LOCAL AND GLOBAL TRANSPORT IN PERTURBATIVE EXPERIMENTS IN THE STELLARATOR W7-AS

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1. Introduction

One of the most interesting questions about confinement raised in recent years is whether electron heat transport is governed by local processes only or also by non-local or global ones. The most sensitive methods to investigate the electron thermal diffusivity χ_e are perturbative experiments like power modulation or impurity injection to the plasma edge. In the first case, a heat pulse in the electron temperature travels from the core to the edge while in the second case, a cold pulse travels from the edge to the core. This paper reports on recent results from W7-AS obtained from heat-pulse experiments, which were carried out in plasmas in a large heating power range and cold-pulse experiments on discharges at very different plasma parameters.

2. Cold-pulse experiments

Systematic cold-pulse experiments were carried out in electron cyclotron resonance heated (ECH) discharges at line averaged densities from 0.7 to 7×10^{19} m^{-3} and a magnetic field strength of B = 2.5 T. The heating power was 0.5 MW.

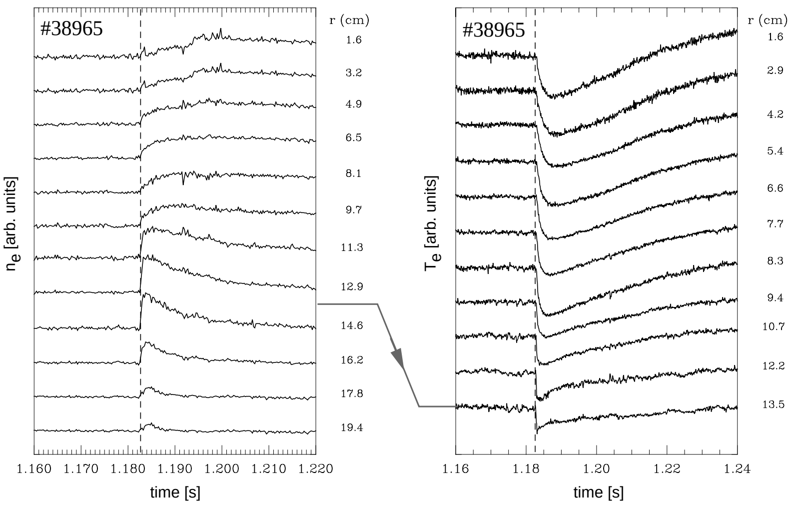

Figure 1. Electron density and temperature evolution at different radii of a cold-pulse induced by carbon injection (dashed line).

In Fig. 1, the electron density and temperature evolution of a relatively large cold pulse are depicted. The density is measured by a 10-chord microwave interferometer. The line-averaged density prior to the injection is $3\times10^{19}\,\mathrm{m}^{-3}$. From the measured density rise, the number of electrons injected into the plasma edge is estimated to be $\lesssim 1\times10^{19}$. This has to be compared with a total number of 3×10^{19} plasma electrons. From the sharp increase in the density as shown in Fig. 1 it can be deduced that the electron source is located between r = 10 and 15 cm. In this region, the carbon clusters are completely ablated and the atoms ionized within 1 ms. The biggest density perturbation is $\Delta n \approx 1.5\times10^{19}\,\mathrm{m}^{-3}$. The fast density rise at the edge is followed by a slower density increase during 10 ms in the plasma center. In W7-AS, strong cold-pulses could only be generated if the amount of electrons introduced led to a maximum local density increase of $(\Delta n/n)_{max} \gtrsim 80\,\%$.

The temporal electron temperature evolution during the cold pulse is measured by an ECE radiometer. The temperature reacts to the density inverse. A sharp temperature drop in the outermost channels reflects the fast density increase in the particle source region. The temperature perturbation propagates to the plasma center. A central temperature increase, as reported e.g. from the TEXT tokamak [1], was never observed in W7-AS.

The cold-pulses were analyzed with the ASTRA time-dependent transport code [2]. The electron heat transport equation is solved including electron-ion coupling. A constant separatrix temperature is assumed as the boundary condition. The radiation losses are taken from bolometer measurements. The temporal evolution of the density profile is prescribed in the calculation according to the inverted line integrated measurements.

The results from two simulations with different models are shown in Fig. 2. The model where χ_e was set to the diffusivity profile χ_e^{pb} obtained from a power balance analysis from before the Carbon injection reproduces the fast temperature drop in the outermost channels (upper figure). This is due to an almost adiabatic temperature response to the density increase. For the dynamics of the edge temperature drop, radiation and ionization losses are of minor importance. This simple model fails to reproduce the temperature evolution at inner radii in detail.

