

Electron Heat Transport in ASDEX Upgrade: Experiment and Modeling

F. Ryter, G. Tardini, H.-U. Fahrbach, K. Kirov, F. Leuterer, A.G. Peeters,
G. Pereverzev, W. Suttrop and ASDEX Upgrade Team
Max-Planck-Institut für Plasmaphysik, EURATOM Association,
D-85748 Garching e-mail: ryter@ipp.mpg.de

1. Electron heat transport driven by turbulence with $\nabla T_e/T_e$ threshold

Studies of electron heat transport in ASDEX Upgrade [1, 2] and other tokamaks [3, 4] suggest that transport is governed by turbulence increasing above a threshold $(\nabla T_e/T_e)_c = 1/L_{Tc}$, named κ in the following. As a consequence the temperature profiles react weakly to changes of the heating power intensity and deposition profile: “profile resilience” of “stiffness”.

Based on these observations a simple analytical transport model has been developed and tested on ASDEX Upgrade data [5]. It is based on the following assumption for the heat diffusivity:

$$\chi_e = \chi_0 + \lambda T_e^\alpha (\nabla T_e/T_e - \kappa)^\beta H_\kappa \quad (1)$$

where λ , α and β are coefficients to be adjusted, H_κ is the Heavyside function equals to zero for $\nabla T_e/T_e < \kappa$ and to unity for $\nabla T_e/T_e \geq \kappa$. We will show below that good results are obtained with $\alpha = 0.5$ and $\beta = 1$. In the remaining of this paper, the units are mks except keV instead of eV for the temperatures. The usual definition of the perturbative heat diffusivity, which defines the propagation of heat pulses, is [6]:

$$\chi_e^{HP} = \chi_e^{PB} + \frac{\partial \chi_e}{\partial \nabla T_e} \nabla T_e \quad (2)$$

with χ_e^{PB} being the power balance or steady-state heat diffusivity. This expression can be derived explicitly from Eq. 1, giving with $\beta = 1$:

$$\chi_e^{HP} = \chi_0 + \lambda T_e^\alpha (2\nabla T_e/T_e - \kappa) H_\kappa \quad (3)$$

under the assumption that χ_0 does not depends on ∇T_e . This expression shows the important property that χ_e^{HP} increases in a step largely above χ_0 as soon as $\nabla T_e/T_e$ is larger than κ , whereas χ_e^{PB} increases continuously with $\nabla T_e/T_e - \kappa$, see [5] and also Fig. 1 right part. The physics validity of the empirical model is supported by the good results obtained in ASDEX Upgrade using the Weiland model for NBI heated plasmas [7] and in ECH heated plasma dominated by electron transport [8]. This first principle model is based on Ion Temperature Gradient for the ions and Trapped Electron Modes driven turbulence for the electrons. These two instabilities both have a respective threshold in $\nabla T/T$. The Electron Temperature Gradient driven turbulence also has a (different) threshold in $\nabla T_e/T_e$, [9].

As a consequence of this transport property, the temperature profiles exhibit very similar values of R/L_T in several tokamaks [3]. Equivalently, this is reflected in each device by the fact that plotted on a logarithmic scale the T_e profiles have the same shape and are shifted according to the edge or pedestal temperature, which is therefore a key parameter.

2. Variation of heat flux at constant edge flux: steady-state and modulation

The ASDEX Upgrade tokamak is equipped with a flexible ECH system composed of 4 beams whose deposition can be varied independently by mirror launchers. The electron temperature, essential here, is provided by 2 diagnostics: the 60 channel ECE heterodyne radiometer with a spatial resolution of about 1 cm and a bandwidth of ≈ 31 kHz; the Thomson scattering with 16 radial channels and a profile every 16 ms. These two diagnostics agree within $\pm 10\%$. The

