Dynamic Transport Study of Electron Thermal Energy in Nonlinear Fusion Plasma

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In nuclear fusion plasmas, both thermal energy and particle transports governed by plasma turbulence are anomalously enhanced above neoclassical levels. Plasma turbulence induces various complex phenomena in transport processes, such as nonlinearity and nonlocality. Therefore, it is very important to clarify the relationship between plasma turbulence and anomalous transports. We have approached these complicated problems by analyzing the dynamics, which are recognized as temporal trajectories in a flux-gradient space, rather than using conventional power balance. In particular, in fusion research, it is critical to elucidate the mechanism of electron thermal energy transport, because the incoming burning plasmas are sustained by the heating of alpha particles. In Large Helical Device (LHD), the dynamic relationships between electron thermal fluxes and electron temperature gradients are investigated using modulated electron cyclotron heating and modern electron cyclotron emission diagnostic systems. Some trajectories, such as a hysteresis loop and a line segment with a steep slope, are observed in high-temperature LHD plasmas. Strong nonlinear properties in the transport are revealed by studying the dynamics.

Keywords: electron thermal transport, dynamic transport, plasma turbulence, Large Helical Device electron cyclotron resonance heating, electron cyclotron emission

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1. Introduction

Anomalous transport induced by plasma turbulence in high-temperature fusion plasmas is one of the most important issues to be clarified. We have looked for clues to comprehend a physical mechanism of arcane anomalous transports. In particular, understanding the physical mechanism of turbulent electron thermal transport is crucial, because a burning plasma is sustained by alpha particle heating, which mainly provides energy to electrons.

Investigating the relationship between the thermal flux and the temperature gradient is essential to understand the transport. In a near-equilibrium system, the thermal flux is proportional to the temperature gradient and its coefficient is called thermal diffusivity. In fusion plasmas, thermal diffusivity is estimated by power balance analysis. However, the thermal diffusivity thus obtained may not give us sufficient information about complicated turbulent transport, since it is premised on the linearity between the thermal flux and the temperature gradient.

In high-temperature fusion plasmas, it has been demonstrated that the thermal diffusivity depends on the temperature gradient [1–7]. This means that the thermal flux is a nonlinear function of the temperature gradient in systems far from equilibrium. For example, when the thermal diffusivity χ_e depends on the temperature gradient ($\chi_e \propto (\nabla T_e)^\alpha$), the ratio of thermal diffusivities inferred from conventional power balance and transient response becomes

$$\chi_e^{\mathrm{h.p.}}/\chi_e^{\mathrm{p.b.}} = \alpha + 1. \quad (1)$$

According to several recent experimental results, the ratio is greater than 1 [8]. This indicates a nonlinear feature, in which drastic enhancement of thermal flux is accompanied by an increase in the temperature gradient. Thermal diffusivity, therefore, is not adequate to describe the transport features.

Such nonlinearities are caused by plasma turbulence. Therefore, elucidating the relationship between them is crucial in this study. Dynamic transport analysis has been recognized as a powerful tool for revealing the nonlinearities in the transport. Also, experimental results analyzed with this scheme will enable a more natural comparison with sophisticated transport simulations, considering microscopic drift wave instabilities such as trapped electron mode (TEM), electron temperature gradient mode (ETG), and ion temperature gradient mode (ITG).

This paper is organized as follows. Section 2 de-

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scribes a dynamic transport analysis based on the relationship between the electron thermal flux and the electron temperature gradient. Section 3 presents the experimental method and results obtained in Large Helical Device (LHD). The dynamic behavior of electron temperature in response to electron heating modulation is reported, and the nonlinearities in the electron thermal transport are discussed. Finally, our findings are summarized in Section 4.

