THEORY BASED MODELING OF EC HEATED DISCHARGES

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1 Introduction

Electron heat transport in tokamaks has recently obtained growing interest, both on the experimental and theoretical side. The experimental heat diffusivity χ_e^{PB} can be determined through a power balance analysis. However, additional information is provided by the perturbed heat flux and temperature gradient, giving the so called heat pulse diffusivity χ_e^{HP} [1]. If the perturbation is periodic, χ_e^{HP} can be obtained through the Fourier analysis of the heat wave [2]. Models with non linear dependence of the electron heat flux (q_e) on ∇T_e (see Fig. 1) yield a different behaviour of χ_e^{PB} and χ_e^{HP}. An eventual critical threshold in ∇T_e or $\nabla T_e/T_e$ can lead to a strong increase of the heat flux with ∇T_e above the threshold. Under the experimental conditions ∇T_e would then be kept close to the critical values. As Fig. 1 shows, χ_e^{HP}/χ_e^{PB} becomes larger than one and power dependent. Therefore, the ratio χ_e^{HP}/χ_e^{PB} is a good measure for T_e profile stiffness.

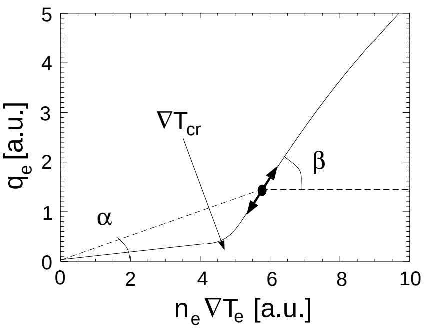

Fig. 1 Example of transport model with critical temperature gradient; $\chi_e^{PB} = \arctan(\alpha)$, $\chi_e^{HP} = \arctan(\beta)$. *Below* ∇T_{cr}, $q_e \propto \nabla T_e$ *and* $\chi_e^{PB} \approx \chi_e^{HP}$. *Above* ∇T_{cr}, $\chi_e^{PB} < \chi_e^{HP}$

Evidence for a threshold behaviour of electron transport is observed on ASDEX Upgrade ECH experiments [3]. Indeed the T_e profiles do exhibit a constant $\nabla T_e/T_e$ in the confinement region, independently of heating power, plasma current, density (n_e) and ion isotope. Experiments with ECH power modulation (MECH) confirm this behaviour: χ_e^{HP} is close to χ_e^{PB} inside the deposition layer and larger outside, where the heat flux is large [4].
To improve the physical understanding of electron transport, a comparison with theoretical predictions is required. Modeling MECH discharges provides a very constraining test for a transport model, which has to reproduce simultaneously the steady state profiles and the heat pulse propagation. The Weiland model [5], already tested successfully for Neutral Beam Injection heated H-mode discharges [6], is applied here to very different plasma conditions, with dominant electron heating provided by ECH. The physics of the model is mainly determined by the Ion Temperature Gradient (ITG) instability combined with the Trapped Electron Mode (TEM), which becomes dominant for these discharges.

2 Diagnostics and modeling set-up

T_e is measured by the Electron Cyclotron Emission diagnostics. The system consists of a superheterodine radiometer and 60 output channels, which allow a fine coverage of the plasma radius, since the spatial resolution is 6-12 mm, compared to the ASDEX Upgrade minor radius a=0.49 m. The sampling frequency is 30 kHz. n_e is measured through the combination of interferometry and Lithium beam diagnostics. The ECH is provided by

four gyrotrons, with a maximum power of about 1.6 MW, operating at the frequency of 140 GHz. The beam, polarized X-mode, experiences a 100 % single pass absorption at the second harmonic of the electron cyclotron frequency. The deposition radius (ρ_{dep}, where ρ is the normalized toroidal radius) can be adjusted by mirrors; it is measured in case of power modulation, otherwise it is calculated with the TORBEAM code [7].
The simulations are performed with the ASTRA transport code [8]. The boundary condition for both T_e and T_i is the experimental T_e value at the separatrix, since T_i profiles are not measured. n_e is taken equal to the experimental profile. The Weiland model is implemented as a subroutine in the ASTRA code, returning the transport coefficients at every time step; only diagonal coefficients are taken into account in the simulations. The version used here is of June 1998, with 7 equations including also impurities (dilution approximation) and collisions on trapped electrons.

3 Transport modeling

Discharges with different n_e, ECH power and ρ_{dep} are modeled. In the discharge # 13558 (see Fig. 2) the line averaged density is $\approx 2 \times 10^{19}$ m^{-3} and the total ECH power about 1.6 MW, with almost central deposition and no power modulation. Both experimental and modeled T_e are averaged over a sawtooth period.

