Proceedings of ITC/ISHW2007

Electron Thermal Energy Transport Research Based on Dynamical Relationship between Heat Flux and Temperature Gradient

Takashi NOTAKE[1], Shigeru INAGAKI[2], Naoki TAMURA[3], Shin KUBO[3],
Takashi SHIMOZUMA[3], Kenji TANAKA[3], Takeshi FUKUDA[4],
Teruo SAITO[1] and Yoshinori TATEMATSU[1]

[1] *Research Center for Development of Far-Infrared Region, University of Fukui, Fukui 910-8507, Japan*

[2] *Research Institute for Applied Mechanics, Kyushu University, Fukuoka, 816-8580, Japan*

[3] *National Institute for Fusion Science, Toki, 509-5292, Japan*

[4] *Graduate school of Engineering, Osaka University, Osaka, 560-0043, Japan*

In the nuclear fusion plasmas, both of thermal energy and particle transports governed by turbulent flow are anomalously enhanced more than neoclassical levels. Thus, to clarify a relationship between the turbulent flow and the anomalous transports has been the most worthwhile work.

There are experimental results that the turbulent flow induces various phenomena on transport processes such as non-linearity, transition, hysteresis, multi-branches and non-locality. We are approaching these complicated problems by analyzing not conventional power balance but these phenomena directly. They are recognized as dynamical trajectories in the flux and gradient space and must be a clue to comprehend a physical mechanism of arcane anomalous transport. Especially, to elucidate the mechanism for electron thermal energy transport is critical in the fusion plasma researches because the burning plasmas will be sustained by alpha-particle heating.

In large helical device, the dynamical relationships between electron thermal energy fluxes and electron temperature gradients are investigated by using modulated electron cyclotron resonance heating and modern electron cyclotron emission diagnostic systems. Some trajectories such as hysteresis loop or line segments with steep slope which represent non-linear property are observed in the experiment.

Keywords: Electron thermal transport, Transient response, Dynamic transport, Plasma turbulence, Gyrotron
Electron cyclotron resonance heating, Electron cyclotron emission, Large Helical Device

1. Introduction

Anomalousness for thermal energy and particle transports triggered by turbulent flow in the high temperature nuclear fusion plasmas has been one of the most controversial issues. Especially, to grasp a physical mechanism of electron heat energy transport will be critical in nuclear fusion plasma researches because the burning plasmas will be sustained by alpha-particle heating which lead to electron heating.

The plasma transport was investigated mainly based on a global scalar quantity so-called the energy confinement time. However, it is nothing but a volume-averaged value of the effective transport coefficient $ÿ_e^{p:b:}$ weighted at plasma peripheral regions. Here, the effective means including not only pure diffusion term but also convection and off-diagonal ones. The $ÿ_e^{p:b:}$ can be deduced by solving the power balance equation, but the $ÿ_e^{p:b:}$ give us no dense information about complicated characteristic of the transport phenomena because the flux is not simply proportional to gradient anymore in the nuclear fusion plasmas. Therefore such analysis based on power balance equation is not suitable for clarifying the mechanism of complex anomalous transport.

2. Transport analysis

By using transport matrix, the electron thermal flux is related with thermodynamic driving forces as follow [1].

$$Q_e = à\ n_e ÿ_e\, r\, T_e + Q_{off}$$

Here, the $Q_e; n_e; T_e$ are the electron thermal flux, electron density and electron temperature respectively. And the Q_{off} is the term having dependences on some gradients except for $r\, T_e$ and may well include even convection term. A thermal diffusive coefficient derived from the power balance is equivalent to

$$ÿ_e^{p:b:} = ÿ_e\ à\ \frac{1}{n_e\, r\, T_e} Q_{off}.$$

This quantity is different from the y_e. Contrastively, a

---

author's e-mail: notake@fir.fukui-u.ac.jp thermal diffusive coefficient derived from the transient response is given as

$$\ddot{y}_e^{h:p:} = \ddot{y}_e \ \grave{a}$$

$$\frac{1}{n_e r \hat{\imath} T_e} \frac{@Q_{off}}{@ r n_e} r \hat{\imath} n_e + \frac{@Q_{off}}{@ r T_i} r \hat{\imath} T_i + \acute{a}\acute{a}\acute{a} \ .$$

Where $\hat{\imath}T_e; \hat{\imath}n_e$ and $\hat{\imath}T_i$ represent the perturbation components of the electron temperature, electron density and ion temperature respectively. When these perturbations except for the electron temperature are negligible, $\ddot{y}_e^{h:p:}$ accord with a thermal diagonal element y_e of transport matrix. In this manner, $\ddot{y}_e^{p:b:}$ and $\ddot{y}_e^{h:p:}$ are another physical quantities.