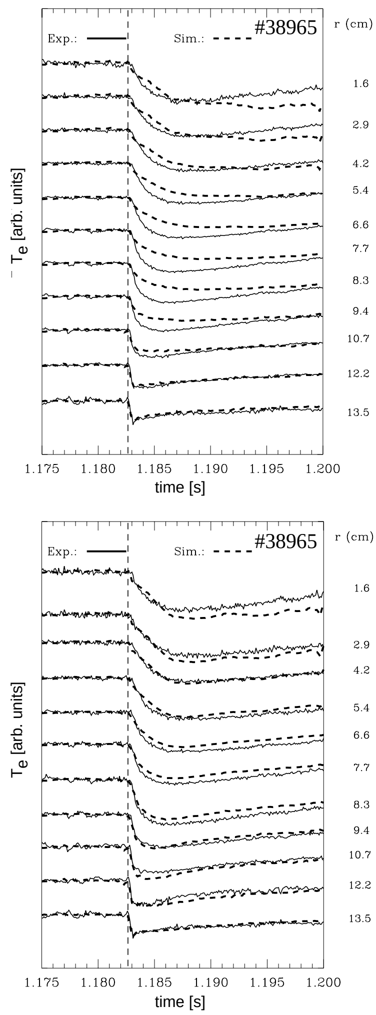

Figure 2. Comparison of the simulated and measured electron temperature evolution for a large cold-pulse using two different models as described in the text.

The agreement in the core between simulation and experiment depends sensitively on how well the outer channels are reproduced. In the lower part of Fig. 2, a simulation is shown where the diffusivity was artificially enhanced by a factor of 2.7 for 1 ms immediately after the injection time. This increase was limited to $r > 10$ cm. The resulting additional reduction in the simulated temperature at $r = 10.7$ cm is small but sufficient to obtain the shown improvement of the fit of the inner channels. Furthermore, a weak local dependence ($\chi_e \sim \nabla T^{0.4}$, $\chi_e \sim T^{0.4}$ and $\chi_e \sim n^{-0.4}$ gives similar results) of the diffusivity was assumed to account for the long term evolution of the temperature. However, for the evolution in the first 2 ms this dependence is only of minor importance.

Although an explicit time dependence of the diffusivity is introduced for the plasma edge, this cannot be considered as a non-local effect. During the short time the diffusivity was enhanced, the electron distribution function was perturbed by a large fraction of cold electrons (the local density is doubled). This could very well lead to an enhancement of the local turbulence level. Hence there exists no evidence for non-local transport in cold-pulse experiments in W7-AS. This also holds for those experiments carried out so far on neutral-beam-heated discharges.

3. Heat Pulses Experiments

In early power modulation experiments in W7-AS, the heat-pulse propagation could be modeled using a χ_e as obtained from power balance analysis [3,4]. This result could be interpreted in terms of a non-local transport model [5]. However, more recent experiments were consistent with $\chi_e \approx 2\chi_e^{pb}$ and therefore with a local ∇T dependence [6]. In order to clarify this contradiction, modulation experiments were carried out in a large power range, which was not accessible previously. The rotational transform was carefully chosen in order to assure optimum confinement conditions. The heating power was varied from 0.2 to 1.4 MW and modulated at 92 Hz for 800 ms. The density was $\bar{n}_e$ = 2×10^{19} m^{-3} and the field 2.5 T. The data obtained are of excellent quality.

In Fig. 3, the heat-pulse diffusivities χ_e^{hp} as obtained from bessel fits to phases and amplitudes of first and second harmonic perturbations are compared with the power balance values. The data confirm a ratio of χ_e^{hp}/χ_e^{pb} of about 2. Only at high power densities, the old result is recovered.

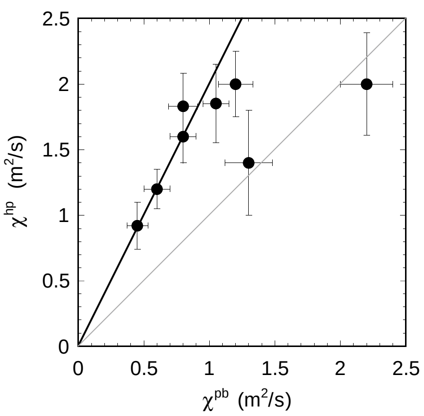

Figure 3. Heat diffusivities from power balance and heat pulse analyses.

