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Transient Response of Electron Temperature to Abrupt Plasma Edge Cooling on LHD

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Abstract

In the Large Helical Device, the tracer encapsulated solid pellet (TESPEL) injection has succeeded to induce electron temperature perturbations. The TESPEL decreases electron temperature locally. A small electron temperature perturbation (cold pulse) then propagates inwardly and thus it is separated from the cooling source. The electron heat diffusivity obtained from the cold pulse propagation was the same order as the electron heat diffusivity, which was estimated from the power balance analysis.

Keywords:

transient response, TESPEL, cold pulse, temperature perturbation, ECE

1. Introduction

The perturbative transport analysis, in which the dynamic response of the plasma to a perturbation is considered, can obtain the local transport coefficient. The value obtained from transient analysis, however, is often different from the one obtained from the steady-state (power-balance) analysis in a Tokamak [1]. The transient analysis usually gives a larger value. A dependence of the transport coefficient on the temperature gradient is one of the candidates used to explain this enhancement of the transport coefficient. Such a dependence on the temperature gradient leads to power degradation of energy confinement. In small-middle sized helical systems, the power degradation has been observed, however, such an enhancement of transport coefficient has not been observed [2]. Thereby, it is hoped that perturbative transport analysis in the large helical device (LHD) will clarify whether the transient transport coefficient is enhanced in a helical plasma. The dependence of the transport coefficient on the temperature gradient may be a result of turbulence driven by electron and/or ion gradients. Thereby the difference in turbulence between Tokamaks and helical systems may explain the discrepancy between the transient analysis and the steady-state analysis observed in Tokamaks but not in small-middle sized helical systems. The LHD can produce the net-current free plasmas with a wide range of gradient. Thus, the results from the LHD experiments are very important for understanding the transport mechanism common to all toroidal plasmas. In this paper, the first result of the transient analysis in LHD using the cold pulse propagation is presented and its validity is discussed.

To induce electron temperature perturbations in LHD, tracer encapsulated solid pellets (TESPEL) are injected. The cold pulses thereby are generated in the edge region of LHD. The local heat diffusivity is estimated from the propagation feature of the cold pulse. As regards diagnostics, good temporal and spatial

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resolutions are prerequisite. The electron temperature measurement by electron cyclotron emission (ECE) suits these requirements (time resolution is 0.01ms and spatial resolution is about 0.02 m). A 32-channel heterodyne radiometer is used to track the small electron temperature perturbations. The 2nd harmonic of the X-mode is optically thick in this experiment. Each radiometer channel is calibrated relative to Thomson scattering measurement on similar NBI plasmas.

2. Transient Analysis

Small perturbations of temperature, $\delta T_e(r,t)$, and density, $\delta n_e(r,t)$ are considered. The mass conservation and energy conservation equations for the electron perturbations can be written as [3],

$$\frac{\partial \delta n_e}{\partial t} = -\nabla\left(\delta\Gamma_e\right) + \delta S_p, \qquad (1a)$$

$$\frac{3}{2}n_e\frac{\partial \delta T_e}{\partial t} + \frac{3}{2}T_e\frac{\partial \delta n_e}{\partial t} = -\nabla\left(\delta q_e + \frac{5}{2}T_e\delta\Gamma_e\right) + \delta S_h, \qquad (1b)$$

$$\delta\Gamma_e = -D\frac{\partial\,\delta n_e}{\partial r}, \qquad (1c)$$

$$\delta q_e = -\,n_e\,\chi\,\frac{\partial \delta T_e}{\partial r}, \qquad (1d)$$

where δS_p is the perturbation of the particle source and δS_h is the perturbation of the heat source including the change in radiation loss and electron-ion energy exchange loss. The scale length of the perturbations is assumed to be much smaller than the equilibrium scale length in these equations. The convective term can be neglected if $D < \chi$, $\delta n_e/n_e < \delta T_e/T_e$ and the scale length of the temperature perturbation is less than that of density perturbation. If the perturbations of particle source and heat source are negligible, the equation (1) in a cylindrical geometry can be written in essential form:

$$\frac{3}{2}n_e\frac{\partial \delta T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\,n_e\,\chi\,\frac{\partial \delta T_e}{\partial r}\right). \qquad (2)$$

