Determining the electron transport mechanisms from direct heat flux reconstructions

M. van Berkel[1,2], T. Kobayashi[3], G. Vandersteen[2], H.J. Zwart[4,5], H. Igami[3], S. Kubo[3]
N. Tamura[3], H. Tsuchiya[3], M.R. de Baar[1,4], and the LHD Experiment Group

[1]DIFFER-Dutch Institute for Fundamental Energy Research, PO Box 6336, 5600HH Eindhoven, The Netherlands

[2]Vrije Universiteit Brussel (VUB), Dept. of Fundamental Electricity and Instrumentation, Pleinlaan 2, 1050 Brussels, Belgium

[3]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-city, Gifu, 509-5292, Japan

[4]Eindhoven University of Technology, Dept. of Mechanical Engineering, Control Systems Technology Group*Dynamics and Control Group, PO Box 513, 5600MB Eindhoven, The Netherlands

[5]University of Twente, Dept. of Applied Mathematics, PO Box 217, 7500AE, Enschede, The Netherlands

Introduction

The heat flux is one of the key parameters used to quantify and understand transport in fusion devices. A new method is introduced to calculate the heat flux including its confidence with high accuracy based on perturbed measurements [1]. It is based on ideal filtering to optimally reduce the noise contributions on the measurements and piece-wise polynomial approximations to calculate the time derivative. Allowing to:

1. estimate the effective diffusion coefficient in a new way
2. assess the relevant transport mechanisms: convective velocity, temperature (gradient) dependencies, etc.
3. non-linear contributions and dependencies.

The methodology is applied to a measurement example using electron cyclotron resonance heating block-wave modulation at the Large Helical Device showing the merit of the new method.

Direct calculation of the heat flux

The heat flux follows from the conservation of energy (assuming no mass transfer and no radiation):

$$\frac{\partial}{\partial t}\left(n_e T_e(\rho,t)\right) = -\nabla_\rho q_e(\rho,t) + p(\rho,t) \qquad (1)$$
$$+ \text{ boundary conditions.}$$

with the electron temperature T_e, density n_e, heat flux q_e, heat source term $p(\rho,t)$ all as function of the dimensionless radius ρ.

Hence, the heat flux can be calculated in cylindrical coordinates by [2, 3]

$$q_e(\rho,t) = \frac{1}{\rho}\int_0^\rho \rho \left(\frac{\partial}{\partial t}\left(n_e T_e(\rho,t)\right) - p(\rho,t)\right) d\rho. \qquad (2)$$

