) in the heat transport has become increasingly recognized in magnetically-confined toroidal plasmas. One of the simulation studies of an electron internal transport barrier (ITB) in a tokamak configuration clearly indicates that a radially-elongated turbulent structure, which originates from the micro-turbulence at the region far from a foot point of the electron ITB, play a significant role in the formation and collapse of the electron ITB [1]. As an experimental work, a spontaneous transition between two different ion temperature profile curvatures inside an ion ITB region has been recently discovered in the JT-60U tokamak [2]. And the spontaneous transition between two different temperature curvatures has been also found in the electron ITB plasmas of the Large Helical Device (LHD) [3]. Since burning plasmas such as in International Thermonuclear Experiment Reactor (ITER) are considered to be highly autonomous, there are limited control knobs in such plasmas. Nevertheless, even in the burning plasmas, dissipative structures in the turbulent transport such as the ITB should be established. Thus in order to achieve a high accuracy of external control of the formation of the dissipative structures in the burning plasmas, it is essential to understand the nonlocality of the heat transport and its dynamics.

The most well-known example of phenomenon, which strongly reflects the nonlocality of

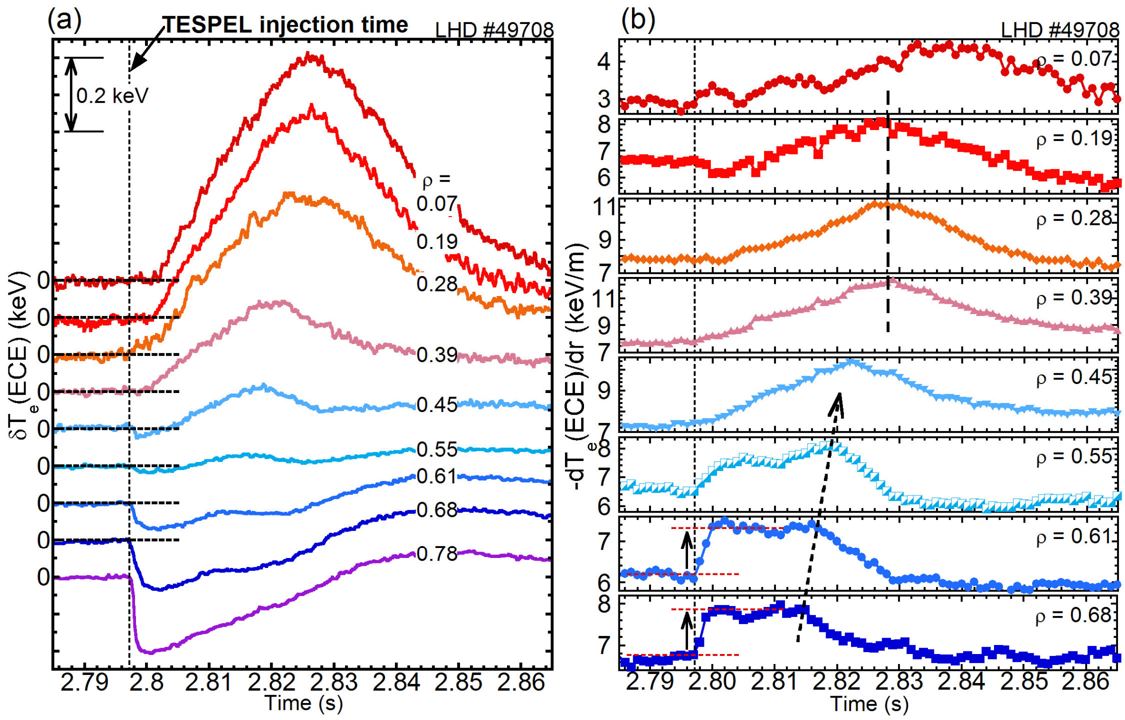

FIG. 1. Temporal evolutions of the (a) electron temperature and (b) electron temperature gradient, which is obtained with the ECE radiometer, at different normalized minor radii in the plasma showing a nonlocal transport phenomenon in LHD. All the data in FIG. 1(b) is plotted at 1 ms interval. The timing of the TESPEL injection is indicated by the vertical short-dashed line.

