Analysis of higher harmonics on bidirectional heat pulse propagation experiment in helical and tokamak devices

T. Kobayashi[1], K. Ida[1,2], S. Inagaki[2,3], C. Moon[4], H. Tsuchiya[1], M. van Berkel[5], G. H. Choe[6], G. S. Yun[6], H. K. Park[7,8], W. H. Ko[7], T. E. Evans[9], M. E. Austin[10], M. W. Shafer[11], D. López-bruna[12], M. A. Ochando[12], T. Estrada[12], C. Hidalgo[12], H. Igami[1], Y. Yoshimura[1], T. Ii. Tsujimura[1], S.-I. Itoh[2,3] and K. Itoh[1,2]

[1]National Institute for Fusion Science, National Institutes of Natural Sciences, Japan
[2]Research Center for Plasma Turbulence, Kyushu University, Japan
[3]Research Institute for Applied Mechanics, Kyushu University, Japan
[4]Max-Planck-Institut für Plasmaphysik, Germany
[5]FOM Institute DIFFER - Dutch Institute for Fundamental Energy Research, The Netherlands
[6]Pohang University of Science and Technology, Korea
[7]National Fusion Research Institute, Korea
[8]Ulsan National Institute of Science and Technology, Korea
[9]General Atomics, San Diego, USA
[10]University of Texas, USA
[11]Oak Ridge National Laboratory, USA
[12]Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

Corresponding Author: kobayashi.tatsuya@LHD.nifs.ac.jp

Abstract:

In this contribution we propose a new method to analyze the modulation electron cyclotron resonance heating (MECH) experiment, aiming to examine the classical local transport model. The method is applied to the MECH experiments performed in various helical and tokamak devices, i.e., the Large Helical Device (LHD), the TJ-II, the Korea Superconducting Tokamak Advanced Research (KSTAR), and the Doublet III-D (DIII-D) with different plasma conditions. The thermal diffusivity and the convective velocity are obtained not only at the fundamental MECH frequency but also at its higher harmonics, as well as from both outward and inward propagating pulses, providing different transport coefficients at a radial region. Results clearly show universality of the violation of the classical local model.

1 Introduction

Proper modeling of thermal transport in the magnetically confined plasmas is mandatory for quantitative prediction of the reactor performance. Recent studies have reported that the electron thermal transport in the axially heated plasma cannot be modeled by a single scaler diffusive coefficient. There can exist a critical gradient-type nonlinearity [1, 2], an inward pinch [3, 4, 5, 6], and ballistic transport events [7, 8, 9]. More recently, the emergence of a *hysteresis* in the flux-gradient relation was discovered [10, 11, 12], involving rapid responses of turbulence intensity and turbulent transport against the heating [11]. This mechanism can also explain a long standing mystery, that is, the rapid increase of the electron thermal diffusivity in response to the electron cyclotron resonance heating (ECH), found in the Wendelstein 7-AS stellarator [13].

The hysteresis in the flux-gradient relation can be assessed by the perturbative heating experiment. In particular, the modulation ECH (MECH) is widely used to provide the perturbation in the electron temperature, since its modulation frequency, input power, and deposition can be precisely controlled [1, 2, 4, 5, 6, 10, 11, 12, 15, 16, 17]. See also a review [18]. By analyzing not only the fundamental MECH frequency but also its higher harmonics, i.e., the so-called higher harmonic method [14], the possible violation from the diffusive transport picture can be discussed [16, 17]. The amplitude radial decay rate of the temperature perturbation is predicted to obey the square root of their frequencies in the case that the linear local theory is valid. The experimental observations [16, 17] showed a clear deviation from the linear local picture, where the almost constant radial decay rates among the fundamental frequency and the higher harmonics were observed. The constant slopes provide the transport coefficients that depend on the frequency, showing a contradiction from the linear local theory. Possible relation between the constant slopes and the transport hysteresis was also discussed [14]

In this contribution, we extend the higher harmonic method in order to discuss the existence of the hysteresis in the flux-gradient relation. In addition, we use both the outward and inward propagating heat pulses to obtain the transport coefficients at one radial position. Here we call this method *bidirectional* heat pulse propagation analysis. The method is applied to the MECH experiments performed in various helical and tokamak devices, i.e., LHD, TJ-II, KSTAR, and DIII-D with different operation conditions. A clear dependence of the transport coefficients on both the propagation direction and the higher harmonic frequency is obtained, showing the possibility of existence of the transport hysteresis [19].

