*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.120 (2004)*

Experimental Evidence for Electron Heat Transport Threshold in ASDEX Upgrade H-modes

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Introduction and experimental conditions

Electron temperature profiles in tokamak plasmas have been observed to weakly react to changes of the auxiliary heating power deposition profile. This property known as 'profile resilience' or 'profile stiffness', can be explained by an increase of transport in reaction to an increase of $\nabla T/T$ above a critical value. Recently, the electron heat transport has been investigated in several tokamaks, in particular using electron cyclotron heating (ECH). The experimental observations suggest that transport is likely to be governed by turbulence increasing above a threshold in $1/L_{T_e} = -\nabla T_e/T_e$. A critical gradient length model has therefore been proposed, first in [1] then modified and applied in [2], to experimentally investigate both the existence of such a threshold and the resilience. The diffusion coefficient is given by $\chi_e \propto \chi_s T_e^{3/2}(R/L_{T_e} - \kappa_c)H(R/L_{T_e} - \kappa_c)$, where κ_c is the threshold, χ_s a non-dimensional stiffness factor (which allows inter-machine comparison [2]) and the term $T_e^{3/2}$ takes into account the Gyro-Bohm dependence of transport driven by micro-turbulence. Some of the recent results [3]-[7] confirm this assumption and are in agreement with the main candidates supposed to cause the anomalous transport, the coupled TEM/ITG and ETG driven turbulence. In contrast to these pure electron heated L-modes ($T_e \gg T_i$), the electron heat transport in H-mode with dominant ion heating ($T_i > T_e$) has been addressed only in JET [2], DIII-D [9, 10] and ASDEX Upgrade [3], but many questions remain open. A detailed investigation of the problem using ECH is therefore the aim of this paper.

For these studies in ASDEX Upgrade, low density, sawtooth free deuterium H-mode plasmas have been used. The dominant ion heating is provided by $5MW$ neutral beam injection (NBI). ECH is added on top to change the electron heat flux. The plasma current is $I_P = 1MA$ and the toroidal field $B_T = 2.4-2.5T$. The power delivered to the ions (P_i) is approximately 65% of the NBI power and to the electrons (P_e) 20% (approximately $1MW$). Due to the low collisional coupling at these low densities, P_e can be more than doubled by applying up to the available $2MW$ of ECH [11], while P_i is not changed significantly. The discharges have been performed at $\bar{n}_e \sim 4.5 \cdot 10^{19} m^{-3}$. The ECH power deposition location ρ_{dep} has been changed between "on-axis" ($0.1 < \rho_{dep} < 0.2$) and "off-axis" ($0.35 < \rho_{dep} < 0.55$). The ECH is modulated (MECH with 50% duty cycle square wave and $\nu_{MECH} = 38.47Hz$) to allow transient transport analysis. The total average ECH power varies from $0.4MW$ during a first MECH phase to $1.2MW$ during a second MECH phase.

Experimental observations

Figure 1 shows the effect of the ECH on T_e, T_i, n_e, R/L_{T_e}, R/L_{T_i} and T_e/T_i for an off-axis ECH discharge. The electron temperature T_e increases to some extent only around the ECH power deposition region, while R/L_{T_e} is unchanged. The ion temperature T_i and R/L_{T_i} are basically unchanged. Essentially no effect is observed also in the density profile. Only when the ECH is deposited in the centre, the core T_e increases while the core