3. Experimental Results

The TESPELs are injected to NBI plasmas on LHD, which have the following parameters: NBI power ~ 2 MW, R_{ax} = 3.5–3.6 m, B_{ax} = 2.75–2.95 T, minor radius ~ 0.6 m, n_e = 1–2$\times$10^{19} m^{-3}, $T_e(0)$ ~ 2 keV, τ_E ~ 0.15 s. The time evolutions of stored energy, line averaged electron density, local electron temperature and ablation light during typical TESPEL injection are shown in Fig. 1. The change in the stored energy is less than 3% and the total input power is constant and thereby the global confinement is not affected by TESPEL injection. After TESPEL ablation, the line averaged density increases about 10%. This increase is consistent with the contribution from the total electrons brought to the plasma by the TESPEL. The TESPELs typically penetrate into the radial region of r/a ~ 0.6, which are estimated from TESPEL velocities and ablation durations (~1 ms). They provide cold electrons and impurity ions and thus reduce the electron temperature. The cold pulses resulting from the cooling

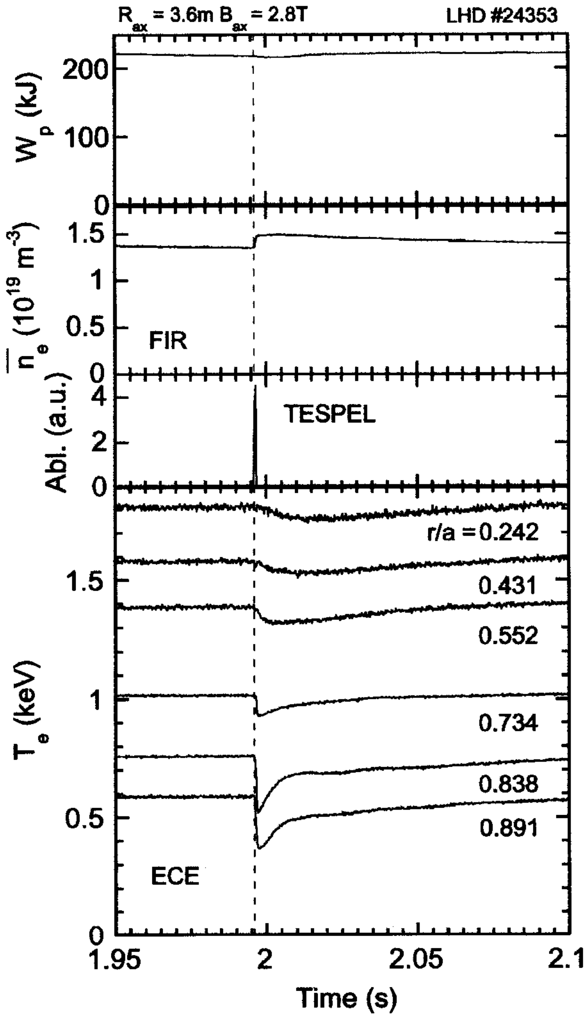

Fig. 1 Typical time evolution of plasma perturbations derived by the TESPEL injection.

of plasma traveled inward on a time-scale of 10 ms as shown in Fig. 1. The relative T_e perturbation is 3–5% in the region of interest ($r/a < 0.6$). The time evolutions of the radial profile of electron density and radiation loss are shown in Fig. 2. A typical error of the local density is estimated from the accuracy of the Abel inversion. The local electron density increases in the ablation region ($r/a > 0.6$) while it doesn't change in core region within the accuracy of the Abel inversion. This suggests that the density perturbation is less than the temperature perturbation in the region of $r/a < 0.6$. Moreover, the typical particle diffusivity ~ 0.1 m^2/s, which is obtained from gas-puff modulation experiments, is much smaller than the typical heat diffusivity ~ 1–3 m^2/s [4], and therefore the convection is neglected. The radiation loss is also unaffected in the region of interest ($r/a < 0.6$). The perturbation of particle source and heat source are therefore negligible in this region. Hence eq. (4) is used in the transient analysis.

