Evidence of Stochastic Region near a Rational Surface in Core Plasmas of LHD

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Abstract. Clear evidence of stochastization of the magnetic surfaces near a rational surface is observed in the core plasma with weak magnetic shear in the Large Helical Device (LHD) by applying heat pulses driven by modulated electron cyclotron heating (MECH). The stochastization of the magnetic surfaces is confirmed by the observation of flattening of electron temperature (T_e) profiles and very fast propagation of the heat pulse, which is in contrast to the slow heat pulse propagation observed in the T_e flat region of the nested magnetic island.

1. Introduction

A global stochastization of the magnetic surfaces is expected to be induced when the magnetic islands are overlapped and their width exceed a threshold in toroidal plasmas and typically take places in the core plasma in the reversed-field pinch (RFP)[1] and ergodic region near the plasma periphery with perturbation fields in tokamaks[2]. A stochastization of the magnetic surfaces has been considered to be important, because the partial stochastization of the magnetic surfaces due to perturbation fields can contribute the mitigation of Edge-Localized-Modes (ELMs). Moreover a spontaneous transition from the stochastic state to helical equilibrium in a RFP[3] and a bifurcation phenomena of a magnetic island at a rational surface in LHD[4] suggest the stochastization of the magnetic surfaces is a self-organized transition phenomena. In spite of the importance of the experimental confirmation of the stochastization of the magnetic surface, it is difficult to measure the stochastization of the magnetic surface directly and it is inferred from the magnetic field measured outside the plasma. Since the heat conductivity parallel to magnetic field is much larger than that perpendicular to magnetic field, the radial heat conductivity (heat diffusivity) should be extremely large. One piece of evidence of stochastization of the magnetic surfaces is the flattening of T_e profile, however, the flattening can occur due to the lack of heat flux crossing the magnetic flux as seen in the magnetic island even if the magnetic flux surface is nested inside.

In the cold pulse propagation experiment using Tracer Encapsulated Solid Pellet (TESPEL[5]) in LHD, slow pulse propagation of a cold pulse has been observed because of the relatively good heat transport in the nested magnetic island[6].In contrast, the heat pulse propagation should be very fast in the region of the stochastization of the magnetic surface, because there are no nested flux surfaces. In this paper, experimental confirmation of stochastization of the magnetic surface is carried out by the analysis of heat pulse propagation driven by modulated electron cyclotron heating (MECH) with a frequency of 39Hz and cold pulse propagation driven by TESPEL in the plasma with a flat T_e profile, which is observed when the magnetic shear at the rational surface measured with motional stark effect (MSE) spectroscopy[7] drops below a critical value.