heat transport, is an abrupt rise of the core electron temperature T_e in response to an edge cooling (so-called "nonlocal transport phenomenon") [4]. The nonlocal transport phenomenon has been observed in many tokamaks [5, 6] and a helical device [7 - 9]. Although more than 10 years have passed after the first observation of nonlocal transport phenomenon in the TEXT tokamak, there is still no rational explanation of that. Thus it is still valuable to accumulate phenomenological knowledge about the nonlocal transport phenomenon in the magnetically-confined toroidal plasmas. In this paper, we firstly describe the characteristics of temporal behavior of local electron temperature gradients after the onset of the nonlocal transport phenomenon. And secondly, results of new analysis applied to the temporal behavior of local electron temperature gradients are reported.

2. Characteristics of local electron temperature gradients in the plasma with a nonlocal transport phenomenon

Figure 1(a) shows typical temporal behaviors of the electron temperature T_e, which is measured with a high time-resolved multi-channel electron cyclotron emission (ECE) radiometer [10], just before and after the onset of nonlocal transport phenomenon (NTP) in LHD. Here, the ECE signals are acquired with a sampling frequency of 5 kHz without aliasing and no band-pass filter is applied to the signals already converted to digital. Thus it should be noted here that the values originates from the ECE signals here will be contaminated with a noise to some extent. As can be easily seen in FIG. 1(a), the core T_e rise is abruptly increased in response to the edge cooling by the TESPEL injection. In this case, the penetration depth of the TESPEL is around ρ = 0.9, which is quite far from the region

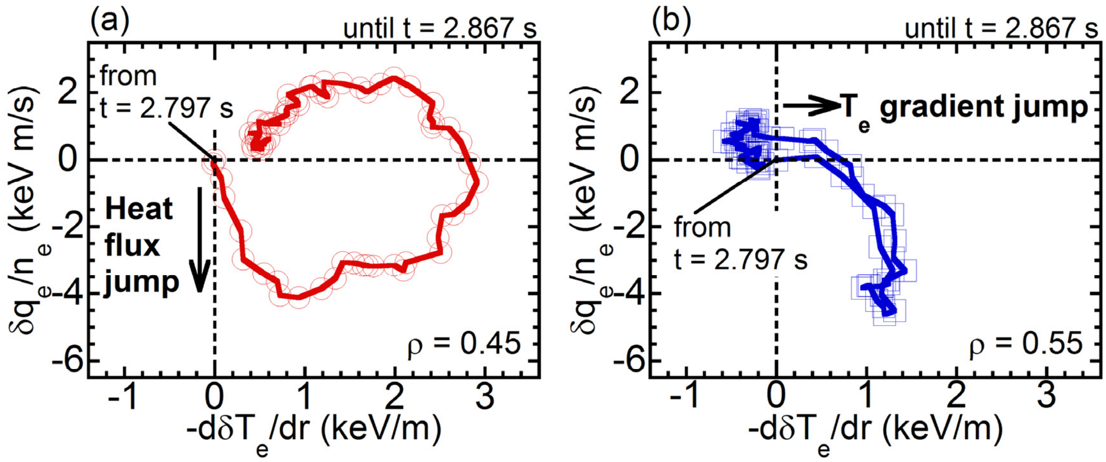

FIG. 2. Relationship between the perturbed normalized electron heat flux and the perturbed electron temperature gradient at (a) ρ = 0.45 and (b) ρ = 0.55. Data from t = 2.797 s to t = 2.867 s is plotted at 1 ms interval.

