J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 489–491

Comparison of Empirical Transport Models with Transient Transport Experiments in LHD

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(Received: 12 December 2003 / Accepted: 17 June 2004)

Abstract

A study of the electron transport in helical plasma of Large Helical Device (LHD) has been performed using a perturbation to an equilibrium state. The periodic perturbation in plasma is induced by on-axis Electron Cyclotron Heating (ECH) modulated signal for different temperatures of plasma electron. The experimental data are compared with results from simulation within framework of the diffusive model with additional convective term. The convection heat flux is introduced to describe the heat propagation in LHD. It has been shown that the dynamic plasma heat diffusivity coefficient χ_e estimated from the transient analysis becomes larger with increasing electron temperature in LHD plasma.

Keywords:

heat diffusivity, temperature perturbation, perturbative transport, Large Helical Device, Electron Cyclotron Heating

1. Introduction

The understanding of transport of charged particles is important to improve the plasma confinement in the toroidal fusion devices but at present time it is not sufficiently understood yet. The study of the electron heat pulse propagation has been widely used to obtain information about local transport coefficient in Tokamak and Stellarator plasmas [1-3]. This paper describes a comparison of the experimental data on heat pulse propagation with simulation results in the case of Large Helical Device.

One of the methods for the measurement of the local heat transport coefficients is the study of the space-time evolution of a temperature perturbation of plasma. Such kind of perturbation could be introduced in plasma by various ways. In the present paper the local transport in plasma is studied by introducing ECH modulated signal. Modulated ECH signal (MECH) is a good tool for perturbative heat transport study because it perturbs almost only electron temperature T_e and has well localized deposition of the heat in space.

2. Method and analysis technique

The MECH power deposition is localized in the center of plasma (r/a < 0.2) thus the heat source can be neglected for the study of heat pulse propagation in the region r/a < 0.2. The observed temperature fluctuations induced by ECH modulation heating are small (typically $\delta T_e(r,t) \ll 0.1\ T_e(r,t)$), thereby one can apply the transport equation in case of perturbed heat propagation without perturbed source, which can be written as:

$$\frac{3}{2}\frac{\partial n_e\,(\delta T_e)}{\partial t} = -\nabla\delta q_e, \tag{1}$$

where n_e is electron density of plasma, δq_e is the perturbated electron heat flux. The heat flux carried by electrons is expressed in common form as $q_e = -n_e\chi_e\nabla T_e$, where χ_e is electron heat diffusivity coefficient. In the case of ECH modulation heating the gradient length of perturbation is assumed much smaller than that of unperturbed profiles, therefore the highest spatial derivatives will not be taken into account [4]. The gradient length of temperature perturbation is assumed to be much larger than density perturbation, thus the electron heat flux could be written in simple form:

$$\delta q_e = -n_e\chi_e\nabla T_e. \tag{2}$$

Taking into account these assumptions and supposing that the particles source perturbation is negligible, the equation (1) in the case of cylindrical geometry takes next form:

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$$\frac{3}{2}n_e\frac{\partial(\delta T_e)}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(rn_e\chi_e\frac{\partial\delta T_e}{\partial r}\right). \quad (3)$$

The Crank Nicholson second order finite difference scheme is used to solve this equation.

The equation for the propagation of heat perturbation (3) is solved numerically with boundary condition at the plasma edge $\delta T(a,t) = 0$, where a is plasma radius. The heat diffusivity coefficient is selected by minimizing the sum of square of difference between result of simulation u and experimental data δT_e. The sum of square of difference is taken with weight coefficients for every channel:

$$S=\sqrt{\sum_{i,j} w_i\,(u_{i,j}-\delta T_{e\,i,j})^2} \quad (4)$$

where the weight coefficient wi is reciprocal of perturbation amplitude for i-channel and j is the index in time.

3. Simulation results and discussion

The perturbative studies described in this paper have been carried out on Large Helical Device dealing with two different scenarios of power deposited in plasma. Heat pulse propagation is introduced in NBI heated plasma of LHD by additional on-axis ECH power (400 kW) with 20 Hz modulation (MECH experiments). The plasma parameters for the discharge #45475 are next: NBI power ~ 2.5 MW, $n_e \cong 2. \times 10^{19}$ m^{-3}, $T_e(r = 0) \cong 1.6$ keV and for the discharge #45474 ~ 5 MW, $n_e \cong 2. \times 10^{19}$ m^{-3}, $T_e(r = 0) \cong 2.1$ keV. Plasma minor radius ~ 0.6 m, major radius $R = 3.5$ m and magnetic filed on major axis ~ 2.8 T.