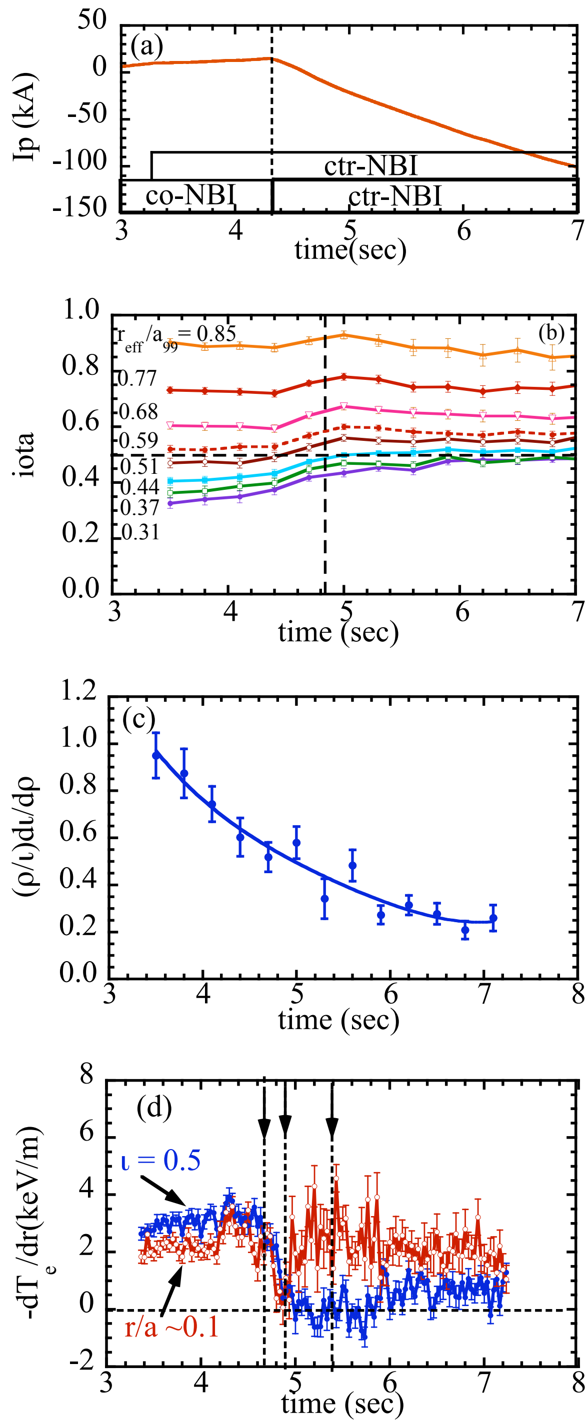

Fig.1 Time evolution of (a)toroidal net current, (b) rotational transform, (c) magnetic shear and (d) electron temperature gradient at a rational surface of ι = 0.5 and near the magnetic axis r_{eff}/a_{99} ~ 0.1) in the discharge, where the direction of NBI switched from balance to counter to equivalent plasma current at t = 4.3s.

2. Abrupt flattening of electron temperature during the drop of magnetic shear

As seen in Fig.1, when the direction of the NBI is switched from balanced to counter to equivalent plasma current, the rotational transform even increases due to the return current, although the edge rotational transform increases due to the non-inductive current by neutral beam current drive (NBCD). Then location of a rational surface of ι = 0.5 moves toward the magnetic axis and the magnetic shear at a rational surface of ι = 0.5 decreases from 1.0 to 0.2 as seen in Fig.1(c). When the magnetic shear drops to the critical value (~ 0.5), sudden flattening of electron temperature take places at the rational surface, as indicated by a sudden drop of electron temperature gradient at the $\iota \sim 0.5$ in Fig.1(d). The flattening of temperature extends to the plasma center as seen in the drop of electron temperature gradient near the magnetic axis at the $r_{eff}/a_{99} \sim 0.1$ (where a_{99} is minor radius flux averaged where the 99 % of stored energy is confined and it is 0.63m in this experiment). However, the flattening near the magnetic axis recovers as shown in the rapid increase of electron temperature gradient at the $r_{eff}/a_{99} \sim 0.1$ after t = 5.0 s. This observation clearly shows the complete flattening appears at the medium magnetic shear.

Figure 2 shows the radial profiles of T_e and the delay time of heat pulses driven by MECH at three time slices; just before the switching of NBI, a half second and one second after the NBI switch. There is no flattening region in the T_e profile before the NBI switch, when the magnetic shear at ι = 0.5 is high enough to heal the magnetic island as seen in Fig.2(a). However, after the magnetic shear drops below a critical value, the large core flattening of T_e up to half of plasma minor radius and partial flattening at one-third of plasma minor radius are observed as seen in Fig.2(b) and Fig.2(c), respectively. The sharp peak of electron temperature is due to the ECH focused to magnetic and therefore this sharp peak is not observed when there is no ECH.