2 Method

Here we attempt to discuss limitations of the local theory with *reductio ad absurdum*. On the one hand, if the local transport model works, the obtained transport coefficients should not depend on the frequency nor on the heat pulse propagating direction. On the other hand, a theory predicts that the hysteresis provides the transport coefficients depend on both, and the difference between the transport coefficients obtained from the outward pulse and the inward pulse becomes larger at the higher frequency [19]. We analyze the one-dimensional heat transport equation in the cylindrical coordinate, considering the locally determined radial heat flux, defined as

$$\frac{\partial T}{\partial t} = \chi_{\mathrm{HP}} \frac{\partial^2 T}{\partial x^2} + \left(\frac{\chi_{\mathrm{HP}}}{x} - V_{\mathrm{HP}} \right) \frac{\partial T}{\partial x} - \left(\frac{V_{\mathrm{HP}}}{x} + \frac{1}{\tau} \right) T, \tag{1}$$

where, χ_{HP} and V_{HP} are the thermal diffusion coefficient and the convective velocity with respect to the heat pulse. The damping coefficient τ is taken as infinity here for simplicity. We analyze the region where the modulation heat source is not deposited. Considering the electron temperature perturbation

$$\delta T_{\mathrm{e}} \propto \exp[-i\omega t + i(k_{\mathrm{r}} + ik_{\mathrm{i}})r], \tag{2}$$

where k_{r}, k_{i} and ω indicate the real part and the imaginary part of the radial wavenumber and the angular frequency, the transport coefficients can be obtained as

$$\chi_{\mathrm{HP}} = \frac{1}{k_{\mathrm{r}}^2 + k_{\mathrm{i}}^2\gamma^2} \frac{k_{\mathrm{i}}\gamma}{k_{\mathrm{r}}}\omega \tag{3}$$

and

$$V_{\mathrm{HP}} = \frac{k_{\mathrm{r}}^2 - k_{\mathrm{i}}^2\gamma}{k_{\mathrm{r}}^2 + k_{\mathrm{i}}^2\gamma^2} \frac{1}{k_{\mathrm{r}}}\omega. \tag{4}$$

The factor $\gamma \equiv 1 - 1/k_{\mathrm{i}}r$ accounts for the divergence between slab and cylindrical geometry. The wavenumbers can be obtained from the Fourier analysis of the δT_{e} combined with the conditional averaging technique at each harmonic frequency $\omega = \omega_{\mathrm{M}}, 3\omega_{\mathrm{M}}, ..., m\omega_{\mathrm{M}}$, where ω_{M} is the MECH angular frequency and m is odd integers. The local model predicts the wavenumbers being nearly proportional to $\sqrt{\omega}$, and thus χ_{HP} and V_{HP} that do not depend on ω [16, 17].

In general, when the values of χ_{HP} and V_{HP} have radial dependences, or when there is a finite value of the damping term τ exists, the obtained χ_{HP} and V_{HP} naturally depend on the frequency. In that case, Eqs. (3) and (4) become

$$\chi_{\mathrm{HP}} = \frac{1}{k_{\mathrm{r}}^2 + k_{\mathrm{i}}^2\gamma^2} \left[\frac{k_{\mathrm{i}}\gamma}{k_{\mathrm{r}}}\omega - \frac{1}{\tau} + k_{\mathrm{i}}(\gamma - 1)\chi'_{\mathrm{HP}} - V'_{\mathrm{HP}} \right] \tag{5}$$