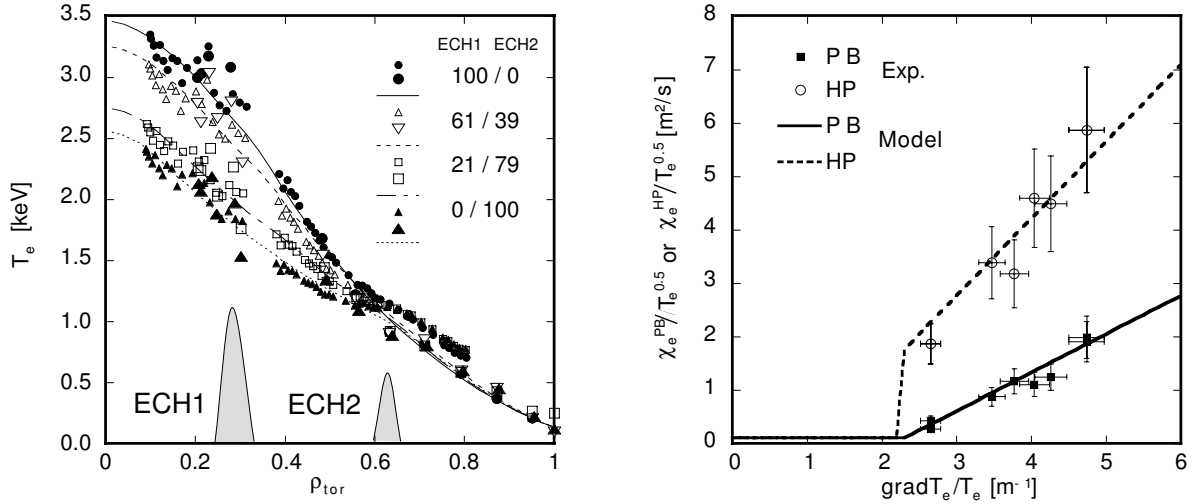


Figure 1: *Left: T_e profiles in the experiments with heat flux variation by ECH in the confinement region with constant edge flux ($P_{ECH1} + P_{ECH2} = 1.3 MW$). Small symbols for ECE, large symbols for Thomson scattering, lines for modelling. Right: Results from power balance and heat pulse analysis at $\rho_t \approx 0.5$. The lines are given by the model from Eq. 1 with $\lambda = 0.72$ and $\kappa = 2.3$*

other quantities are provided by the usual diagnostics available on a modern tokamak.

According to the considerations of Sect. 1, it is essential in transport studies to vary the heat flux in the confinement region at constant edge temperature. This was achieved in new experiments where we varied the electron heat flux in the confinement region ($0.35 \leq \rho_t \leq 0.7$) by one order of magnitude while keeping the heat flux at the plasma edge ($\rho_t \geq 0.65$) constant. For this purpose, we deposited the ECH power at $\rho_1 \approx 0.35$ and $\rho_2 \approx 0.65$ with the respective intensities P_{ECH1} and P_{ECH2} . These were varied while keeping $P_{ECH1} + P_{ECH2}$ constant at about 1.3 MW. The discharges were run in deuterium at $I_p = 800$ kA, $B_T = 2.3$ T, and $\bar{n}_e = 210^{19} m^{-3}$ to reduce the electron-ion energy transfer and provide good conditions to study the electron heat transport. In addition, modulation of P_{ECH1} or P_{ECH2} allows to compare transient transport (χ_e^{HP}) to power balance (χ_e^{PB}). In both experiment and modelling the Fourier transform of the modulated T_e data yields profiles of amplitude and phase at the frequency of the power modulation for a quantitative comparison. The values of χ_e^{HP} are deduced from these profiles by the usual techniques described in [6, 1].

The steady-state temperature profiles are shown in Fig. 1 left part for a selection of these discharges. Indeed, under these conditions a clear variation of ∇T_e and $\nabla T_e/T_e$ can be achieved, which is not the case when central heating only is varied because the edge temperature increases with heating power. Note here the reproducibility of the edge profiles for $\rho_t \geq 0.65$. The results of power balance and transient transport $\rho_t \approx 0.5$ are shown in Fig. 1 right part. There, the χ values are divided by the $T_e^{1/2}$ dependence of the model to correct for the (moderate) variation of T_e in the region of analysis. A linear fit through the power balance data, neglecting the very small contribution from χ_0 , yields $\lambda = 0.72$ and $\kappa = 2.3$ (solid line in the figure). According to Eq. 3 we can also calculate the corresponding values for transient transport. The result, dashed line in Fig. 1 right part, agrees well with the experimental data. These values of λ and κ were then taken for transport simulations with the ASTRA code using Eq. 1. The results, lines in Fig. 1 left part, agree very well with the experimental data over the whole radius. The boundary condition is the temperature at $\rho_t = 1.0$. It must be mentioned

