*32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, O-2.006 (2005)*

Transient transport analysis of improved confinement plasmas in LHD

K.Ida, S.Inagaki, R.Sakamoto, N.Tamura, K.Tanaka, H.Funaba, S.Morita, Y.Takeiri, K.Ikeda, T.Shimozuma, S.Kubo, C.Michel, T.Tokuzawa, O.Kaneko, A.Komori, O.Motojima and the LHD experimental group

National Institute for Fusion Science, 322-6 Oroshi, Toki, 509-5292, Japan

1. Introduction

In LHD, the thermal diffusivity depends on temperature rather than on the temperature gradient in the inner region of the plasma (r < a/2), which is in contrast to tokamaks in which the dependence on the temperature gradient is stronger. Therefore the thermal diffusivity driven by transient transport with heat propagation is similar to the steady state transport analysis given by the so-called power balance analysis in the core plasma in LHD. However, the global energy confinement scaling, which represent the transport characteristics outer region of the plasma (r > a/2) shows the parameter dependence of $\iota_E \propto (n/P)^{0.6}$ which is predicted by the gyro-Bohm transport with strong temperature dependence of $\chi_e \propto T^{1.5}$. These facts suggest that there are two transport, one has a weak temperature gradients which is dominant in the inner region of the plasma, the other has a strong temperature dependence which is dominant in the outer region of the plasma. The transient transport analysis have been done for the plasmas with improved confinement in LHD using cold pulse propagation with a plastic pellet, heat propagation with modulated ECH and transport analysis between repetitive pellets. The transport characteristics in the inner region is investigated with the cold pulse propagation and ECH modulation technique, while the transport characteristics in the outer region is investigated by repetitive pellets.

In this paper, two types of bifurcation of transport are discussed based on transient transpot analysis. One is bifurcation from the L-mode to the electron internal transport barrier (ITB), which is characterized by peaked electron temperature profiles associated with the transition from ion root (negative Er) to electron root (positive Er) when electron cyclotron heating is applied to a low density NBI plasma. The other is a bifurcation from L-mode to the pellet enhanced confinement mode, which is characterized by an increase of global energy confinement time by a factor of 1.5.

2. Bifurcation of transport associated with the electron ITB in the inner region of the plasma

Associated with the formation of ITB, a significant drop of thermal diffusivity near the plasma center (ρ < 0.3) is observed both the steady state transport analysis (power balance) and transient transport analysis (cold pulse) as seen in Fig.1. Without a formation of ITB, there is no drop of thermal diffusivity and thermal diffusivity is relatively high ($10m^2/s$) at the plasma center.

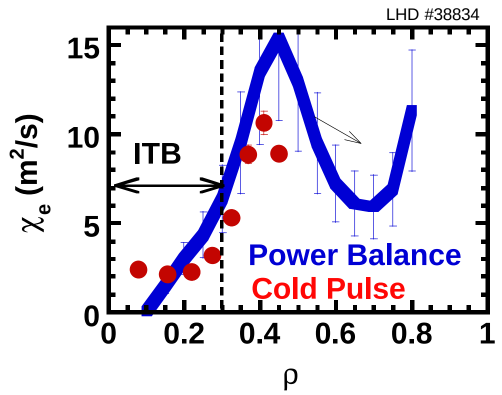


Fig.1 Radial profile of thermal diffusivity estimated from cold pulse and steady state power balance analysis

In the region where ITB appears, the bifurcation phenomena of electron transport is observed. The drop of local heat flux associated with the spontaneous rise of electron temperature is one of the evidence of bifurcation characteristics, because the temperature gradient increases although the heat flux decreases. Figure 2 shows the spontaneous temperature rise after the TESPEL injection. The heat flux near the plasma center drops significantly just after the injection then the increase of temperature gradient with constant heat flux indicated the good transport state sustains transiently (up to B) then the plasma goes back to the original transport (after D). This experiment shows there are two state of transport (B and D) exists because the heat flux is different even for the same temperature gradients. The location where the drop of heat flux due to the bifurcation has maximum is ρ = 0.3 – 0.4, which is consistent with that the ITB appears near the plasma center (ρ < 0.3).