Discharge overview and noise reduction

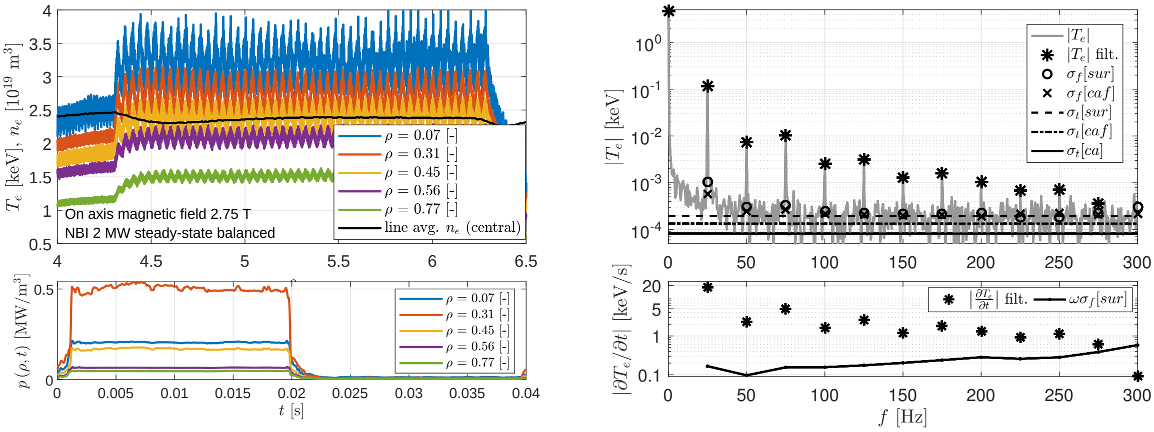


Fig. 1: LEFT: Overview of discharge LHD#111121 (a) time evolution of the temperature and density; (b) power density averaged over periods. RIGHT: Spectrum of the time trace of at $\rho = 0.47$ *(LHD#111121). (a) Shows the original signal in grey and the filtered signal with stars. Various estimates of the standard deviation are shown where* σ_f *is the standard deviation in the frequency domain and* σ_t *time domain (stationary white noise). The abbreviations stand for sur: surrounding frequency lines used to calculate variance,* caf*: variance per frequency line, ca: variance calculated over over windowed time samples. (b) Amplitude of* $\nabla_t T_e$ *calculated by multiplication with* $i\omega$ *and the corresponding standard deviation of the individual frequency lines in the time derivative spectrum.*

Steps taken to increase the accuracy of the heat flux reconstruction:

1. average over periods + use only sparse harmonic content (see Fig. 2(a) and Fig. 1(LEFT), respectively).
2. variances estimated from data (Fig. 2).
3. inverse Fourier transform: time domain one period (Fig. 1(LEFT) and Fig. 2).
4. piece-wise polynomial fit to suppress oscillations (Fig. 2).