In order to test the parameter dependence of χ_e in detail, amplitudes and phases were simulated with the ASTRA code using the following models: (a) $\chi_e = \chi_e^{pb}$, (b) $\chi_e \sim T_e$, (c) $\chi_e \sim \nabla T_e$ and (d) $\chi_e \sim P^{0.5}$. In Fig. 4 calculated and measured amplitudes and phases are compared for two examples, P = 0.43 and 0.95 MW. In all cases, the central measured amplitudes are consistent with the ECH modulation amplitude and so, in contrast in to earlier experiments, no missing power was observed. At low heating power the models (a) - (c) fit the amplitude profile, and (c) and (d) fit the phase profiles. For all experiments with an ECH power $\lesssim$ 0.8 MW the model linear in ∇T reproduces the measurements. For high power, the Shafranov shift modulation leads to asymmetric amplitude and phase profiles. With a simple radial shift, simultaneous symmetrization of both profiles is not possible. In Fig. 4 the symmetrization was done for the phase profile. The amplitudes on the high and low field side differ as shown in the Fig. 4. The phases are reproduced rather well by (a) and (b). (c) fails completely and (d) deviate at larger radii and also cannot account for amplitudes.

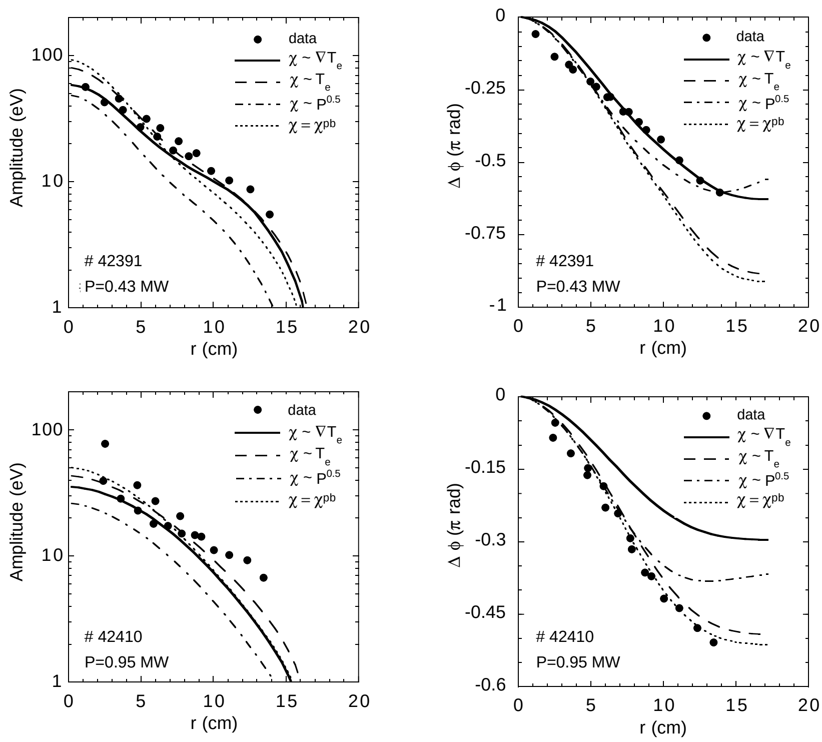

Figure 4. Comparison between measured and simulated amplitude and phase profiles. ECH power is depicted in the center.

These results confirm the results from Ref. [6] which were deduced from data with lower quantity. The question is, how to reconcile those results with the previous ones. One possible explanation could be that in the plasma a transition occurs from a local to a global model if e.g. the temperature gradient, which is related to the power per particle, exceeds a critical value. In the power scan, at $P > 0.8$ MW or $P/n > 2 \times 10^{-14}$ Wm^3 the old result of $\chi_e^{hp}/\chi_e^{pb} \approx 1$ is recovered. The early experiments were done in this range, although at B = 1.25 T. In order to investigate this hypothesis, the available data from a power scan at lower density and from the temperature decay phase after power switch-off have to be analyzed.

References

[1] K.W. Gentle et al.: Phys. Fluids **2**, 2292 (1995)

[2] G. Pereverzev et al.: IPP report 5/42, Max-Planck-Institut für Plasmaphysik, Garching, F.R.G. (*unpublished*)

[3] L. Giannone et al.: Nucl. Fusion **32**, 1985 (1992)

[4] H.J. Hartfuß et al.: Plasma Phys. Controlled Fusion **36**, B17 (1994)

[5] U. Stroth, L. Giannone, and H.J. Hartfuß: Plasma Phys. Controlled Fusion **38**, 1087 (1996)

[6] M. Peters: Ph.D. thesis, Technische Universiteit Eindhoven, 1995