The discussion mentioned above still based on the linear theory for thermal diffusion. In the nuclear fusion plasmas, it has been demonstrated that the y_e itself depends on $r T_e$ and T_e[2-5]. In the case of the y_e has dependence like $\ddot{y}_e \ / \ (r T_e)^{\ddot{e}}$, the ratio of $\ddot{y}_e^{h:p:}$ to $\ddot{y}_e^{p:b:}$ called the stiffness factor becomes as follow.

$$\ddot{y}_e^{h:p:} = \ddot{y}_e^{p:b:} = \ddot{e} + 1$$

According to many experimental contributions all over the world, it has been reported that the $\ddot{y}_e^{h:p:}$ is larger than $\ddot{y}_e^{p:b:}$. This fact implies that drastic enhancement of electron thermal flux is accompanied with increment of electron temperature gradient.

The foregoing non-linearity on the transports is caused by the turbulent flow. Therefore, to grasp the relation between them has been the high-priority issue and it has been observed that the turbulent flow induces various patterns in the transport processes such as non-linearity, non-locality, multi-states, transition, hysteresis and so on [6-7]. The anomalous transport phenomena will be discriminated and described by apprehending these patterns. Therefore, to investigate the dynamical relationship between electron energy flux and electron temperature gradient directly over the wide plasma parameter regions must be essential. Also, experimental results analyzed with this scheme will give us a more natural comparison with sophisticated transport simulations considering microscopic instabilities such as TEM, ETG. and ITG.

3. Flux-gradient technique

The electron thermal flux can be evaluated from the electron energy conservation under the approximation of cylindrical geometry as below.

$$Q_e = \frac{1}{r^0} \int_0^{r^0} r\,d r \ P_e \ \grave{a} \frac{@}{@t} \frac{3}{2} n_e T_e$$

It is no necessity to introduce magnetic-coordinate system if the aspect ratio of the plasma confinement device is large. The P_e indicates effective input power to electrons per unit volume and should include the electron-ion energy equipartition and radiative transfer in a precise sense. But a contribution from the ECRH is only considered here for simplification. Modulated electron cyclotron resonance heating (MECH) can be used as perturbation source of the electron temperature [8] and which is measured with 32-channel ECE radiometer with high spatial and temporal resolutions. This sophisticated ECE system makes possible dynamical transport research that excludes the use of any transport models and gives us the radial electron energy flux as a function of the electron temperature gradient. The electron density is measured with FIR-interferometer and subtle density fluctuation during modulated ECRH can be neglected because the amplitude of the fluctuation much less than that of electron temperature. A merit of the flux-gradient technique is that the heat fluxes are deduced from integrals which are robust to errors of the integrands [9].

4. Experimental setup and results

To investigate the effect of electron thermal transport on the electron temperature gradient, productions of target plasmas with different electron temperature gradients are attempted. In LHD, ECRH system consists of five 84GHz range gyrotrons and three 168GHz ones [10]. One of 168 GHz gyrotrons is used as modulation source and the target plasmas are sustained by only ECRH using residual gyrotrons. Fig.1 shows all ECRH deposition profiles estimated from ray-tracing calculations. The solid line shows the case of the almost power is deposited within the ρ=0.4. The open circles show the case of certain power is deposited more outward to suppress the electron temperature gradient.

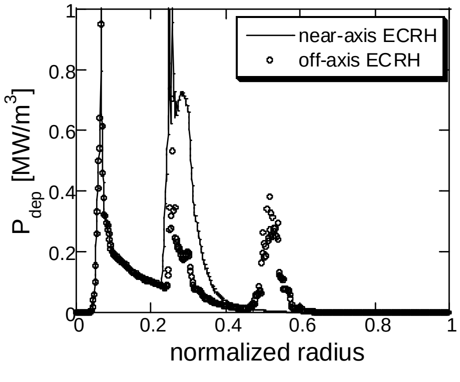

Fig.1. ECRH power deposition profiles in the experiment.

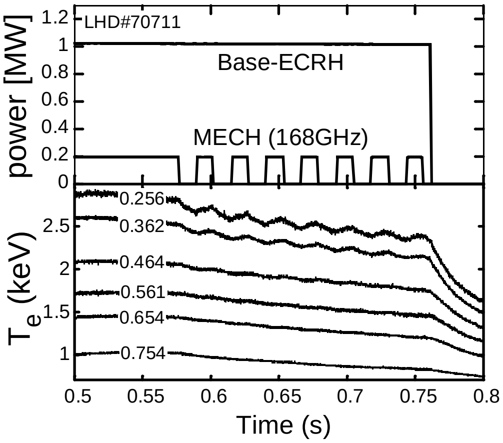

Fig.2 Temporal evolutions of injected ECRH power and electron temperature profiles measured with ECE. For clarity, not all of the 32 channels are shown.