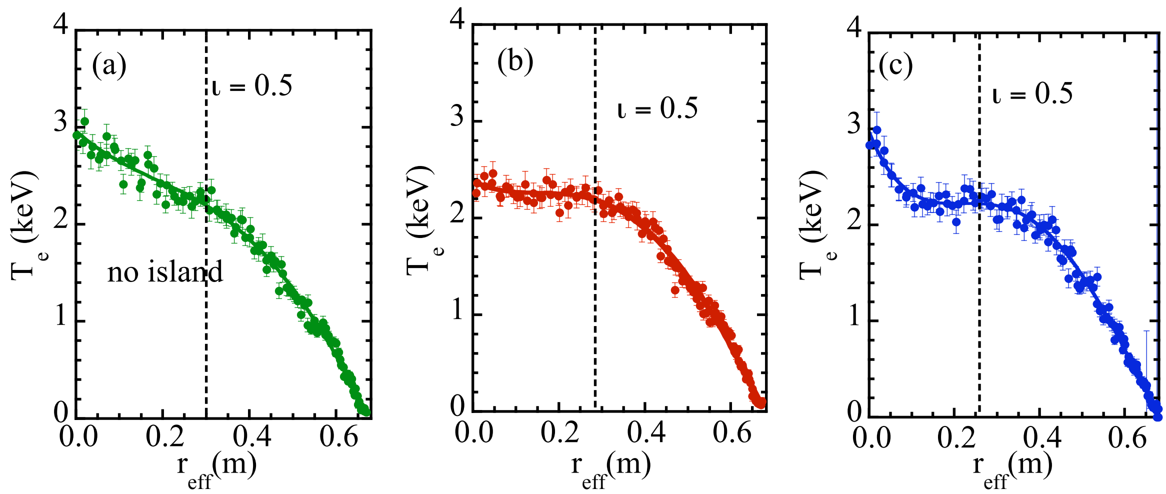

Fig.2 Radial profile of electron temperature with (a) no magnetic island (t=4.7s), (b) stochastic region (t=4.9s) and (c) m/n=2/1 magnetic island (near the O-point) (at t= 5.4s). The locations of rational surface of ι = 0.5 are indicated with dashed lines.

It is important issue whether there is a growth of MHD activity (interchange mode[8]) just before the even to temperature flattening. In this experiment, temperature fluctuation with the amplitude of > 1% is observed in ECE signal in the frequency range of 0.4 – 1.4kHz later in the discharge. However, there is no significant activity observed at the onset of electron temperature flattening as seen in the contour map of amplitude in Fig.3. The significant MHD activity of interchange mode appears at t = 5.8s at the half of the plasma minor radius (r_{eff}/a_{99} ~ 0.5), which corresponds to the shoulder of the temperature flattening region. It should be noted that no MHD activity is observed before or during the phase where the electron temperature gradients drops significantly at t = 4.8s as indicated in Fig.1(d). This fact suggests that the flattening of electron temperature is due to the formation of magnetic island or overlapping of magnetic islands rather than the growth of interchange mode.