and

$$V_{\mathrm{HP}} = \frac{1}{k_{\mathrm{r}}^2 + k_{\mathrm{i}}^2\gamma^2} \left[\frac{k_{\mathrm{r}}^2 - k_{\mathrm{i}}^2\gamma}{k_{\mathrm{r}}}\omega + k_{\mathrm{i}}(\gamma + 1)\frac{1}{\tau} + (k_{\mathrm{i}}^2 + k_{\mathrm{r}}^2)\chi'_{\mathrm{HP}} + k_{\mathrm{i}}(\gamma + 1)V'_{\mathrm{HP}} \right], \tag{6}$$

respectively. Important fact is that the denominator $k_{\mathrm{r}}^2 + k_{\mathrm{i}}^2\gamma^2$ increases as the frequency increases, keeping the first terms constant, if the local model is correct. As a result, the impacts of the other terms become smaller at higher frequencies. This asymptotic behavior is not identical for the outward propagating pulse and the inward propagating pulse, therefore the difference of the transport coefficients obtained from the both pulses would decrease as the frequency increases. The asymptotic behavior of the higher harmonic terms is essential to discuss the cause of the frequency dependence of the transport coefficients.

TABLE I: EXPERIMENTAL CONDITIONS

Device	R [m]	a [m]	B [T]	I_p [MA]	$\bar{n}_e$ [10^{19}m^{-3}]	$f_{\rm MECH}$ [Hz]	$\delta P_{\rm MECH}$ [MW]
LHD	3.6	0.6	2.75	–	1.3	18	0.76
TJ-II	1.5	0.2	1	–	0.5	180	0.05
KSTAR	1.8	0.5	2.9	0.5	2	25	0.5
DIII-D	1.7	0.6	1.97	1.29	3.35	50	2.7

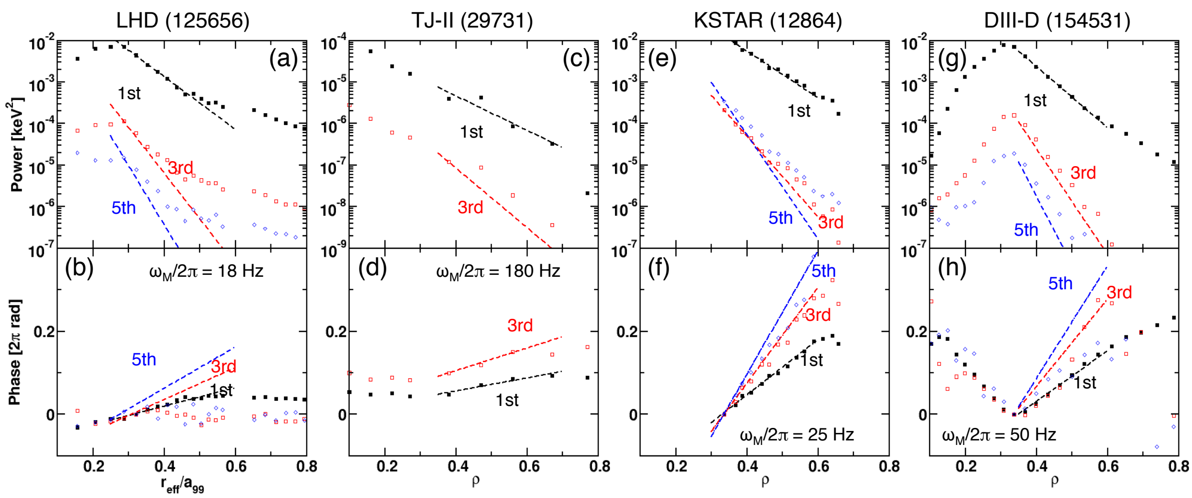

Figure 1: Radial profiles of the electron temperature perturbation (top) and the phase difference (bottom) for LHD, TJ-II, KSTAR, and DIII-D for analyzing the outward propagating pulses. Dashed lines in the figure show the prediction from the pure diffusion theory, in which the thermal diffusivity is obtained from the fundamental mode.