For simulations the heat diffusivity is supposed to be homogenous in radial direction. Under such assumption the best agreement of simulation result with experimental data is obtained when $\chi_e = 2.9$ m^2/s (pulse #45475) and $\chi_e = 5.5$ m^2/s (pulse #45474). The profiles of the perturbation amplitude A and phase φ are shown in Figs. 1 and 2 for the simulation and experimental results. The simulation result is not in a good agreement with experiment. Even if we try to attain best fitting of phase by selecting appropriate χ_e the amplitude of perturbation will remain in disagreement with experiment. So, on the basis of this simple model it is not possible to fit both amplitude and phase simultaneously.

To describe such amplitude behaviour the additional effective convection flux [5] is introduced in equation (2)

$$\delta q_e = -n_e\chi_e\nabla\delta T_e + n_eV_e\delta T_e. \quad (5)$$

The transport equation for perturbed heat propagation (3) in this case should be rewritten as

$$\frac{3}{2}n_e\frac{\partial(\delta T_e)}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(rn_e\chi_e\frac{\partial\delta T_e}{\partial r}-rn_eV_e\delta T_e\right) \quad (6)$$

here V_e is convection velocity.

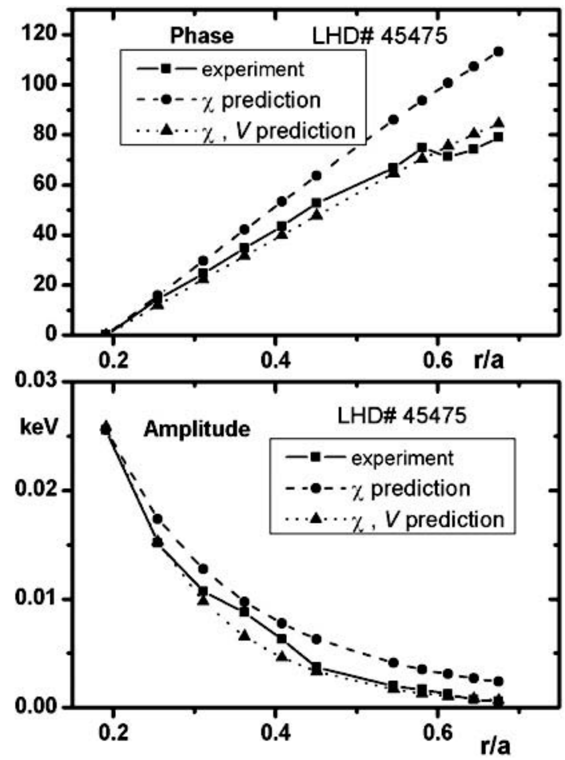

Fig. 1 Profile of φ and A for discharge #45475.

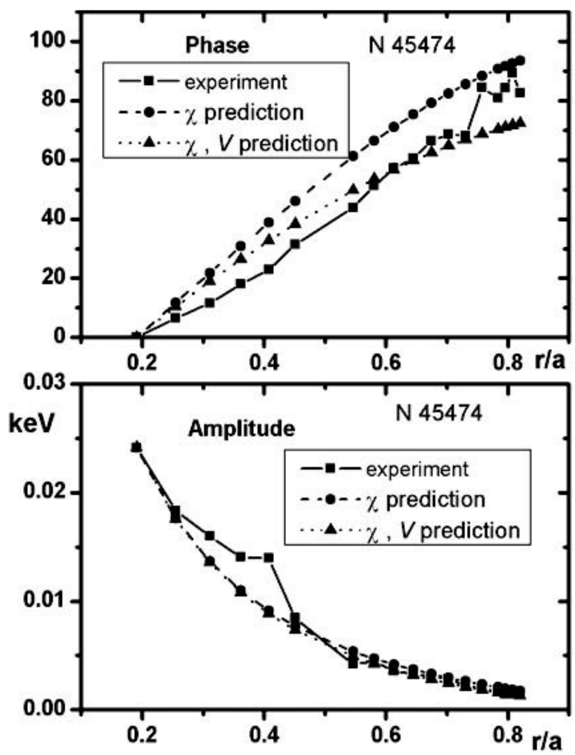

Fig. 2 Profile of φ and A for discharge #45474.