2. Flux-Gradient Technique

The electron thermal flux can be evaluated from the electron energy conservation under the approximation of cylindrical geometry, as given below [8, 9].

$$Q_e = \frac{1}{r'}\int_0^{r'} r dr \left[P_e - \frac{\partial}{\partial t}\left(\frac{3}{2}n_e T_e\right)\right]. \quad (2)$$

It is not necessary to introduce a magnetic-coordinate system when the aspect ratio of the plasma confinement device is large. P_e is the effective input power to electrons per unit volume, which should include electron–ion energy equipartition and radiative transfer in a precise sense. However, only the contribution from electron cyclotron resonance heating (ECRH) is considered here, since radiation losses and electron–ion exchange terms are too small to be important for the discussion. Modulated electron cyclotron resonance heating (MECH) can be used as a perturbation source of electron temperature. In MECH, the density perturbation is considered to be negligible because no particle source/sink exists. In some cases, however, the thermal transport couples with particle transport. Clamping is observed in a low-density plasma in the Compact Helical System (CHS) and LHD [10]. In this experiment, such an off-diagonal effect is not observed, and the particle diffusivity is less than the thermal diffusivity; therefore, the off-diagonal term is neglected. The electron temperature is measured with a 32-channel electron cyclotron emission (ECE) radiometer having high spatial and temporal resolutions. This sophisticated ECE system facilitates dynamic transport study, which excludes the use of any transport models, and provides the radial electron energy flux as a function of the electron temperature gradient. The electron density is measured using a far-infrared radiation (FIR) interferometer.

An advantage of the analysis technique using the flux-gradient relationship is that the thermal fluxes are deduced from integrals that are robust to the errors of the integrands [11].

3. Experimental Setup and Results

To investigate the effect of electron thermal transport on the electron temperature gradients, production of target plasmas with different electron temperature gradients is attempted. In LHD, the ECRH system consists of five 84-GHz and three 168-GHz gyrotrons [12], and one of the 168-GHz gyrotrons is used as the power modulation source. The target plasmas are sustained by only ECRH using residual gyrotrons. Figure 1 shows all ECRH deposition profiles in the experiment estimated from ray tracing calculations. The solid line shows the profile when nearly all the power is deposited within the normalized radius $\rho = 0.4$. We call this target plasma the "near-axis" plasma. The open circles show the case where a certain power level is deposited more outward to suppress the electron temperature gradient. We call this target plasma the "off-axis" plasma. The total injection power of ECRH is more than 1 MW, and the averaged electron density is about 0.6×10^{19} m^{-3} in the experiment. The power deposition region of MECH as a thermal pulse source is located at $\rho = 0.25$ in both the cases, and the target plasmas are subjected to MECH from 0.557 to 0.756 s, as shown in Fig. 2. ECRH power was modulated by adjusting the anode voltage; therefore, the power was almost 100% modulated.

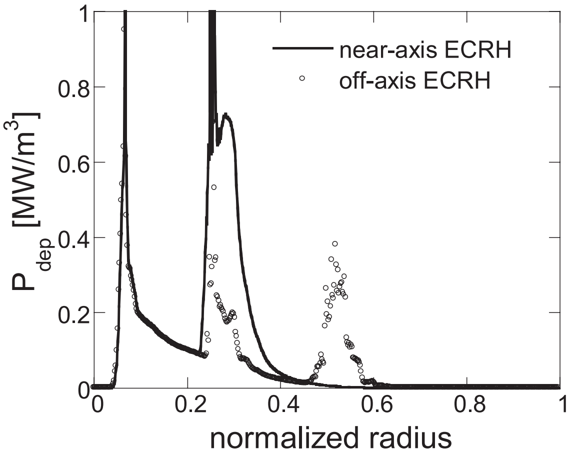

Fig. 1 Absorbed power density profiles as function of normalized radius for two target plasmas. Profiles are estimated using multi-ray tracing code.

The solid line with closed circles in Fig. 3 represents a difference between the realized electron temperature profiles for two target plasmas at 0.57 s before subjecting them to MECH. The broken line in Fig. 3 also shows the difference in the power flux of ECRH between the two cases. These target plasmas have some differences in their electron temperature gradients from $\rho = 0.25$ to 0.4. However, the electron temperature gradients from $\rho = 0.4$ to 0.5 are hardly changed, although there is a large difference in the power fluxes. This is far different from the conventional diffusive concept.