3 Experimental parameters

The experiments are performed in the steady state L-mode plasmas. The experimental conditions (the major radius R, the minor radius a, the toroidal magnetic field strength B, the plasma current I_p, the line averaged electron density $\bar{n}_e$, the MECH frequency $f_{\rm MECH}$, and the MECH power $\delta P_{\rm MECH}$) are summarized in Table I. In order to show the wide coverage of the method, various experimental conditions are used. By changing the MECH deposition location, the outward and inward propagating electron temperature perturbations are generated in LHD and KSTAR, during which the electron temperature profiles do not change drastically. In KSTAR, the electron temperature perturbation is measured with an Electron Cyclotron Emission Imaging (ECEI) system, while the traditional ECE systems are used in the other three devices.

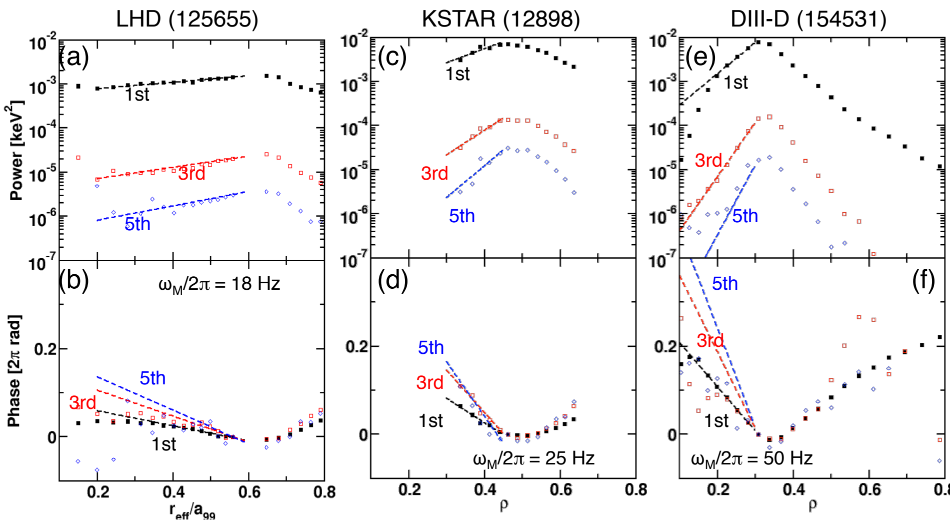

Figure 2: Radial profiles of the electron temperature perturbation (top) and the phase difference (bottom) for LHD, KSTAR, and DIII-D for analyzing the inward propagating pulses. Dashed lines in the figure show the prediction from the pure diffusion theory, in which the thermal diffusivity is obtained from the fundamental mode.

4 Results

Figure 1 shows the radial profile of the T_e perturbation power and the phase difference (symbols) for the case of the outward propagating pulse. The helical plasmas seem to have much faster phase propagation speed compared to the tokamak plasmas. Dashed lines in the figures show the prediction from the local model, in which the transport coefficients are obtained by fitting the slopes of the fundamental mode. The results clearly show that the local model cannot explain the power and the phase profiles.

The similar plots are given for the inward propagating pulses as shown in Fig. 2. Note that we do not have inward propagating heat pulse data for DIII-D and TJ-II. For the case of DIII-D, the inner side of the MECH deposition is analyzed. The dashed lines look to better fit the experiments with the inward propagating heat pulse, in particular for the case of KSTAR.

The slopes of Figs. 1 and 2 directly correspond to k_i and k_r, i.e., $k_i = A'/A$ and $k_r = \phi'$, where A and ϕ show the amplitude profile and the phase profile. Using k_i and k_r obtained from the linear fit of the experimental data, χ_{HP} and V_{HP} are calculated for the outward and inward propagating heat pulses as shown in Fig. 3 as a function of the order of the harmonics m (only for the outward pulse in the case of TJ-II). In the cases of the LHD, TJ-II and DIII-D, the obtained coefficients strongly depend on the value of m, i.e., the frequency, in which the local theory predicts constant coefficients against m. The KSTAR plasma shows the strong frequency dependence only in the convective velocity. The polarity of the convective velocities depends on the direction of