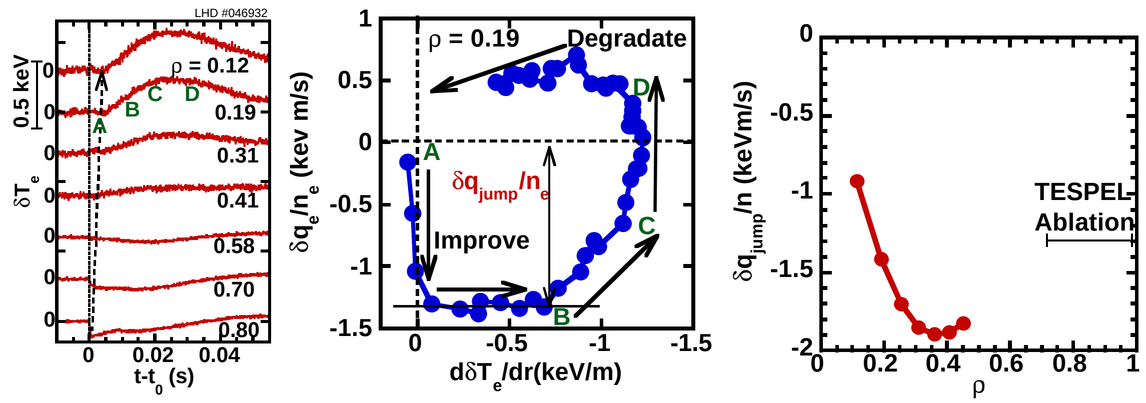


Fig.2 (a) Time evolution of electron temperature after the TESPEL injection and (b) heat flux normalized electron density as a function of temperature gradient 0.005-0.05sec after the TESPEL injection at ρ = 0.19 and (c) radial profile of jump of the normalized heat flux.

3 Bifurcation between gyro-Bohm and weak T_e transport in the outer region of the plasma

The relation between the heat flux normalized by the electron density and temperature gradient is investigated by taking advantage of perturbation of density by repetitive pellet injection. As seen in Fig.3, there are three phases are observed after each pellet injection. Just after the pellet injection the heat transport has weak temperature gradient dependence in the first phase. Then the plasma shows slow phase transition to the transport which has strong temperature gradient dependence. During the phase transition, a negative transient thermal diffusivity $d(Q/n_e)/d(dT_e/dr) < 0$ appears, which is clear evidence of phase transition associated with the bifurcation of two transport,

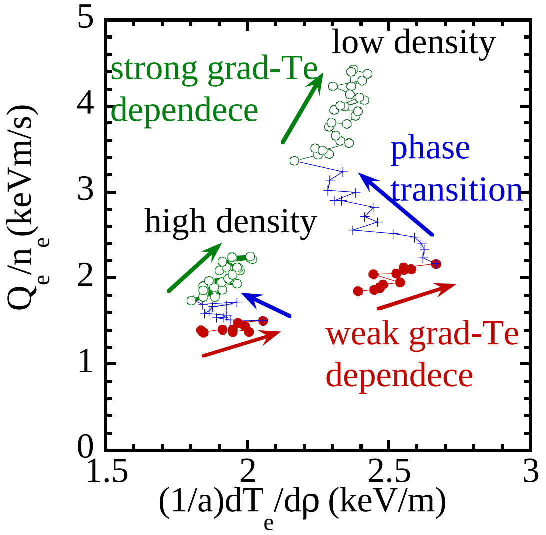


Fig.3 Heat flux normalized electron density as a function of electron temperature gradient 0.06-0.17sec (open circles), 0.17-0.33sec (cross) 0.33-0.57sec (open circles) after the pellet injection at ρ = 0.7.