In addition, the amplitude and phase profiles of thermal perturbation are analyzed by FFT, and the results are shown in Fig. 4. Extreme values of amplitude and phase are clearly observed at $\rho = 0.25$, where the MECH power is deposited. The thermal pulse propagates toward both sides. According to the conventional linear theory, the solution of the thermal diffusion equation under the slab geometry with the modulation frequency ω_{mod} [13] is given

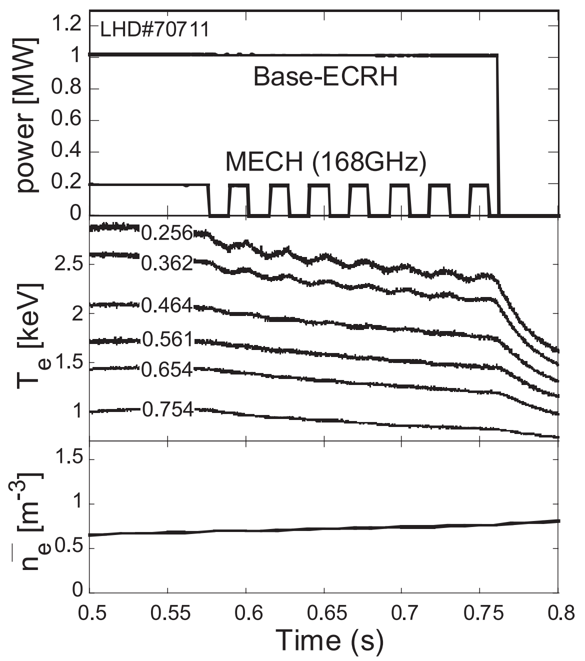

Fig. 2 Temporal evolutions of typical parameters in experiment. Electron temperature profiles are measured with ECE. For clarity, not all 32 channels are shown.

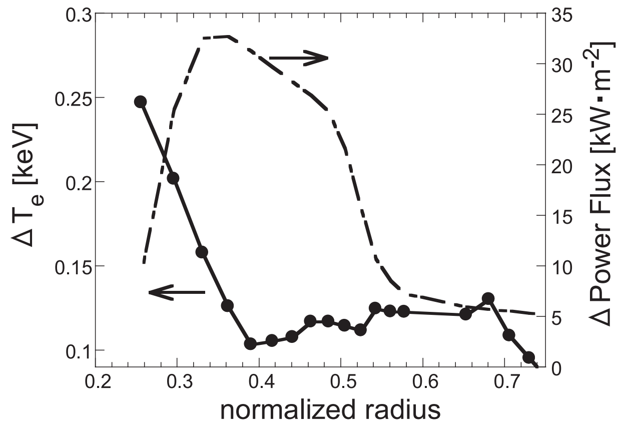

Fig. 3 Differences in electron temperature and total power flux profiles between two target plasmas at 0.57 s.

as follows:

$$\delta T_e(x,t) = \delta T_{e0} \exp\left[i\omega_{\rm mod} t - r\sqrt{3\omega_{\rm mod}/4\chi_e}\,(1+i)\right]. \tag{3}$$

The amplitude of the electron temperature perturbation generally decreases exponentially, while the time delay increases linearly with the distance from the power deposition region. The modulation frequency of ECRH should be much higher than the inverse of the characteristic time of the transport. However, the perturbation amplitude will be low when the modulation frequency is set too high. In the

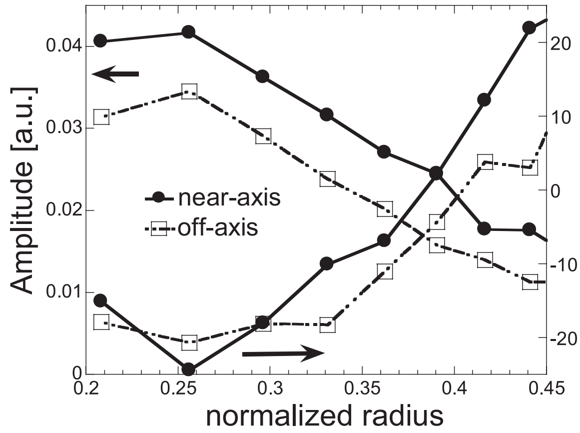

Fig. 4 Amplitude and phase profiles of electron temperature perturbation deduced by FFT. Extreme values were observed at ρ = 0.25.

experiment, the modulation frequency is 50 Hz. A smaller thermal diffusivity, which allows better confinement, produces slower thermal pulse propagation. $\chi_e^{\rm h.p.}$ can be estimated from only radial derivatives for phase distribution as follows:

$$\partial\varphi/\partial r = \sqrt{(3/4)\,\omega_{\rm mod}\chi_e^{\rm h.p.}} \tag{4}$$

