New Method of Analysis for Dynamical Transport

Shigeru INAGAKI[1,2], Tokihiko TOKUZAWA[3], Tatsuya KOBAYASHI[4], Sanae-I. ITOH[1,2], Kimitaka ITOH[2,3], Katsumi IDA[2,3], Shin KUBO[3], Takashi SHIMOZUMA[3], Naoki TAMURA[3], Akihide FUJISAWA[1,2], Naohiro KASUYA[1,2], Hayato TSUCHIYA[3], Yoshio NAGAYAMA[3], Kazuo KAWAHATA[3], Hiroshi YAMADA[3], Akio KOMORI[3] and LHD Experiment Group

[1]*Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[2]*Itoh Research Center for Plasma Turbulence, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*
[3]*National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[4]*Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

(Received 5 September 2013 / Accepted 28 October 2013)

By employing a new method for studying dynamical transport, hysteresis in the flux–gradient relation was recently discovered for modulated heating. In this paper, the new method is compared to the conventional heat-pulse propagation method. We also demonstrate integration of results from the new method with the power balance thermal conductivity.

Keywords: heat-pulse propagation, transport dynamics, conditional averaging

DOI: 10.1585/pfr.8.1202172

1. Introduction

There are two conventional methods for estimating heat transport coefficients across magnetic surfaces. One is the power balance approach in which the ratio between heat flux and temperature gradient is evaluated in a stationary state. The other is to observe the propagation of a heat pulse under modulated heating power. The resulting thermal conductivities in the former and latter approaches are often indicated by χ_{pb} and χ_{hp}, respectively. These two are unambiguously different, which has stimulated much discussion [1, 2]. A recent detailed study of dynamical transport under modulated heating has shown that the flux–gradient relation is not monotonic (which has been intuitively assumed in introducing χ_{pb} and χ_{hp}); instead, there is a hysteresis in the flux–gradient relation [3]. This discovery resolved the long-standing mystery of the difference between χ_{pb} and χ_{hp}. This rapid communication explains the advanced analysis method used in [3] and compares it to conventional methods.

2. Experimental Setup

A modulation ECH power of 2 MW was imposed on a low-density (central density of $1.35 \times 10^{19}\text{m}^{-3}$) NBI-heated plasma (balanced injection of 2 MW) confined in LHD (major radius $R_{\text{ax}} = 3.6$ m, averaged minor radius $a = 0.6$ m, on-axis magnetic field B_{ax} of 2.75 T) [4]. The period of the modulation frequency was $f_{\text{mod}} = 25$ Hz, and the ECH power was absorbed in the central core $\rho \approx 0.2$ [3], where $\rho = r/a$ is the normalized minor radius. The electron temperature was measured at 25 points in the region $0.3 \le \rho \le 0.9$ with a time resolution of 4 µs. By overlaying 35 modulation pulses, temperature modulations at 25 points were reconstructed with a high signal-to-noise ratio and high temporal resolution.

3. Dynamical Method of Transport

The normalized temperature modulation is illustrated in Fig. 1. Figure 1 (c) shows the spatiotemporal structure of the normalized temperature modulation, which was obtained by the conditional averaging method. To eliminate fine-scale corrugations in the contour lines, Fig. 1 (c) was drawn using a low-pass filter (low-frequency components

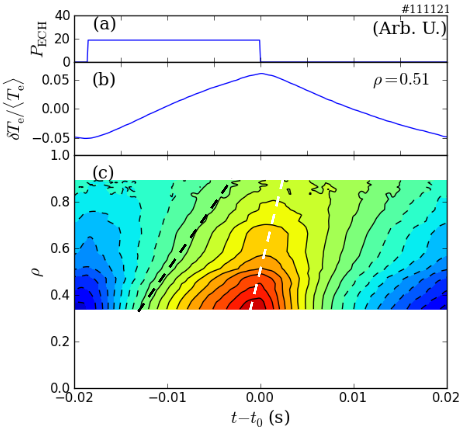

Fig. 1 Time evolution of (a) ECH power, (b) the normalized temperature perturbation (δT_e) at $\rho = 0.51$, and (c) spatiotemporal evolution of δT_e.