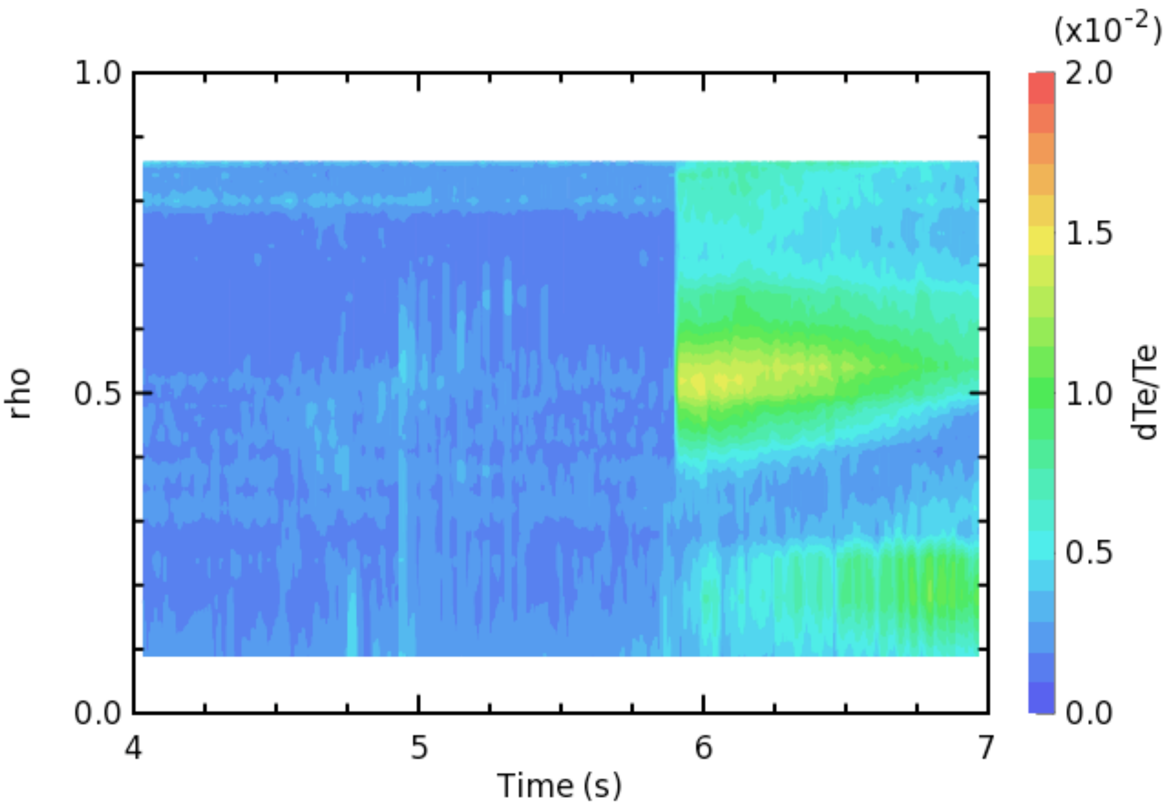

Fig.3 Contour of amplitude of fluctuation of electron temperature in the frequency range of 0.4 – 1.4kHz measured with ECE.

3. Heat pulse propagation experiment

The flattening of electron temperature is observed in the magnetic island, where the nesting magnetic flux exists. In general, the flattening inside the magnetic island is due to the lack of heat flux not due to the large thermal diffusivity, because the radial heat flux is localized at the X-point. The heat transport inside the magnetic island was studied by applying the heart pulse or cold pulse inside the magnetic island. In order to study the heat pulse propagation in the temperature flat region, the modulated electron cyclotron heating (MECH) with a frequency of 39Hz is applied to the plasma center.

3.1. Modulation power

As seen in Fig.4(a), the modulation power (square of amplitude of modulation) is peaked at the plasma center and it clearly show the power deposition of MECH is localized at the magnetic axis within $r_{eff}/a_{99} < 0.1$. When there is no magnetic island or no stochastic region, modulation power is peaked at the plasma center. When the temperature profiles are flat (Fig.4(b) and Fig.4(c)), the modulation power profiles are also flat. This is because the deposited power spread quickly in the wide region much faster than the time scale of transport in the nesting magnetic flux surface. The sharp peak of modulation power profile near the magnetic axis at t =5.4 sec indicate that the magnetic island does not extend to the magnetic axis, which is also consistent with the sharp temperature gradient near the magnetic axis observed in Fig.3(c).