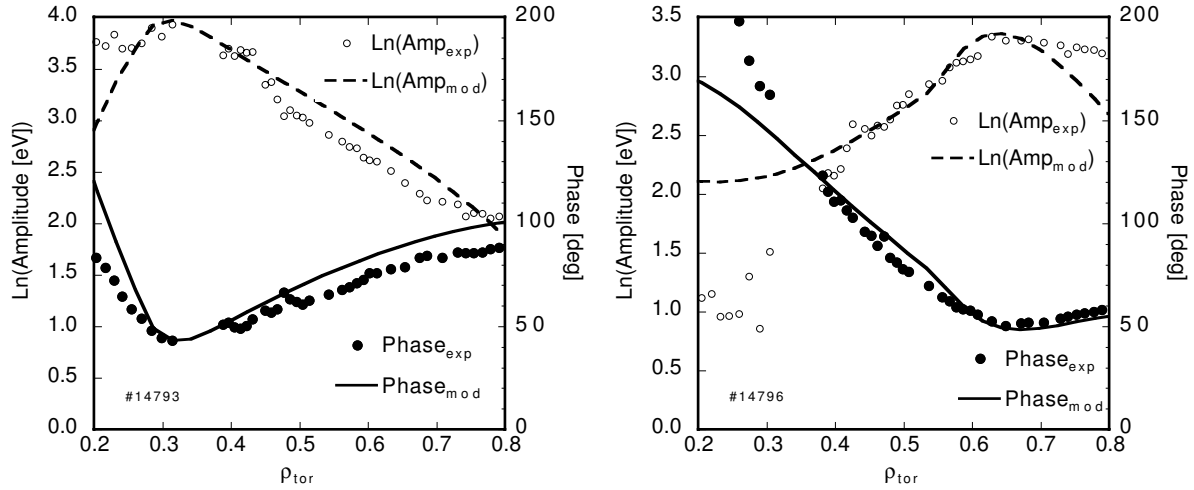


Figure 2: Amplitude and phase of the T_e modulation for the two extreme cases of Fig. 1, $P_{ECH1} = 100\%$ (left) or $P_{ECH2} = 100\%$ (right). The points are the data, the lines the empirical model, both with the same values $\lambda = 0.72$ and $\kappa = 2.3$.

that dividing the χ values by $T_e^{3/2}$, as taken in [5], instead of $T_e^{1/2}$ yields values which are lower by about a factor of 2 for λ and by about 30% for κ . With these values the simulations yield quite poor agreement.

The simulations also include the power modulation made in the experiment. The results of the Fourier transform of the experimental and modelled T_e are illustrated in Fig. 2 by the two extreme cases with central or edge heating. The agreement is quite satisfactory. The intermediate cases give comparably good results. It must be underlined that under these experimental conditions with the pure off-axis heating the T_e profiles inside the ECH2 deposition is just above but close to the threshold κ . Indeed, in such off-axis cases, χ_e^{PB} is very low, but, as expected from the model and also shown by Fig. 1 χ_e^{HP} stays rather high. We also observed experimentally and in the model that, as expected, this ratio goes down to about unity, with very low values of $\approx 0.2 m^2/s$ for both χ_e^{PB} and χ_e^{HP} , when the T_e profile drops below the threshold. It must be emphasized that the rapid variation of χ_e^{HP} for very small changes of χ_e^{PB} and $\nabla T_e/T_e$ is a monitor of the status of the T_e profile: above or below the threshold. Therefore, such conditions deliver a *direct* measurement of the threshold and might allow to discriminate between physics hypotheses on the turbulence involved. In particular, the good results obtained using κ without dependence on radius or plasma parameters suggest that the actual threshold should also be quite insensitive to plasma values. This is the case for the TEM driven turbulence [10], not for the ETG turbulence for which the threshold depends strongly on T_e/T_i and s/q [9].

As already found for others discharges with similar conditions the ITG/TEM Weiland model [10] gives for both the steady-state and modulation data quite good results [8], which are very similar to those obtained with the empirical model.

3. Variation of plasma current

We compare now two L-mode discharges at $B_T = 2.3$ T, 800 kA ($q_{95} = 4.8$, from Sect. 2) and 400 kA ($q_{95} = 9.8$), in their Ohmic phase and in their phase heated almost centrally ($\rho_t \approx 0.35$) by 1.3 MW of ECH. The discharge at 800 kA is sawtoothing, the inversion radius being $\rho_t \approx 0.25$ whereas that at 400 kA is sawtooth-free due to the high q_{95} value. The density