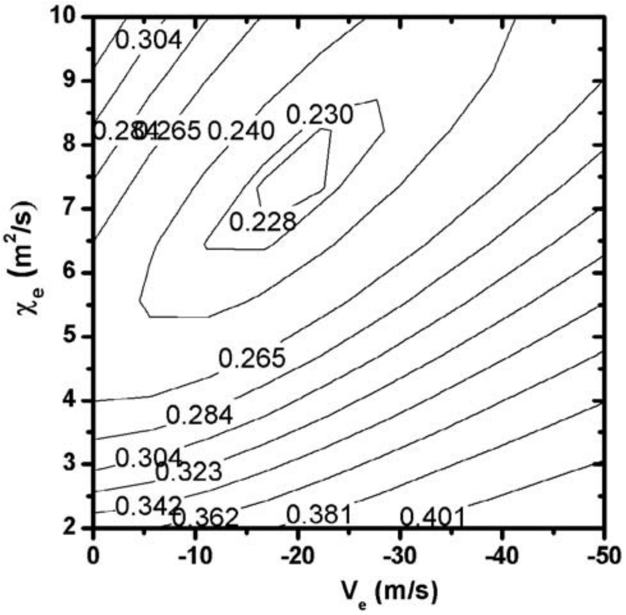

Fig. 3 A contour plot for the sum of square of difference S.

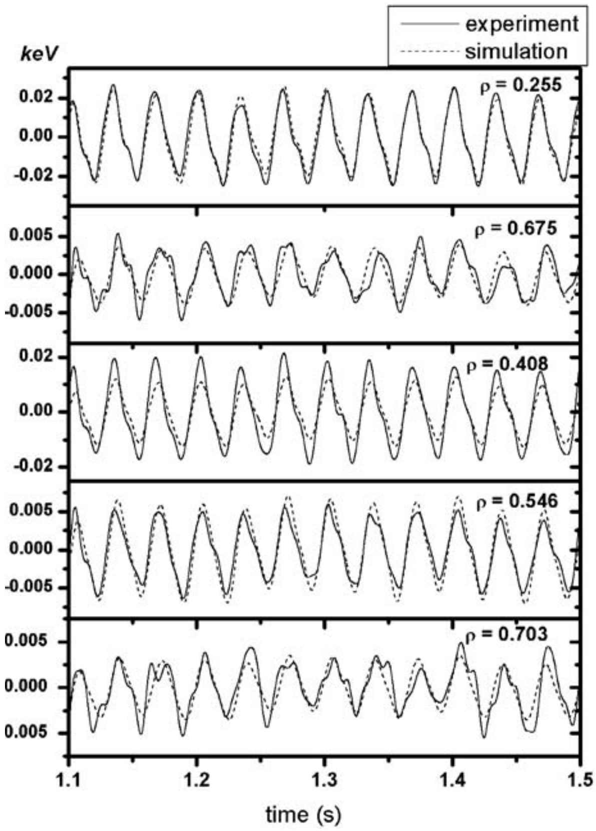

Fig. 4 The time evolution of temperature perturbation for discharge #45474 at different channel $\rho = r/a$.

The heat diffusivity coefficient and convection velocity for this case are also determined to minimize the sum of square S of difference between result of simulation and experimental data. The heat diffusivity and convection velocity are supposed to be homogeneous. The contour plot for S (pulse #45474) is presented in Fig. 3. The predicted values for heat diffusivity and convection velocity are χ_e = 4.8 m²/s , V_e = –30 m/s (pulse #45475) and χ_e = 7.3 m²/s, V_e = –17 m/s (pulse #45474). The profiles of the perturbation amplitude and phase for predicted values of heat diffusivity and convection velocity are plotted in Figs. 1 and 2. One can compare the results from two models. The simulation result from the model based on χ_e and V_e looks much closer to experiment than simulation result from the model based on only heat diffusivity. The time evolution of propagation of heat perturbation is shown in Fig. 4 for different positions at plasma radius. It demonstrates the good agreement between simulation result and experiment.

The comparison of evaluated heat diffusivities indicates the dependence of heat diffusivity on electron temperature in plasma. The heat diffusivity χ_e in the higher temperature plasma is 1.5 times larger than that in the lower temperature plasma. The difference in the heat diffusivities can be expected by the Gyro-Bohm like dependence of χ_e i.e. $\chi_e \sim T_e^{\alpha}$ with $\alpha = 3/2$. The heat diffusivity that obtained from transient analysis is much larger than the neoclassical diffusivity $\chi_e^{NC} \approx 10^{-2}$ m²/s as well as power balance analysis. The heat diffusivity obtained from the transient analysis is not consistent with neoclassical diffusivity not only magnitude but also T_e dependence. A turbulence model, which can explain the observed T_e dependence of χ_e is left for future work.

4. Summary

The heat transport in LHD plasmas is investigated by using the transient analysis for the periodic in time electron temperature perturbation induced by modulated ECH. The diffusive model with additional convective term is used to simulate electron temperature perturbation in plasma. The simulation result indicates that the convective term may be essential to explain the observed the heat pulse propagation because the simple diffusion model (no convection term) can not explain the amplitude of the heat pulse. The Gyro-Bohm like T_e dependence of χ_e is observed in LHD.

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