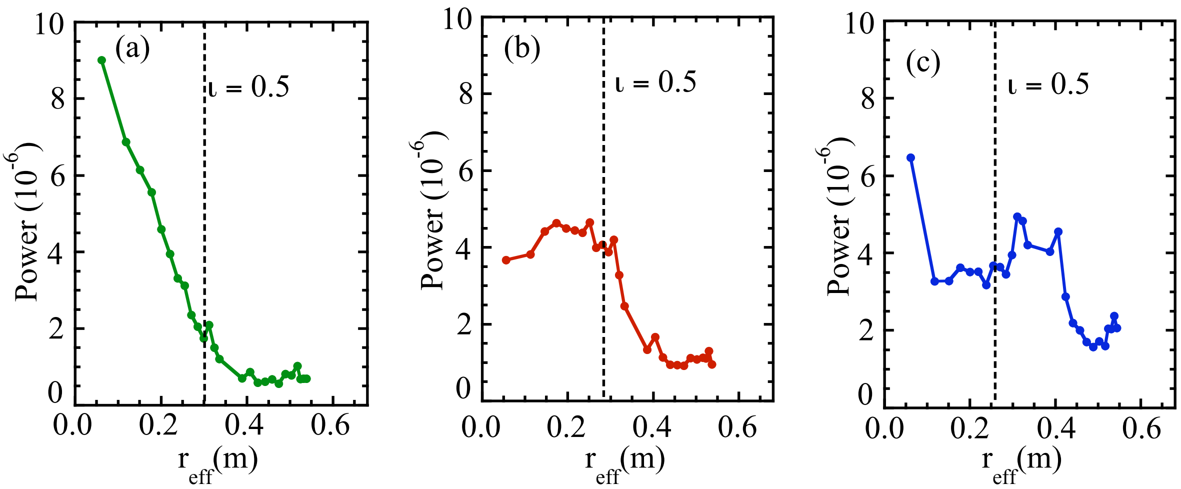

Fig.4 Radial profile of power of the heat pulse due to the modulated ECH in the plasma with (a) no magnetic island (t=4.7s), (b) stochastic region (t=4.9s) and (c) m/n=2/1 magnetic island (near the O-point) (at t= 5.4s). The locations of rational surface of ι = 0.5 are indicated with dashed lines.

3.2. Delay time

Although the radial profile of modulation power shows flattening in the region of temperature flattening both at t = 4.7s and t =5.4, there are significant difference in the radial profiles of delay time between these two time slices. Because the power deposition of MECH is localized at the magnetic axis, a heat pulse propagates from the plasma center toward the plasma edge (outward) when there is no magnetic island as seen in Fig.5(a). However, when there is flat region of T_e profile, the heat pulse propagates rapidly in the T_e flat region (no time delay within the accuracy of the measurements) as seen in Fig.5(b), which is a clear evidence stochastization of magnetic surface. This is contrast to that the slow propagation of the heat pulse observed in the partial flat region of T_e as seen in Fig.5(c).

The propagation of the heat pulse inside the m/n=2/1 magnetic island is bidirectional (inward and outward radially, from the magnetic island boundary to the magnetic island center at O-point) and is even slower than that outside the magnetic island because of better heat transport. It should be noted that the radial profile of delay time near the rational surface of $\iota \sim 0.5$ shows significant difference between the plasma at t =4.7 [Fig.5(b)] and at t = 5.4 s [Fig.5(c)], although the electron temperature and modulation amplitude profiles are somewhat similar. The peaked profile of delay time is an evidence of existence of nesting magnetic island, while the flat profile of delay time is an evidence of stochastic region due to the overlapping of magnetic island with higher mode number. The flat profile of delay time is observed in the plasma with the medium magnetic shear and is not observed afterword where the weak magnetic shear becomes weak. This fact also supports the hypnosis that the overlapping of magnetic island [9] causes the stochastization of magnetic field observed.