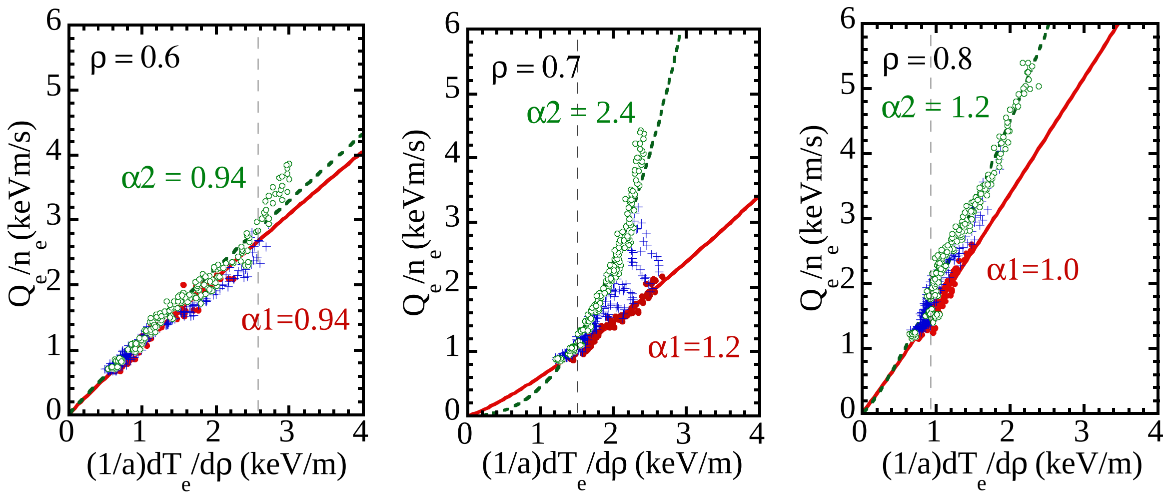
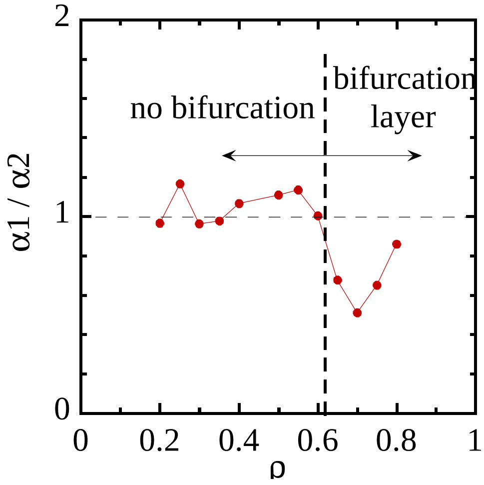


Fig.4 Heat flux normalized electron density as a function of electron temperature gradient 0.06-0.17sec (open circles), 0.17-0.33sec (cross) 0.33-0.57sec (open circles) after the pellet injection at ρ = 0.6, 0.7 and 0.8. The dashed and solid lines are fitting curves with $Q/n_e = [(1/a)(dTe/d\rho)]^{\alpha}$, where α is temperature dependence coefficient and before (α1) and after (α2) the phase transition, respectively.

It is interesting that there are two state of transport as shown in Fig.4. One is the transport which has strong temperature gradient like gyro-Bohm transport or critical temperature gradient transport and the other is the transport with weak temperature gradient dependence, which is observed in the high density plasma, where the temperature gradient is small. Before the pellet injection the plasma is in the sate of higher heat flux (dashed line). After the pellet injection the plasma goes to the lower heat flux state (solid lines), and the plasma shows spontaneous phase transition as described above and goes back to the higher heat flux state. It is interesting that the two state exist only higher temperature gradient region and there is only one state below the critical temperature gradient for merging the two states.



Therefore the bifurcation can occur where the temperature gradient exceed the critical temperature gradient. The critical temperature decreases towards the plasma edge. Therefore the bifurcation layer appears near the plasma edge for $\rho > 0.65$ as seen in Fig.5. As the normalized heat flux is increased by the increase of heating power or the decrease of electron density, the temperature gradient increases and the bifurcation layer extend to inward.

4 Summary

The transient transport analysis applied to the improved modes in LHD clearly show a bifurcation characteristics both in the inner and outer region of the plasma. The transient bifurcation of transport appears in the inner region of the plasma ($r < a/2$) after the TESPEL injection as a drop of heat flux associated with the spontaneous rise of electron temperature. in the with ITB and also outer region of the plasma in the pellet enhanced mode. The region where the bifurcation appears is consistent with the region where the ITB appears. The other bifurcation between gyro-Bhom transport and a weak temperature dependent transport is observed after the repetitive pellet injection in the outer region of the plasma [$r > (2/3)a$]. The time trace of heat flux and temperature gradient shows a negative transient thermal diffusivity, which is a clear evidence of bifurcation of transport.