---

author's e-mail: inagaki@riam.kyushu-u.ac.jp

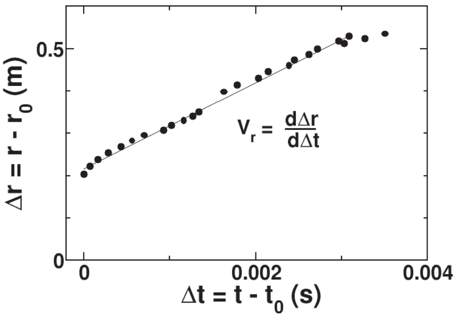

Fig. 2 Relation between time delay and distance of heat pulse.

below 1 kHz were retained). The essential features are demonstrated in Fig. 1 (c), i.e., there are two distinct time scales in the periodic modulation: one very short, the other much longer. During the very short time scale, the change in the time derivative of temperature at the time of switch-off (periodic time $t = t_0$) propagates very rapidly over the radius. The white dotted line, which is drawn to guide the eye, shows that the time delay between $\rho = 0.3$ and $\rho = 0.9$ is ~ 1 ms. Note that the low-pass filter imposes a lower limit of 1 ms on temporal accuracy. Therefore, the propagation of the change in the time derivative of temperature at the time of switch-off is complete in 1 ms or less. The same argument applies to the transient response at the time of switch-on of ECH power.

During the much longer time scale, the phase of vanishing perturbation ($\delta T_e = 0$) propagates slowly, as denoted by the broken line in Fig. 1 (c). Along this line of slow propagation, the time delay between $\rho = 0.3$ and $\rho = 0.9$ is ~ 10 ms. The space–time response shown in Fig. 1 (c) is unified by a hysteresis loop for the flux–gradient relation, as is explained in [3].

This advanced result can be compared to the standard method of analysis. In the conventional analysis, the relation $\delta q_e = -n\chi_{hp}\nabla\delta T_e$ is assumed, and the oscillation component at the fundamental frequency f_{mod} is retained. From this method, one obtains χ_{hp} as $V_r^2/4\pi f_{mod}$, where V_r is the radial propagation velocity in the equiphase plane of the heat pulse (δT_e). The phase delay of this component at the fundamental frequency is measured, as is illustrated in Fig. 2. The solid line is a fit in the region $0.3 \le \rho \le 0.8$, which yields $V_r \approx 100$ m/s. Therefore, we obtain $\chi_{hp} \approx 32$ m^2/s. In this procedure, only the fundamental component of the frequency is kept, and the presence of the two time scales in Fig. 1 (c) is ignored.

Figure 3 illustrates the flux–gradient relations obtained by the new dynamical method (with hysteresis, solid line), the power balance analysis (blue dashed line), and the conventional heat propagation analysis (red chain line, denoting χ_{hp}). The power balance conductivity is evaluated in a stationary state and is hence close to the diagonal line of the flux–gradient relation, which is obtained by the new method. In contrast, the standard heat-pulse propagation analysis does not capture the hysteresis (i.e., the two time scales in the response in Fig. 1) but fits to one parameter χ_{hp}. Therefore, it provides a steep single line in Fig. 3. The comparison in Fig. 3 resolves the long-standing problem of the difference between χ_{pb} and χ_{hp}.

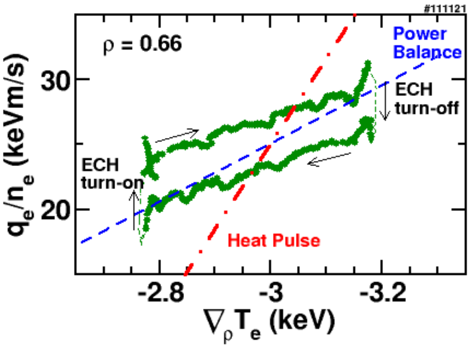

Fig. 3 Flux–gradient relations obtained by the new method (closed green circles with hysteresis), χ_{pb} (blue dashed line), and χ_{hp} (red chain line).

4. Summary

A new method for study of dynamical transport is compared to a conventional method. The new method shows there are two distinct time scales in the radial propagation of periodic perturbations: (a) a short time scale in which the peak and bottom of a perturbation propagate in radius at a rapid velocity and (b) a longer time scale in which the radial phase velocity for the period of gradual change is slow. (The presence of these two distinct phase velocities is caused by hysteresis in the flux–gradient relation.) Nevertheless, only the transport time scale is considered in the conventional heat-pulse propagation method. The neglect of these two time scales in plasmas explains why an erroneous heat-pulse thermal conductivity has been calculated. Hence, the developed dynamical method should be employed in studying plasma transport.

This work is partly supported by the Grant-in-Aid for Scientific Research of JSPF, Japan (21224014, 23244113, 23360414) and by the collaboration programs of NIFS (NIFS13KOCT001) and of the RIAM of Kyushu University and Asada Science Foundation.

[1] F. Ryter *et al.*, Phys. Rev. Lett. **86**, 5498 (2001).
[2] S. Inagaki *et al.*, Nucl. Fusion **46**, 133 (2006).
[3] S. Inagaki *et al.*, Nucl. Fusion **53**, 113006 (2013).
[4] A. Iiyoshi *et al.*, Nucl. Fusion **39**, 1245 (1999).