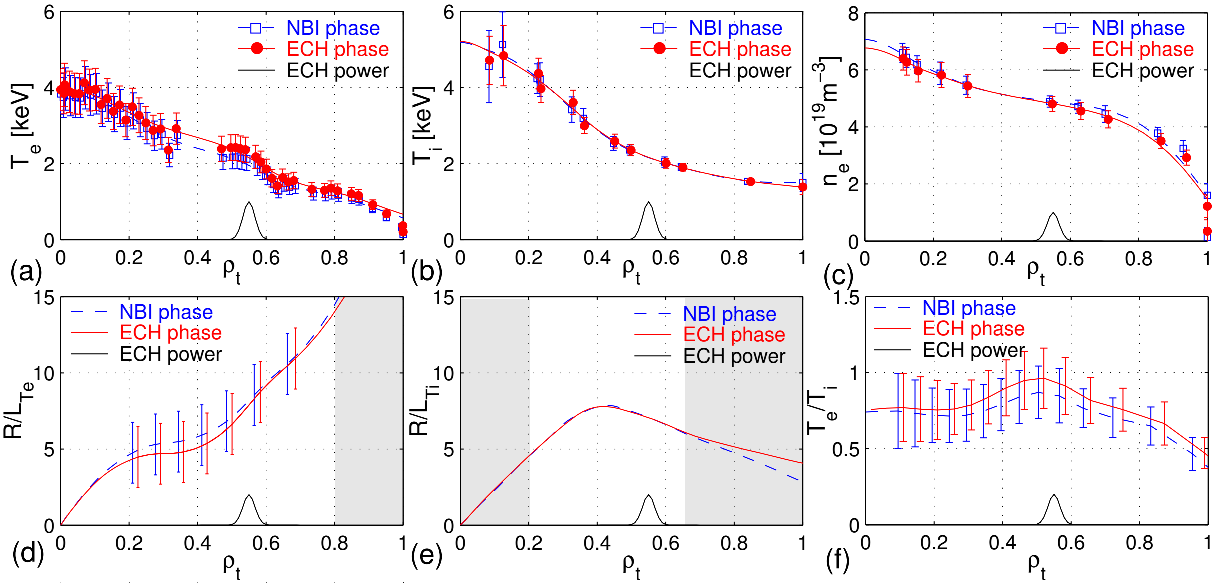

Figure 1: Effects of the switching on of the ECH on the profiles of (a) T_e, (b) T_i, (c) n_e, (d) R/L_{T_e}, (e) R/L_{T_i} and (e) ratio T_e/T_i for an off-axis ECH discharge. T_e/T_i, R/L_{T_e} and R/L_{T_i} are calculated from the fits made using cubic tension splines.

T_i slightly decreases, typically for $\rho_t < 0.5$. These observations are rather astonishing, especially considering that, locally, the electron heat flux is increased by a factor up to 1.6. In practice, the strong ECH power almost does not produce any T_e variations.

Transport analysis

The electron heat transport, assumed to be purely diffusive, is investigated with power balance (PB) and heat pulse (HP) propagation analyses using the ASTRA transport code. PB analysis yields the power balance heat diffusivity χ_j^{PB}, where $j = e, i$ is related to the species. HP analysis is carried out as described in [12, 13] yielding the so-called "(incremental) HP diffusivity": $\chi_e^{HP} = -\frac{\partial q_e}{n_e \partial \nabla T_e}$. The MECH discharges with power depositions at $\rho_{dep} = 0.1, 0.35, 0.55$ are analysed. The off-axis discharges allow the determination of χ_e^{HP} for the heat pulses propagating from the power deposition to both the plasma centre (low electron heat flux) and edge (high electron heat flux).

Figure 2 summarises the results of both PB and HP analyses, which have been carried out at $\rho_{an} = 0.25$ for the discharges with the MECH depositions at $\rho_{dep} = 0.1, 0.35$, and at $\rho_{an} = 0.45$ for those with the MECH deposition at $\rho_{dep} = 0.35, 0.55$. In figure 2 (a,b) we observe that, as usual, $\chi_e^{HP} > \chi_e^{PB}$ and that χ_e^{HP} is always higher for high electron heat flux ($\rho_{dep} < \rho_{an}$) than for low electron heat flux ($\rho_{dep} > \rho_{an}$). At $\rho_{an} = 0.25$, χ_e^{PB} and χ_e^{HP} change only little with increasing R/L_{T_e}. This can be interpreted with the T_e profiles being weakly resilient at $\rho_t = 0.25$. At $\rho_{an} = 0.45$, χ_e^{HP} and χ_e^{HP} increase significantly for small variations of R/L_{T_e} just above $R/L_{T_e} \sim 6$. Hence, the T_e profiles exhibit a strong resilient behaviour, and a threshold is estimated at $(R/L_{T_e})_{crit} \sim 6$. This interpretation is supported by figures 2 (c,d). Figure 2 (c) shows the dependence of q_e on $n_e \cdot \nabla T_e$, the ratio of which, by definition, yields the power balance heat diffusivity. The slope of the curve q_e versus $n_e \cdot \nabla T_e$ at each point is χ_e^{HP}, which is calculated from the HP analysis and is represented by segments at each full symbol. The points for the analyses carried out at $\rho_t = 0.25$ and $\rho_t = 0.45$ are clearly separated, indicating a different resilient behaviour between these two locations. Assuming for the heat transport the model introduced in