However, judging from the phase distribution around ρ = 0.25 shown in Fig. 4, it can be said that the electron thermal transport in the plasma with a more gradual gradient becomes more extensive. Therefore, the experimental result did not obey the linear theory based on the conventional diffusive concept. There are strong nonlinearities and/or other effects. Thus, the thermal transport coefficient no longer has any significance with regard to high-temperature fusion plasmas. We need to discuss the relationship between the electron thermal flux and the electron temperature gradient without the intervention of the thermal diffusivity.

To investigate the dynamic behavior between fluxes and gradients, ECE data are used to obtain the temporal electron energy fluxes, and are spatially differentiated to derive the gradients at each normalized radius. Time is a parameter used for describing the dynamic trajectories in the flux-gradient space. Figure 5 shows the experimentally obtained trajectories during a cycle of MECH from 0.576 to 0.603 s for two target plasmas with different electron temperature gradients. The solid and broken lines correspond to the near- and off-axis ECRH, respectively. The vertical axis indicates the thermal flux per electron and the horizontal line is the electron temperature gradient. A diagonal line showing a thermal diffusivity of 10 is plotted as a reference. The results show complex relationships between the fluxes and the gradients, far from those expected based on the diffusive concept.

In the peripheral regions near ρ = 0.7, rough line seg-

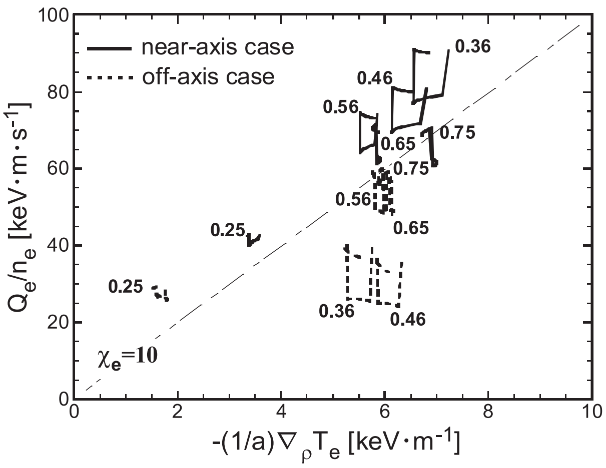

Fig. 5 Dynamic relationship between electron thermal energy fluxes and electron temperature gradients at each normalized radius. Modulated ECRH power is deposited at ρ = 0.2.

ments with distinctly steep slopes are observed, which suggest strong stiffness, i.e.,

$$\chi_e^{\mathrm{h.p.}}/\chi_e^{\mathrm{p.b.}} \gg 1. \tag{5}$$

In the intermediate region, such as at ρ = 0.36, 0.46, and 0.56, multiple values characterizing a hysteresis loop appeared. This signifies that the transport is not uniquely determined by the flux and the gradient. In addition, the electron temperature gradients barely changed; however, the thermal energy fluxes changed a great deal in both cases in this region. This implies the feature predicted by the critical gradient model. According to this theory, the growth of the gradient is restricted when the gradient exceeds a certain critical value, because the transport is significantly enhanced by excitation of drift waves such as TEM, ETG, and ITG [14–16]. As a result, the temperature profiles tend to become stiff irrespective of the heating power.

In the inner region, near the magnetic axis, the modulation of both the thermal flux and the gradient becomes very small, and non-negligible measurement errors of the ECE system are detected. Hence, the results are less definitive and are not shown here. The investigation of the dynamics in such plasma core regions, where the appearance of more interesting results is expected, is left for future work. In addition, extending the experimental plasma parameter regions will provide more useful information for understanding the complex turbulent transport mechanism.

4. Summary

In this paper, we presented the initial results of a dynamic electron thermal transport study using MECH in high-temperature LHD plasmas. Strong nonlinearities are observed, and the in-depth discussions became possible through the dynamic study, which were impossible by conventional power balance analysis. Applying this investigation to wider plasma parameter ranges should provide a more comprehensive understanding of electron thermal transport in nuclear fusion plasmas.

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