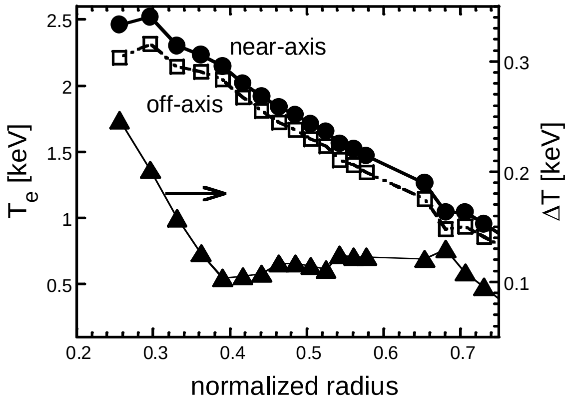

Fig.3. Electron temperature profiles of target plasmas and the difference of them at 0.57 s. The gradient have some differences from ρ=0.25 to ρ=0.4.

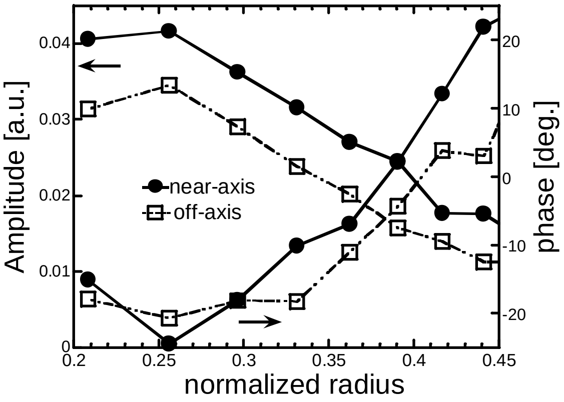

Fig.4. Amplitude and phase profiles deduced from the FFT. The extremal values appeared at the ρ=0.25.

Total injection power of ECRH is more than 1MW and the electron density is about 0.5x10^{19} m^{-3} at the experiment. The power deposition of the MECH as the heat pulse source is located at ρ=0.25 in both cases and the MECH is superposed to the target plasmas from 0.557 sec. to 0.756 sec. as shown in Fig.2. The power was modulated by handling anode voltage, so the power was almost 100% modulated.

Fig.3 shows the realized electron temperature profiles for two target plasmas at 0.57 sec. which is a timing before MECH was injected. And the triangles represent the temperature difference of them. These target plasmas have slight difference of electron temperature gradients from ρ=0.25 to ρ=0.4. In addition, amplitude and phase profiles of heat perturbation are analyzed at Fig.4. It is found that the peak of the amplitude and bottom of the phase profiles are located at the ρ=0.25 where the MECH power is deposited. The heat pulse propagates toward both sides as a center on there. According to the conventional linear theory, the solution of the heat diffusion equation under the slab geometry is given as follows with the modulation frequency $!_{\text{mod}}$.

$$\text{î}T_e(x;t) = \text{î}T_{e0}\exp\ \text{i}\,!_{\text{mod}}\,t\ \text{à}\ r\ \sqrt{3!_{\text{mod}}=4\text{ÿ}_e}\ 1+\text{i}$$

The amplitude of the temperature perturbation generally decreases exponentially, while the time delay increase linearly with the distance from the power deposition region. The modulation frequency of ECRH should be well higher than the inverse of the characteristic time of transport. But the amplitude will be poor when the modulation frequency is set too high. In the experiment, modulation frequency is set to 50 Hz. The smaller y_e which means better confinement give the slower heat pulse propagation. The $\text{ÿ}_e^{h:p:}$ can be estimated from only phase distribution as follows.

$$@'=@r = \sqrt{(3=4)\,!_{\text{mod}}\text{ÿ}_e^{h:p:}}\ .$$

However, judging from the phase distribution around ρ=0.25 shown in Fig.4, the electron thermal transport in the plasma with more gradual gradient become more extensive. So the experimental result markedly didn't obey the linear theory based on the diffusive concept. There are strong non-linearity and/or any other effects. In this way, the heat transport coefficient y_e has no crucial meaning any longer in the high temperature nuclear fusion plasmas. We had better to discuss the relationship between the electron thermal flux and electron temperature gradient genuinely without intervention of the y_e.