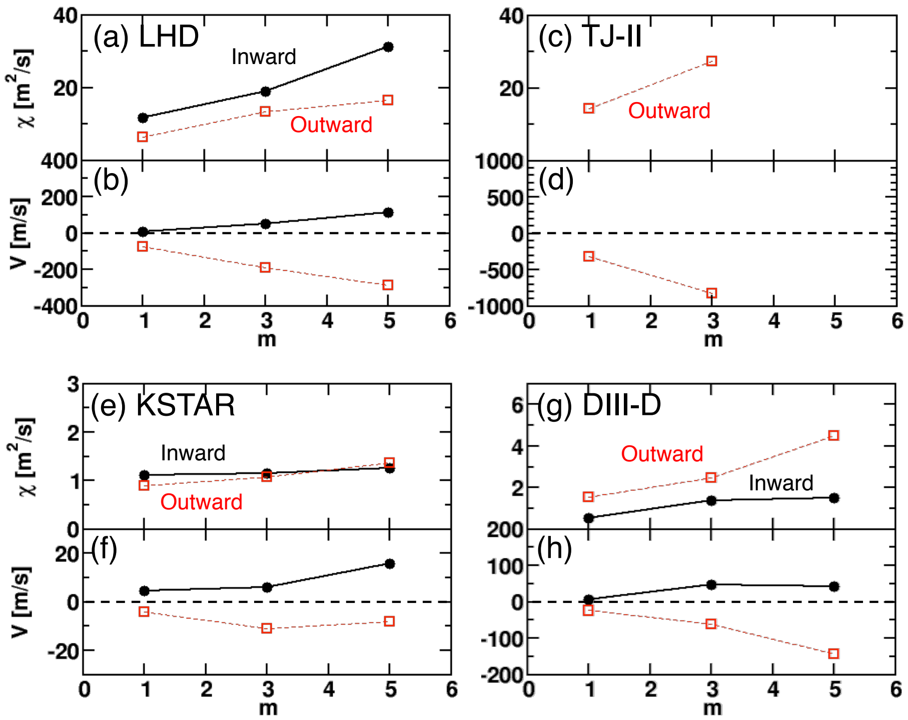

Figure 3: The thermal diffusivity (top) and the convective velocity (bottom) as a function of the order of the harmonics m.

the heat pulse propagation. The difference between the transport coefficients obtained from the outward pulses and the inward pulses becomes larger as the frequency increases. Therefore, this frequency dependence is not due to the radial dependence of χ_{HP} and V_{HP} nor the finite value of the damping term, as discussed in Sec. 2. Relatively low density or high MECH input power conditions have been found to benefit emerging the nonlocal feature [11], which does not contradict the observations here. The jump in the flux-gradient relation [11] is found to correlate with the m dependence of χ_{HP} [14]. The strong m dependence of transport coefficients in the proposed analysis indicates that the transient response during the MECH cannot be expressed in the classical local view of transport. The results showing a clear dependence of the transport coefficients on both the propagation direction and the higher harmonic frequency can correspond to the possibility of existence of the transport hysteresis [19].

5 Summary

In this contribution, we extended the higher harmonic method in order to discuss the existence of the hysteresis in the flux-gradient relation. We used the bidirectional heat pulse propagation method in order to discuss limitations of the classical local model with *reductio ad absurdum*. The method was applied to the MECH experiments performed in various helical and tokamak devices, i.e., LHD, TJ-II, KSTAR, and DIII-D with different operation conditions. The results showed clear dependences of the transport coefficients on both the propagation direction and the higher harmonic frequency, showing the possibility of existence of the transport hysteresis [19]. The observations clearly show the universality of the violation of the classical local view of transport. More intensive experimental verifications of the dynamic transport models are mandatory for the future fusion reactors.

Acknowledgments

We thank Professor S. Sakakibara for strong support. This study is partly supported by a Grant-in-Aid for Scientific Research of JSPS, Japan (15H02155, 15K14282, 15H02335 and 16H02442) and by the collaboration programs of NIFS (NIFS13KOCT001) of the RIAM of Kyushu University, and by Asada Science Foundation.