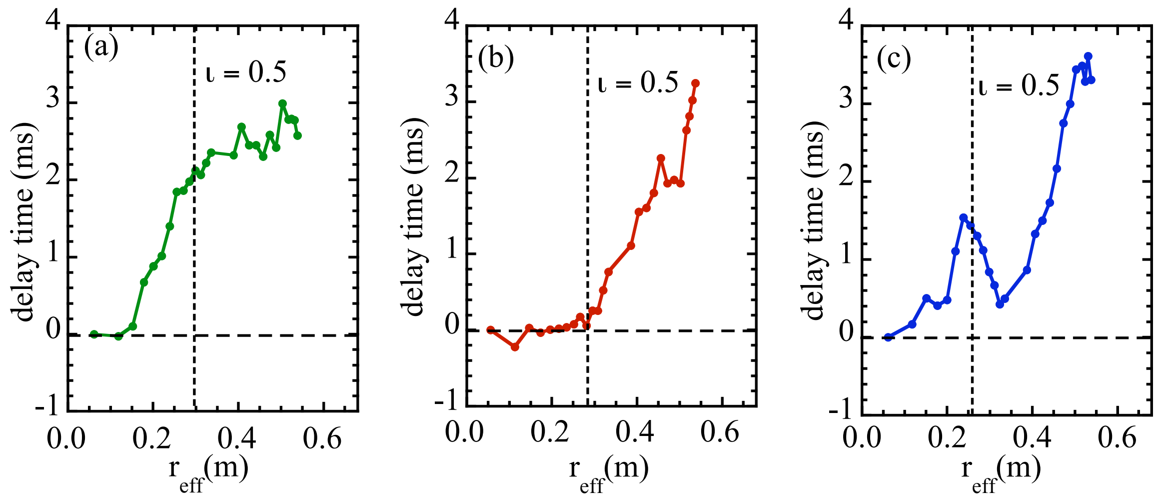

Fig.5 Radial profile of time delay of the heat pulse due to the modulated ECH in the plasma with (a) no magnetic island (t=4.7s), (b) stochastic region (t=4.9s) and (c) m/n=2/1 magnetic island (near the O-point) (at t= 5.4s). The locations of rational surface of ι = 0.5 are indicated with dashed lines.

4. Cold pulse propagation experiment

The cold pulse propagation experiment by TESPEL also gives consistent results. In order to produce a cold pulse inside or outside the magnetic island, a tracer encapsulated solid pellet (TESPEL) is injected into the LHD edge (TESPEL consists of polystyrene as an outer shell and tracer particles as an inner core. The TESPEL ablates within 1 ms and provides a cold pulse which propagates toward the magnetic axis. Figure 6 show the radial profile of electron temperature and time response of ECE signal to the TESPEL injection. Before the drop of magnetic shear there is no flattening of electron temperature in the temperature profile [Fig.6(a)], while a clear flattening of electron temperature is observed after the drop of magnetic shear [Fig.6(b)].

TESPEL is injected to these discharges in order to study the cold pulse propagation. Significant differences in cold pulse propagation are observed in this experiment. The propagation of cold pulse is very fast (< ms) in the region of T_e flat region, while it is relatively slow (a few ms) in the plasma with peaked T_e profile. Since there is no delay time of cold pulse observed in Fig.6(b), this flattening is due to the stochastization of magnetic flux not the formation of magnetic island, This observation is contrast to the previous work[6], where the bidirectional propagation of cold pulse are observed in the m/n = 1/1 magnetic island near the plasma edge.