In order to investigate the dynamical behaviors, ECE data are used to obtain temporal electron energy flux and they are spatially differentiated to derive the gradients at each normalized radius. Time is a parameter to describe the dynamical trajectories in the flux-gradient space. Fig.5 shows the experimentally obtained trajectories during a cycle of MECH for two target plasmas with different electron temperature gradients. The figures (a) and (b) correspond to near-axis ECRH and off-axis ECRH cases respectively. The vertical axis indicates themal flux per electron and the horizontal line is electron temperature gradient. The diagonal line showing $\text{ÿ}_e^{p:b:}=10$ is also plotted as a mere indicator. The results show complicated relationships far from the expected ones based on diffusive features.

In the peripheral regions near the ρ=0.7, rough line segments with distinctly steep slopes are observed which suggest the strong stiffness, $\text{ÿ}_e^{h:p:}=\text{ÿ}_e^{p:b:}$ ý 1. And this slope may imply the critical gradient. In the intermediate region such as ρ=0.36, 0.46 and 0.56, multivalues like hysteresis loop appeared. This result signifies that transport is not uniquely decided to the flux and gradient. In the inward region near the magnetic axis, the modulation of both heat flux and gradient becomes very small and there are non-negligible measurement errors of ECE system. Hence, the results are less definitive and not shown here. The investigation of the dynamics in the plasma core regions where the appearances of more interesting results are expected is left as future works. Also, extending experimental plasma parameter regions will give us more effective information in order to grasp transport mechanism.

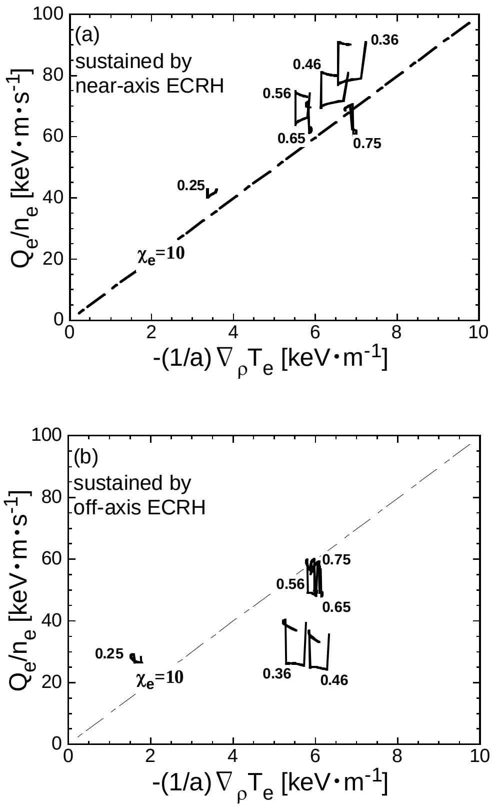

Fig.5. Dynamical relationship between electron thermal fluxes and electron temperature gradients at each normalized radius for (a) near-axis ECRH target plasma and (b) off-axis ECRH target plasma.

5. Summary

In this paper, we showed the initial results of dynamical electron thermal transport research by using MECH in high temperature LHD plasmas. Strong non-linearity is observed and the in-depth discussions have been possible by the dynamical research although they were impossible by the conventional power balance analysis. By applying this investigation in wider plasma parameter ranges, more comprehensive understanding to electron thermal transport in nuclear fusion plasmas will be expected.

Acknowledgment

I gratefully acknowledge fruitful discussions with Prof. Tetsuo Watari of NIFS. This work was supported by the NIFS under the Grant Number of NIFS06ULRR501,502 and 503.

References

1). N.J.Lopes Cardozo, Plasma Physics and Controlled Fusion, vol.**37** (1995), pp799-852

2). U.Stroth, L.Giannone, et.al., plasma Physics and Controlled Fusion. Vol.**38** (1996), pp.611-618

3). A.Jacchia, et.al., Physics of Fluids, B3**(11)** (1991)

4). K.W.Gentle, M.E.Austin and P.E.Phillips, Physical Review letters, vol.**87**, 125001 (2001)

5). S.Inagaki, et.al., Nuclear Fusion, vol.**46** (2006)p.133

6). S.Inagaki, N.Tamura, et.al., Plasma Physics and Controlled Fusion, vol.**48** (2006).pp251-257

7). K.Ida, S.Inagaki, R.Sakamoto, et.al., Physical Review Letters, vol.**96**, 125006 (2006)

8). V.Erckmann and U.Gasparino, Plasma Phys. Control. Fusion, vol.**36**, 1869(1994)

9). K.W.Gentle, M.E.Austin, J.C.DeBoo, T.C.Luce and C.C.Petty, Physics of Plasmas, vol.**13** (2006).

10). T.Notake, S.Ito, S.Kubo, T.Shimozuma, et.al., Transaction of Fusion Science Tecnology, **51**(2007)