Heat flux reconstruction

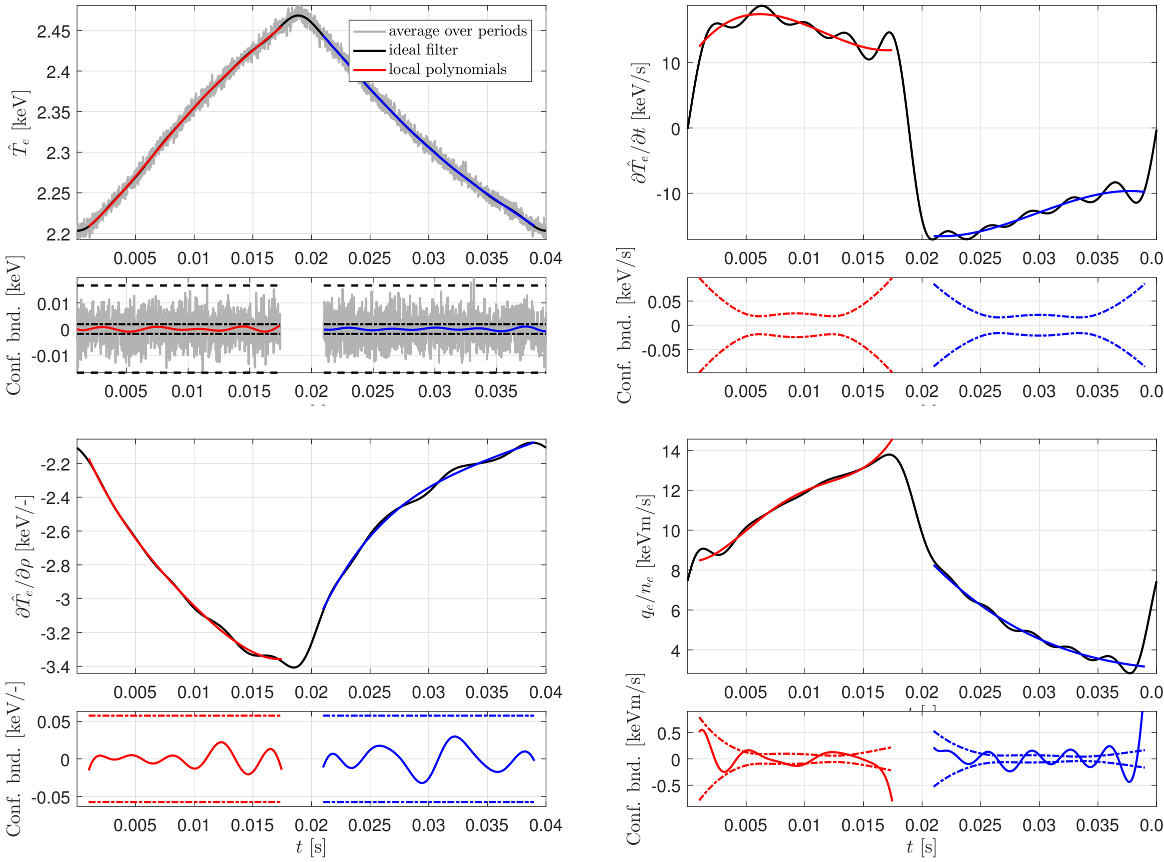


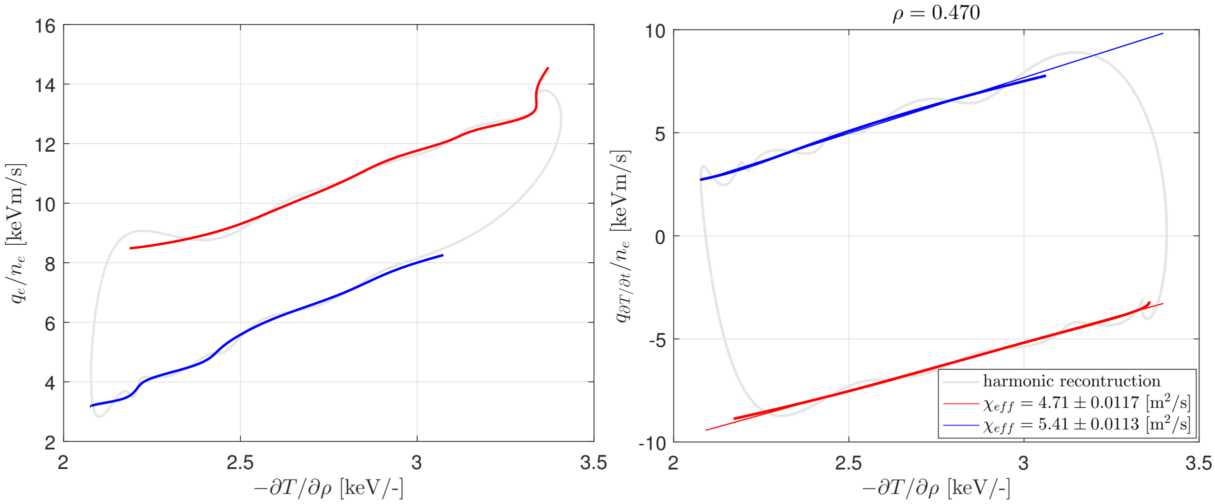
Fig. 2: Time evolution of average over periods of discharge LHD#111121 at $\rho = 0.47$ *(a) temperature; (b) time derivative of the temperature; (c) spatial derivative of the temperature; and (d) perturbative heat flux. The different lines are the average over periods (light grey), harmonic reconstruction using ideal filtering (black), and piece-wise polynomials (red and blue). In the bottom subfigures are the confidence bounds (conf. bnd. 1.96*σ*) in dashed (dotted) lines and the difference between the harmonic reconstruction and the piece-wise polynomials (full lines).*

Resulting perturbative heat flux and estimation of χ_e using slopes

Errors due to

- synchronization errors between RF and ECE measurements
- sensor dynamics
- deposition profile

can break the straightness of the lines and/or cause errors in the estimate of the diffusion coefficient χ_e. However, for the estimation of χ_e knowledge of the heat source is not required when it is constant. Removing the perturbation from equation (2) results in extraordinary straight slopes. These slopes are a measure of the diffusion coefficient [4], i.e., $q_e(\rho,t) = \chi_e \quad \partial T/\partial \rho$.



LEFT: Perturbative heat flux based on (2) versus $-\partial T/\partial \rho$ based on piece-wise polynomial (color) and harmonic reconstruction (grey). RIGHT: Perturbative heat flux based on temperature only ($p(\rho,t) = 0$) in (2) versus $-\partial T/\partial \rho$ based on piece-wise polynomial (color) and harmonic reconstruction (grey).

Conclusion

A new methodology has been presented to assess the heat flux and diffusion coefficient resulting for this discharge and operating point in

- accurate estimates of diffusion coefficient (relative errors between heat source on and off extremely small confidence bounds, absolute errors can be larger than given due to calibration errors).
- no dependency of $\partial T/\partial \rho$ on $\chi_e(\partial T/\partial \rho)$ observed.
- no convective velocity observed.
- apparent dependency of χ_e on the total heating power.

References

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