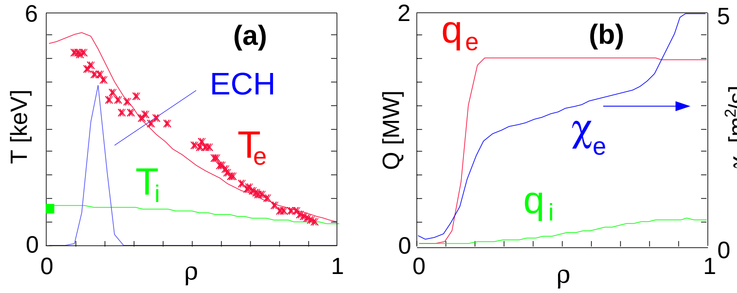

Fig. 2 Discharge 13558: (a) Experimental (points) and modeled (continuous line) temperature profiles; ECH power density after TORBEAM is overplotted. (b) Heat fluxes; χ_e from the Weiland model

The reproduction of the experimental T_e profile is quite good on the whole profile, although gradients are not very well predicted at every radial position. T_i profiles are not measured in these discharges, however the central value is measured to be about 1 keV, and it is matched by the model.
The good results of the steady state modeling motivate to push further the comparison between theory and experiment, involving also transient transport. Since the gyrotrons can be switched on and off periodically, it is possible to induce and let propagate heat waves in the plasma. The pulse propagation is almost source free over a wide radial extension because the ECH deposition layer is very thin: w/a < 0.1. For the selected MECH discharges n_e varies between 2 and $4 \times 10^{19} m^{-3}$, the ECH power between 0.2 and 1.6 MW and ρ_{dep} from 0.1 to about 0.35. The modulation frequency is 29.4 Hz. In some cases, several harmonics of $\tilde{T}_e$ are available, allowing to study the heat wave propagation at different frequencies with identical plasma conditions. An example is the discharge 13722 shown in Fig. 3, with plasma density about 4×10^{19} m^{-3} and off-axis MECH. Amplitude and phase of $\tilde{T}_e$ at 29.4, 58.8, 88.2 and 117.6 Hz are modeled, since the measured profiles exhibit a good signal to noise ratio over a wide region. The data are matched very well at all four harmonics, and both amplitude and phase. In particular the asymmetry is well reproduced, with steeper profiles (lower χ_e^{HP}) inside the deposition than outside; also quantitatively the slopes are very close to the experimental ones at all harmonics.

Besides, the correct absolute values of the amplitude and the phase at ρ_{dep} are obtained, which corresponds to realistic wave forms for the T_e time traces and to a correct delay of the perturbation at the different radial positions.

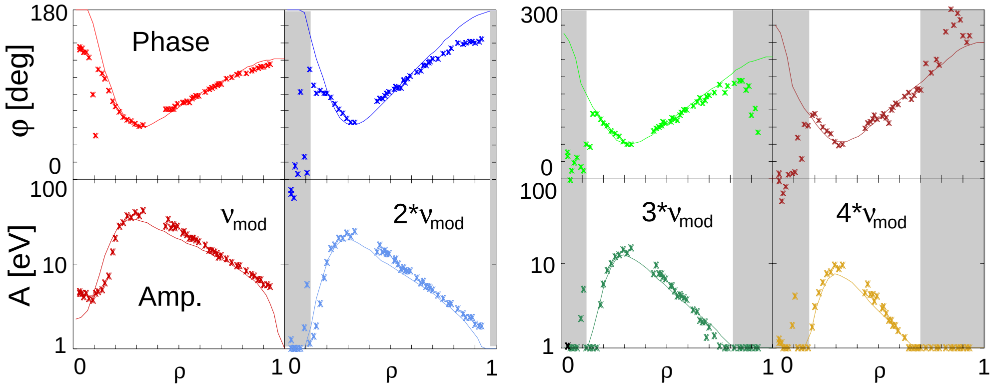

Fig. 3 Discharge 13722 with MECH at $\rho \approx 0.33$, ν_{mod}=29.4 Hz: experimental (points) and modeled (lines) amplitude and phase profiles of $\tilde{T}_e$ at the frequencies ν=29.4, 58.8, 88.2 and 117.6 Hz. The shaded regions have a poor signal to noise ratio.

The discharge 12935 has MECH at $\rho \approx 0.75$, for a time-averaged power of roughly 0.2 MW [4]. In Fig. 4 (a) the points represent the measured amplitude and phase profiles of the T_e perturbation. Two further gyrotrons are switched on later in the discharge, delivering 0.8 MW at half radius. In this way the heat flux dependence of transport can be investigated decoupled from the analysis tool. The experimental amplitude and phase profiles change their slope in correspondence of the deposition layer (see the points in Fig. 4 (b)). This means a clear increase of χ_e^{HP} outside the deposition, where the heat flux is larger. Therefore, the higher transport outside ρ_{dep} observed also in other ECH discharges is not an artifact of ECH modulation nor of the analysis method, but states an increase of χ_e^{HP} when the heat flux is enhanced.