References

[1] F Ryter, G Tardini, F De Luca, H-U Fahrbach, F Imbeaux, A Jacchia, KK Kirov, F Leuterer, P Mantica, AG Peeters, *et al* 2003 *Nucl. Fusion* **43** 1396

[2] J C DeBoo, C C Petty, A E White, K H Burrell, E J Doyle, J C Hillesheim, C Holland, G R McKee, T L Rhodes, L Schmitz, *et al* 2012 *Phys. Plasmas* **19** 082518

[3] T C Luce, C C Petty, and J C M De Haas 1992 *Phys. Rev. Lett.* **68** 52

[4] P Mantica, G Gorini, G M D Hogeweij, N J Lopes Cardozo, and A M R Schilham 2000 *Phys. Rev. Lett.* **85** 4534

[5] P Mantica, F Ryter, C Capuano, H U Fahrbach, F Leuterer, W Suttrop, Jan Weiland, and ASDEX-Upgrade Team 2006 *Plasma Phys. Control. Fusion* **48** 385

[6] S D Song, X L Zou, G Giruzzi, W W Xiao, X T Ding, B J Ding, J L Ségui, D Elbèze, F Clairet, C Fenzi, *et al* 2012 *Nucl. Fusion* **52** 033006

[7] E D Fredrickson, K McGuire, A Cavallo, R Budny, A Janos, D Monticello, Y Nagayama, W Park, G Taylor, and M C Zarnstorff 1990 *Phys. Rev. Lett.* **65** 2869–2872

[8] M W Kissick, E D Fredrickson, J D Callen, C E Bush, Z. Chang, P C Efthimion, R A Hulse, D K Mansfield, H K Park, J F Schivell, *et al* 1994 *Nucl. Fusion* **34** 349

[9] K W Gentle, W L Rowan, R V Bravenec, G Cima, T P Crowley, H Gasquet, G A Hallock, J Heard, A Ouroua, P E Phillips, D W Ross, P M Schoch, and C Watts 1995 *Phys. Rev. Lett.* **74** 3620–3623

[10] K W Gentle, M E Austin, J C DeBoo, T C Luce, and C C Petty 2006 *Phys. Plasmas* **13** 012311

[11] S Inagaki, T Tokuzawa, N Tamura, S-I Itoh, T Kobayashi, K Ida, T Shimozuma, S Kubo, K Tanaka, T Ido, *et al* 2013 *Nucl. Fusion* **53** 113006

[12] K Ida, Z Shi, HJ Sun, S Inagaki, K Kamiya, JE Rice, N Tamura, PH Diamond, G Dif-Pradalier, XL Zou, *et al* 2015 *Nucl. Fusion* **55** 013022

[13] U Stroth, L Giannone, HJ Hartfuss, ECH Group, *et al* 1996 *Plasma Phys. Control. Fusion* **38** 611

[14] K Itoh, S-I Itoh, S Inagaki, N Kasuya, and A Fujisawa 2015 *J. Phys. Soc. Jpn.* **85** 014501

[15] L Giannone, V Erckmann, U Gasparino, HJ Hartfuss, G Kuhner, H Maassberg, U Stroth, and M Tutter 1992 *Nucl. Fusion* **32** 1985

[16] S Inagaki, S-I Itoh, K Itoh, N Kasuya, T Kobayashi, A Fujisawa, T Tokuzawa, K Ida, S Kubo, T Shimozuma, *et al* 2013 *Plasma Fusion Res.* **8** 1202173

[17] S Inagaki, S-I Itoh, K Itoh, K Ida, D López-Bruna, M A Ochand, T Estrada, B Ph van Milligen, C Hidalgo, and N Kasuya 2014 *Plasma Fusion Res.* **9** 1202052

[18] N J Lopes Cardozo 1995 *Plasma Phys. Control. Fusion* **37** 799

[19] K Itoh 2016 Hysteresis and Fast Timescale in Transport Relation of Toroidal Plasmas *Proc. 26th IAEA Fusion Energy Conf. (Kyoto, Japan)* (Vienna: IAEA) OV/P-8