where T_e is increased appreciably. Thus this experimental result clearly suggests the existence of the edge-core coupling in electron heat transport. It should be noted here that here the T_e at ρ = 0.07 and 0.19 is increased 4 milliseconds behind the TESPEL injection time. Such perceptible delay is one of the features of the NTP [9]. The NTP usually takes place in the high-temperature and low-density regime, in other words, in the low-collisionality regime in LHD as well as in tokamaks [11]. In this case, the central electron density n_{e0} and electron temperature T_{e0} is 0.8 x 10^{19} m^{-3} and 3.7 keV, respectively. Although this regime is surely close to that for the electron ITB formation, such distinguishing structure was not formed before and after the onset of the NTP. The plasma around the time of interest is heated continuously by a 2 MW negative-ion-based neutral beam injection (nNBI) and a 1 MW electron cyclotron heating (ECH). The focus of all ECH beams (the applied frequencies: 82.7 and 84 GHz) is adjusted near the magnetic axis. Since the high-energy (140 ~ 180 keV) nNBI power is mainly transferred to the electrons, the electron loss channel dominates the ion loss channel and thus the ratio of electron temperature to ion temperature T_e/T_i is naturally larger than unity. Figure 1(b) shows temporal evolutions of the electron temperature gradient $-dT_e/dr$, which is evaluated from the data shown in FIG. 1(a). Right after the TESPEL injection, as indicated by the arrows in FIG. 1(b), a jump of the $-dT_e/dr$, is found to take place in the region extending from ρ ~ 0.6 to at least ρ ~ 0.7. Although this $-dT_e/dr$ jump is surely affected by a jump in electron density due to the TESPEL injection, the increased $-dT_e/dr$ is sustained for a while unlike the usual case (see FIG. 3(b) shown later). Thus, a first order transition of electron heat transport, which is categorized by a discontinuity in $-dT_e/dr$ [12], appears over a wide region (at least 6 cm wide) in the periphery of the plasma. At about the same time, a second order transition of the electron heat transport, which is characterized by a discontinuity in the time derivative of the electron temperature gradient $d(-dT_e/dr)/dt$, appears over a wide region (0.28 < ρ ≤ 0.45, corresponds to a width of about 10 cm) in the plasma core. These facts indicate the existence of large scale coherent structures in both core and edge regions, which are of a scale larger than a typical micro-turbulent eddy size (a few mm in this case), and their interaction can cause the nonlocal T_e rise. As shown in FIG. 2(b), the jump of the electron temperature gradient at ρ = 0.55 is still noticeable in the relative relationship between the electron heat flux normalized by the electron density $\delta q_e/n_e$ and the gradient of the electron temperature $-d\delta T_e/dr$ just after the TESPEL injection. On the other hand, at ρ = 0.45, where it is not far from the region at ρ = 0.55, a jump of the $\delta q_e/n_e$ becomes pronounced in the dynamic flux-gradient relationship. Here, the δq_e is evaluated by using the following equation

$$\delta q_e(r,t) = -\frac{1}{r}\int_0^r \frac{3}{2} n_e \frac{\partial \delta T_e(r,t)}{\partial t} \rho d\rho,$$

where n_e is the electron density, δT_e is the difference electron temperature measured with the ECE diagnostics, S is the surface area of the closed flux surface and V is the volume inside that, respectively. These facts suggest the core turbulence is suppressed through interaction with the edge turbulence, not due to the expansion of the mechanism of edge heat transport improvement. And then the second-order transition of the electron heat transport as a backward transition appears spontaneously in a wide region (ρ > 0.45) and seems to propagate towards the core (indicated by the short-dashed arrow in FIG. 1(b)). This suggests the large scale coherent structure in the edge region no longer exists at this phase. It should be noted, however, that in the core region (0.19 ≤ ρ ≤ 0.39), the backward second-order transition of the electron heat transport seems to start simultaneously (indicated by the long-dashed line in FIG. 1(b)). This indicates the core large scale coherent structure still exists at this time. Consequently, the core T_e rise due to the NTP seems not necessarily to require the well-known turbulent transport reduction process, the breaking of turbulent eddies [13], in other words, the disappearance of the nonlocality in the core region.