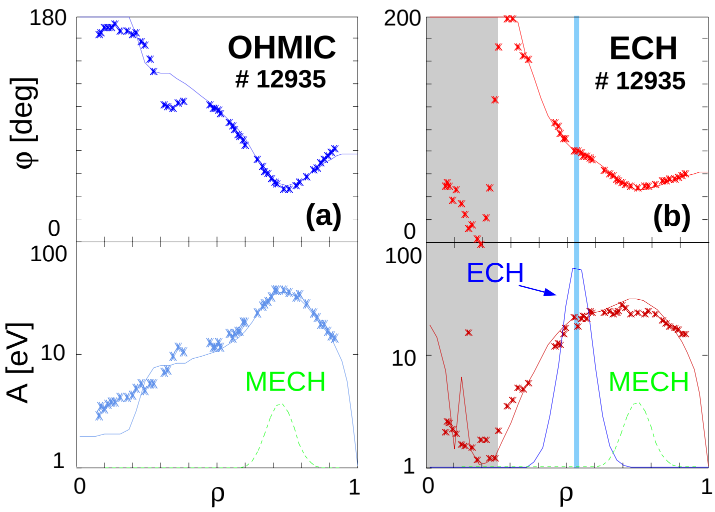

Fig. 4 Discharge 12935: experimental (points) and modeled (lines) amplitude and phase profiles of $\tilde{T}_e$ at $\nu = 29.4 Hz$. MECH (dashed line) is deposited at $\rho \approx 0.75$, with ν_{mod}=29.4 Hz and $\overline{P}_{MECH} = 0.2$ MW. (a) Quasi ohmic phase (b) After switching on ECH (0.8 MW) at $\rho \approx 0.5$.

The Weiland model reproduces the incremental transport before and after the onset of the two gyrotrons. The slope flattening outside the ECH deposition layer is predicted in excellent agreement with the experiment, qualitatively and quantitatively (see Fig. 4).

4 Discussion and conclusion

The Weiland model succeeds in the simultaneous description of the steady state as well as the transient transport. Therefore, it is possible to extract useful information about the properties required by a transport model in order to predict correctly ECH discharges, at least on ASDEX Upgrade. It is not obvious that a transport model is able to predict the behaviour shown by the ASDEX Upgrade MECH experiments presented above, first of all the asymmetry between inside and outside ρ_{dep}. To match the steady state results, the value of χ_e^{PB} must be realistic on the whole profile. For a good reproduction of the heat pulse, the χ_e^{HP}/χ_e^{PB} ratio must be predicted correctly and it has to fulfill the experimental heat flux dependence. Considering the experimental results [3] [4], it is important to check the profile stiffness predicted by the model, and how much the experimental and modeled R/L_{T_e} are close to the critical threshold, where R is the major radius and $L_{T_e} = |\nabla T_e|/T_e$. In Fig. 5 (a) the critical threshold is calculated at every radial position considering the experimental background profiles of the above mentioned discharge 13588. The points are calculated by running the Weiland model stand-alone, with experimental background profiles and increasing artificially ∇T_e until it drives $\chi_e > 0.2$ m^2/s; 0.2 is chosen instead of 0 to avoid the small residual transport, occurring in the model also for zero ∇T_e. The experimental R/L_{T_e} profile (continuous line) exceeds the predicted threshold by a factor ≈ 3 in the confinement region. This means that profiles are not close to marginal stability.

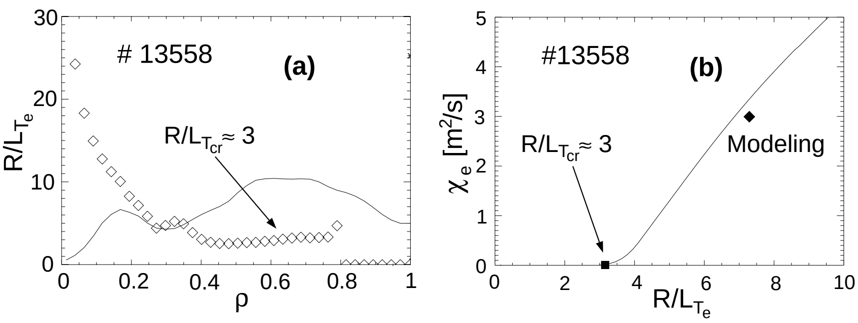

Fig. 5 (a) Critical (points) and experimental (line) R/L_{T_e} profiles. (b) χ_e dependence on R/L_{T_e} from the Weiland model (other parameters from experiment at $\rho = 0.63$); modeled χ_e and R/L_{T_e} at $\rho = 0.63$ (diamond).

A more careful investigation reveals indeed that the electron heat diffusivity does not increase very steeply beyond the critical gradient (Fig. 5 (b)), so that one can force higher gradients by increasing the heating power. Whether the TEM physics is a complete description or not, for ASDEX Upgrade ECH discharges it is not necessary to introduce further theoretical assumptions to describe electron transport, even varying the plasma parameters significantly. Besides, it appears possible to reproduce the experimental data with models which do not exhibit strong profile stiffness.

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