4. Simulation Results

The perturbation equation is solved numerically and compared with the experimental result to estimate the heat diffusivity. For simplification, the heat diffusivity is assumed to be homogeneous. The density profile is flat in the core region and thereby eq. (2) is reduced to the simplest form:

$$\frac{\partial \delta T_e}{\partial t} = \frac{2}{3}\chi \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \delta T_e}{\partial r}\right). \qquad (3)$$

The eq. (3) is solved by using experimental data at $r/a = 0.552$ as a time dependent boundary. The heat diffusivity is determined to minimize the sum of squares of the difference between the simulation result and the experimental result. The best fit is obtained when χ is 3.3 m^2/s and the simulation result is shown in Fig. 3. The experimental result is also shown in Fig. 3. The simulation is in good agreement with the experimental

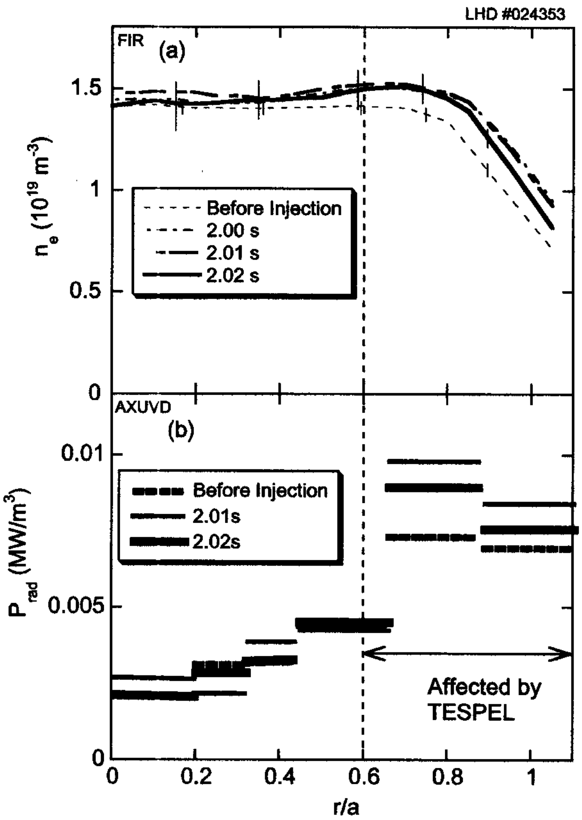

Fig. 2 Radial profiles of (a) electron density and (b) radiation power density.

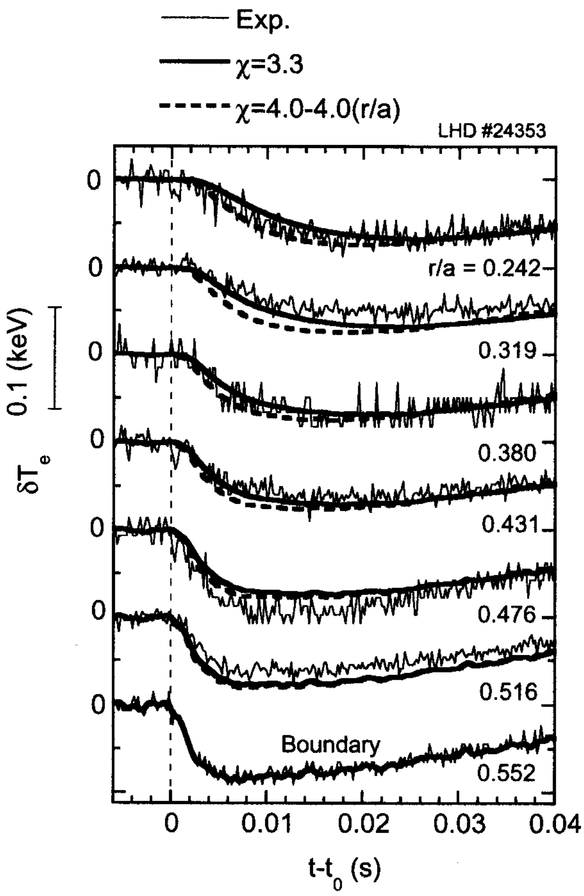

Fig. 3 Time evolution of electron temperature measured with heterodyne radiometer. The TESPEL is injected at $t = t_0$. The simulation results are also shown.