3. Application of a transit time distribution analysis

As already shown in FIG. 2(a), the existence of the hysteresis loop on the flux-gradient space in the core region of the plasma with the NTP indicates several possibilities of changing in core heat transport, such as bifurcation and/or transition. Thus it is important to assess dynamic characteristics of the transport state in the core region during the NTP. In the turbulent heat transport of magnetically-confined toroidal plasmas, it is expected that there is a consistent relationship among the heat flux normalized by the density, the temperature and the temperature gradient, since the state of turbulence, which is mainly specified by the temperature and its gradient, determines the heat flux for the given temperature gradient and the temperature gradient is tuned by the externally-input heat flux. When there is a unique solution in the relationship, the temperature and its gradient are set uniquely with the given normalized heat flux. According to Fick's law, the proportionality coefficient between the normalized heat flux and the temperature gradient is defined as a thermal diffusivity. Consequently, in order to investigate the dynamic response characteristics of the transport state, a deviation probability of the temperature gradient against the perturbation is evaluated with a transit time distribution (TTD) for a certain window of the $-d\delta T_e/dr$, which can be interpreted as an index of the extent to which plasma can be attracted by a certain transport state. The example for evaluating the TTD of the $-d\delta T_e/dr$ is shown in FIG. 3. As an example phenomenon to be applied the TTD, a conventional phenomenon, a usual cold pulse propagation induced by the TESPEL injection as shown by FIG. 3(a), is chosen. Figure 3(b) shows the temporal behavior of the $-d\delta T_e/dr$ at ρ = 0.68 just around the time of the TESPEL

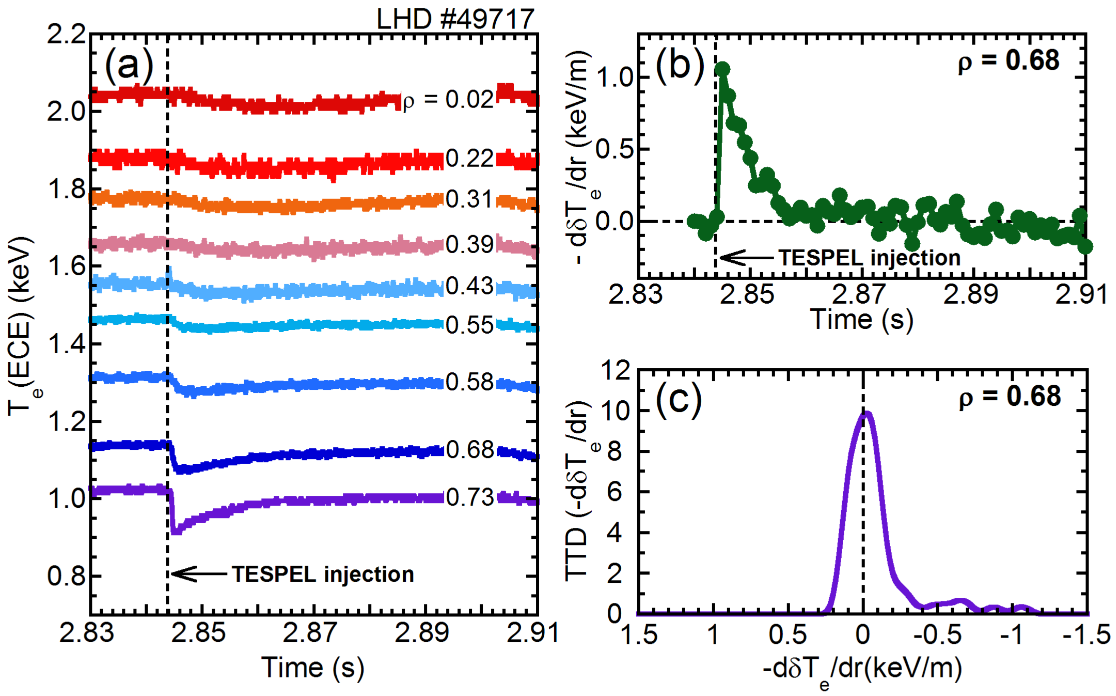

FIG. 3. Evaluation example for the transit time distribution (TTD) of the $-d\delta T_e/dr$ evaluated with the ECE diagnostics. Temporal evolutions of (a) the measured electron temperature at different normalized minor radii and (b) the evaluated electron temperature gradient at ρ = 0.68. The dashed line indicates the time of the edge perturbation. Just after the edge perturbation, the cold pulse propagation is appreciable in (a). (c) Transit time distribution (TTD) of the evaluated $-d\delta T_e/dr$ at ρ = 0.68.