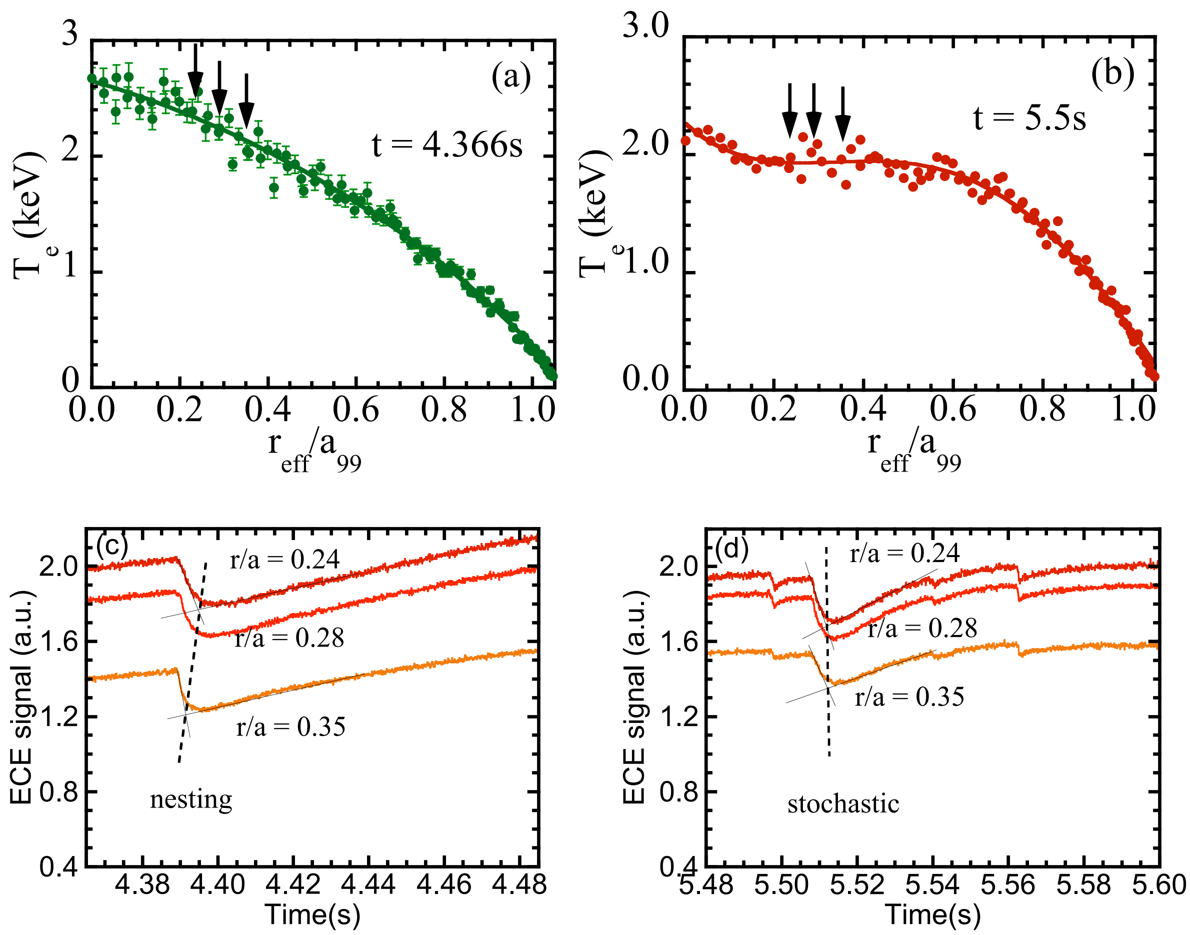

Fig.6 (a)(b) Radial profiles of electron temperature and (c)(d)time evolution of ECE signal at various radii (indicated with arrows in Fig(a) and (b)) in the discharge with TESPEL injection in the phase (a)(c) with no temperature flattening and (b)(d) with temperature flattening.

5. Summary

Clear evidence of stochastization of the magnetic surfaces near a rational surface is observed in the core plasma with weak magnetic shear in LHD by applying heat pulses driven by MECH. There are significant differences (slow and fast) in the heat pulse propagation at the electron temperature flat region in LHD between the plasma with medium magnetic shear and weak shear. A slow heat pulse propagation observed in the weak shear is an evidence of a nested magnetic island, while the fast heat pulse propagation observed in the plasma with medium magnetic shear is an evidence of stochastization of the magnetic surfaces. A cold pulse propagation driven by TESPEL also shows the fast pulse propagation, which is consistent with the heat pulse propagation experiments.

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