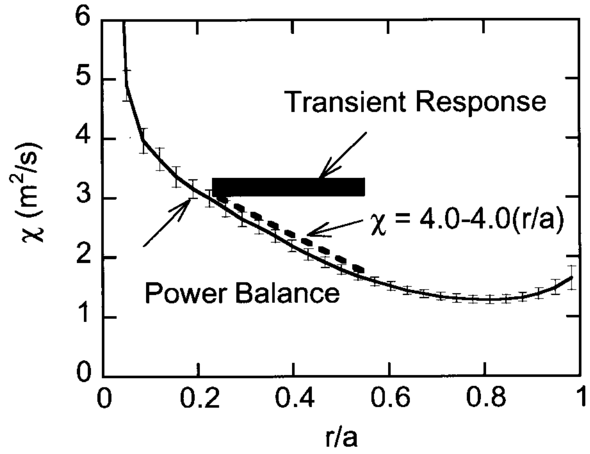

Fig. 4 Comparison between the transient analysis and the power balance analysis.

result. The transient analysis should be compared with the power balance analysis to see whether the transient transport coefficient is enhanced in LHD. The radial profile of electron heat diffusivity, which is determined from the power balance analysis, is shown in Fig. 4. The equilibrium T_e and n_e profiles just before the TESPEL injection are used and the beam power deposition profile is calculated numerically in the power balance analysis. The difference in magnitude of χ between the transient analysis and the power balance analysis is small in the region of $0.552 \le r/a \le 0.242$. The power balance χ is written as $\chi = 4\text{–}4(r/a)$ in the region of $0.552 \le r/a \le 0.242$ and the simulation using this model of χ is also shown in Fig. 3 to compare the transient analysis with the power balance analysis more directly. The simulation result does not differ greatly from the experimental result. However, the homogenous model is better than the power balance model as shown in Fig. 3. This may suggest that the transient analysis gives the radial profile of χ different from the power balance analysis in the LHD. The heat diffusivity from transient analysis may depend on the employed model of χ. A more suitable model is left to future work. It must be emphasized still that the agreement between the magnitude of χ from the transient analysis and the power balance analysis indicates that the propagation of cold pulse can be explained by the heat diffusive nature.

5. Discussion

The Tokamak like power degradation has been observed in LHD [5]. And thus the enhancement of the transport coefficient determined from transient analysis is expected. However an enhancement of heat diffusivity has not been observed in the cold pulse experiments on LHD. In W7-AS, the same value for the electron diffusivity was found from power balance and transient analysis [2]. Instead of a local model, the global model of χ is employed to interpret the observed power degradation in W7-AS [2]. Unfortunately the first experiments of cold pulse have been carried out under a low heating power and therefore the experimental data are insufficient to compare with theoretical models in LHD. In the near future it is expected that further experimental work will be carried out.

6. Summary

To understand the transport in magnetically confined thermonuclear plasmas, the transient transport analysis is important as well as the steady-state transport analysis. In the Large Helical Device, the TESPEL is injected to induce electron temperature perturbations. The TESPEL typically affects the radial region of $r/a > 0.6$. The cold pulse resulting from the cooling of the edge plasma propagates inwardly in the region of $r/a > 0.6$, while the electron density and other parameters are essentially unaffected in this region. The cold pulse is separated from the cooling source and radiating source, and hence the simple model is used to simulate the electron temperature perturbations. The electron heat diffusivity obtained from the simulation method is the same order as the electron heat diffusivity, which is estimated from the power balance analysis.

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