injection, which is evaluated with an interval of 1 millisecond. Just after the TESPEL injection, the $-\mathrm{d}\delta T_e/\mathrm{dr}$ is suddenly increased and decreases gradually. And finally it goes back to the pre-injection level. The TTD of the $-\mathrm{d}\delta T_e/\mathrm{dr}$ at ρ = 0.68 is estimated with the temporal evolution of the $-\mathrm{d}\delta T_e/\mathrm{dr}$ before and after the TESPEL injection (t = 2.84 s ~ 2.91 s) and is shown in FIG. 3(c). As can be easily recognized in FIG. 3(c), the TTD of the $-\mathrm{d}\delta T_e/\mathrm{dr}$ shows a very sharp peak at the zero of $-\mathrm{d}\delta T_e/\mathrm{dr}$. This means that the original transport state at ρ = 0.68 is robust against the perturbation. Figure 4 shows the contour plot of the TTD of the $-\mathrm{d}\delta T_e/\mathrm{dr}$ at 20-ECE measuring points for the case of FIG. 3. In this case, as seen in FIG. 4, the original transport states at all the locations seem to be robust against the perturbation, although a very slight shift of the transport state is appreciable around ρ = 0.2 and 0.4. Indeed, after the cold pulse propagation, the plasma certainly goes back to the original state as shown in FIG. 3(a).

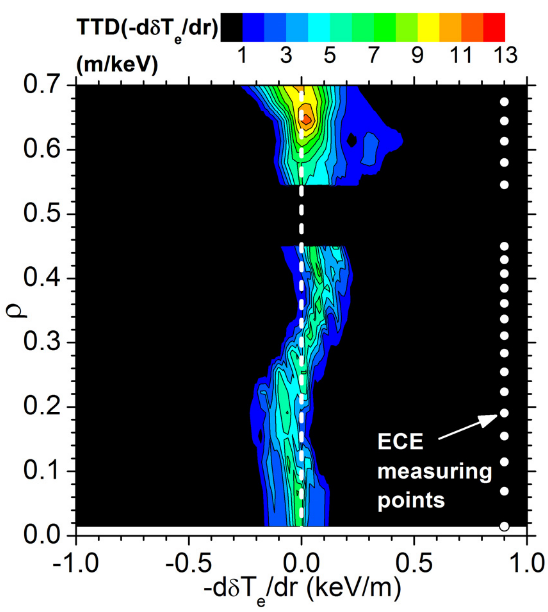

FIG. 4. Contour plot of the transit time distribution (TTD) of the evaluated $-d\delta T_e/dr$ at 20- ECE measuring points for the plasma with a diffusive propagation of the cold pulse (LHD #49717). The ECE measuring points are indicated by white circles.

Figure 5 shows the contour plot of the TTD of the $-d\delta T_e/dr$ at 20-ECE measuring points for the case of FIG. 1. Here, the $-d\delta T_e/dr$ data before (from t = 2.780 s) and after (until t = 2.887 s) the NTP, which is partly shown in FIG. 1(b), is analyzed. As seen in FIG. 5(a), around mark "A", there are two peaks corresponding to two transport branches. On the other hand, around mark "B", the TTD of the $-d\delta T_e/dr$ has a broad structure. In order to evaluate strength of attractor by a certain transport state more clearly, a new concept "transport potential" is introduced. Recently, this concept clearly succeeded to show the bifurcation of transport branch in LHD [12]. From the theoretical viewpoint, the transport potential is determined by the robustness of the transport equation that includes the turbulence condition. In the framework of the statistical theory of plasma turbulence, the transport potential can be expressed as –ln(TTD), since the TTD is almost equivalent to the probability distribution function of the transport state, which is determined by the magnitude of turbulence [14]. Figure 5(b) shows the transport potential profile in the edge region (ρ = 0.65). As shown in FIG. 5(b), the sharp peak at non-zero displacement of the $-d\delta T_e/dr$ clearly shows the existence of another transport branch again. This branch does not have a stronger attraction, compared with the original branch (at zero displacement), and thus the edge plasma can go back easily to the original branch. This can cause the backward second-order transition of the edge electron heat transport. On the other hand, a wide and shallow potential well is found to exist in the plasma core, as seen in FIG. 5(c). This demonstrates that various values of the dT_e/dr can exist despite a lack of another apparent transport branch. In light of the near lack of change in profiles of the density and heat deposition in the plasma core after the onset of the NTP, a high degree-of-freedom of turbulence condition in the plasma core is considered to be existed.