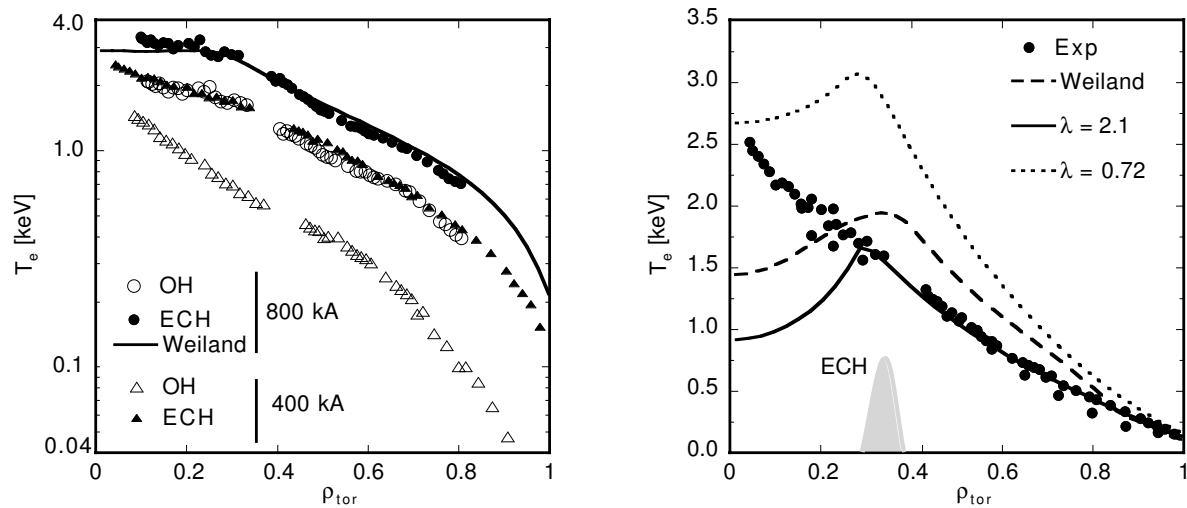


Figure 3: Experimental and modelled T_e profiles for L-mode plasmas with 1.3 MW ECH central deposition. Left: Experiment at $I_p = 800$ kA and 400 kA, and comparison with the Weiland model at 800 kA (log scale). Right: Data at 400 kA and models as indicated in the legend and text.

is kept low ($\bar{n}_e = 210^{19} m^{-3}$) to reduce the ion-electron energy exchange. The temperature profiles are shown in Fig. 3. We do not consider the part of the plasma inside the ECH deposition where the electron heat flux is very low which makes modelling or power balance very delicate, and where in addition sawteeth mainly determine the profile at 800 kA.

The data in the left plot (log scale) show the very similar slope of the profiles over a major part of the core plasma, as mentioned in Sect. 1. In this region $\nabla T_e / T_e$ is almost constant and the profiles are shifted, depending on the temperature in the edge region. The Ohmic case at 400 kA seems to behave differently, which might be attributed to the very low temperature, low electron heat flux and strong losses to the ions. Note the almost perfect coincidence of the profiles with ECH at 400 kA and Ohmic at 800 kA. The Weiland model agrees well with the ECH shot at 800 kA, as also shown in [8]. In the right part of the figure we compare the profile with ECH at 400 kA with the models. For the empirical model (Eq. 1) we could keep $\kappa = 2.3$. However the value of λ must be different for the two values of current: $\lambda = 0.72$ at 800 kA and $\lambda = 2.1$ at 400 kA. Note the perfect agreement with $\lambda = 2.1$ and the strong disagreement with $\lambda = 0.72$. This means that transport is much higher at 400 kA, in agreement with the usual I_p dependence. The Weiland model does not perform well at 400 kA, as shown in Fig 3 right, even forcing the temperature to take the experimental value at $\rho_t \approx 0.8$.

References

- [1] RYTER, F. et al., Phys. Rev. Lett. **86** (2001) 2325.
- [2] RYTER, F. et al., Phys. Rev. Lett. **86** (2001) 5498.
- [3] RYTER, F. et al. Plasma Phys. Contr. Fusion **44** (2002) A407.
- [4] HOANG, G. T. et al., Phys. Rev. Lett. **87** (2001) 125001.
- [5] IMBEAUX, F. et al., Plasma Phys. Controlled Fusion **43** (2001) 1503.
- [6] LOPES CARDOZO, N. J., Plasma Phys. Controlled Fusion **37** (1995) 799.
- [7] TARDINI, G. et al., Nucl. Fusion **42** (2002) 258.
- [8] TARDINI, G. et al., Nucl. Fusion **40** (2002), in press.
- [9] JENKO, F. et al., Phys. Plasmas **8** (2001) 4096.
- [10] NORDMAN, H. et al., Nucl. Fusion **30** (1990) 983.