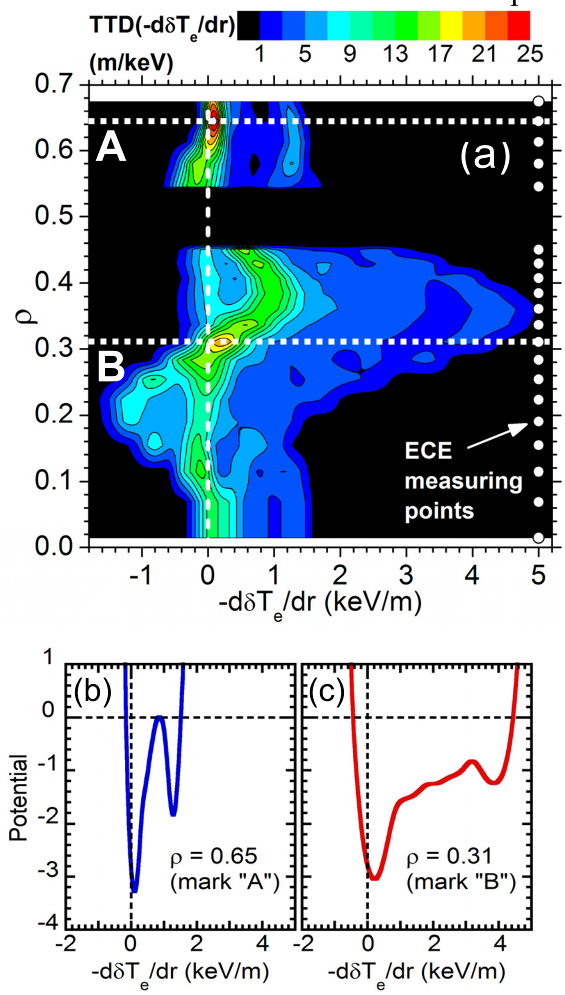

FIG. 5. (a)Contour plot of the transit time distribution (TTD) of the evaluated $-d\delta T_e/dr$ at 20-ECE measuring points for the plasma with the nonlocal transport phenomenon (LHD #49708). The ECE measuring points are indicated by white circles. Transport potential profiles, which are defined as –ln(TTD), (b) for ρ = 0.65 at mark "A" in (a) and (c) for ρ = 0.31 at mark "B" in (a).

4. Discussion and Summary

Based on the statistical theory of plasma turbulence, theoretical studies of the nonlocal response of heat transport have been developed [15]. In this framework, a global structure having a long radial correlation length, such as a zonal flow, can be a mediator for a nonlocal interaction between micro-turbulences that are widely separated. This is called "seesaw mechanism via zonal flows" [16]. This mechanism could be a candidate for forming the large scale coherent structures in electron heat transport. Lately, in LHD, such a global structure, low frequency temperature fluctuations with a long-range radial correlation were experimentally discovered [17] and its impact on the nonlocal transport phenomenon is investigated [18]. The initial analysis results seem to be promising, but further investigation is necessary to conclude that.

In conclusion, the detailed investigation on the characteristics of the electron temperature gradients revealed that the large scale coherent structures in the electron heat transport of both core and edge plasmas are existed in the plasma with the nonlocal transport phenomenon (an abrupt core electron temperature rise in response to the edge cooling) on LHD. At the onset of the nonlocal transport phenomenon, a first order transition of the electron heat transport is found to take place over a wide region (at least 6 cm wide) in the periphery of the plasma. At about the same time, over a wide region (about 10 cm wide) of the plasma core, a second order transition of the electron heat transport appears. The both large scale coherent structures are of a scale larger than a typical micro-turbulent eddy size (a few mm in this case). In order to assess dynamic characteristics of the electron heat transport state after the onset of the NTP, the transit time distribution analysis is applied to the temporal behaviors of electron temperature gradient. The analysis results more clearly show the existence of the large coherent structures in electron heat transport. Thus the NTP obtained in LHD is considered to be invoked by the interaction of those structures.

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