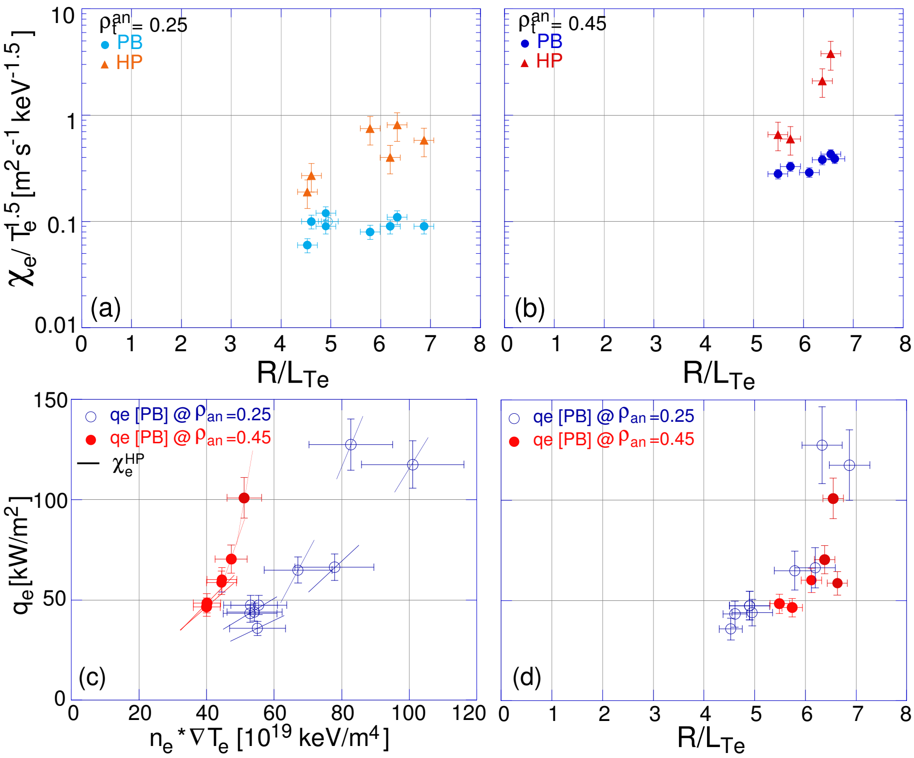

Figure 2: Heat diffusivity dependence on R/L_{T_e} at (a) $\rho_t^{an} = 0.25$ and (b) $\rho_t^{an} = 0.45$. Dependence of the electron heat flux on (c) $n_e \cdot \nabla T_e$ (segments on the points represent the χ_e^{HP}) and on (d) the R/L_{T_e} for all analysed discharges.

the beginning, it is logical to plot q_e versus R/L_{T_e}, as shown in figure 2 (d). Here, the points at $\rho_t = 0.25$ and $\rho_t = 0.45$ are clearly unified and the existence of a threshold in the electron heat transport properties around $(R/L_{T_e})_c = 6$ is strongly suggested.

Interpretation and comparison with other experiments

As already mentioned, the most probable candidates believed to cause the turbulent transport are the coupled TEM/ITG and, perhaps, in addition the ETG driven turbulence. These instabilities have the common property of developing above respective thresholds in R/L_T. When strong heat fluxes are transported in both the electron and ion channels, like in the here considered plasmas, turbulence involving both ITG and TEM is most likely to be responsible for the heat losses. We have verified that in this experimental domain, the value $R/L_{T_e} = 6$ does not correspond to an effective threshold for the TEM instability. This indicates that such value should rather correspond to the boundary between an instability domain in which the heat transport is weakly determined by R/L_{T_e} (at $\rho_t = 0.25$, $R/L_{T_e} < 6$, low heat flux) and a domain in which R/L_{T_e} is a drive for the instability (at $\rho_t = 0.45$, $R/L_{T_e} > 6$, high heat flux). Moreover, in the core region of the plasma $R/L_{T_i} \geq R/L_{T_e}$, while for $\rho_t \gtrsim 0.5$ the ratio is the opposite, with $R/L_{T_e} \geq R/L_{T_i}$. This could in principle lead to a transition in the dominant modes governing the transport in the core (inside ECH deposition) and in the outer regions (outside ECH deposition). Further investigation and experiments are needed in order to verify this possibility. Another difficulty is added by possible ETG modes being active: the profiles are in fact very close to the ETG threshold calculated according to [14].

Figure 3 (a) and (b) show the comparison of the R/L_{T_e} dependence of q_e and $\chi_e^{PB,HP}/T_e^{3/2}$

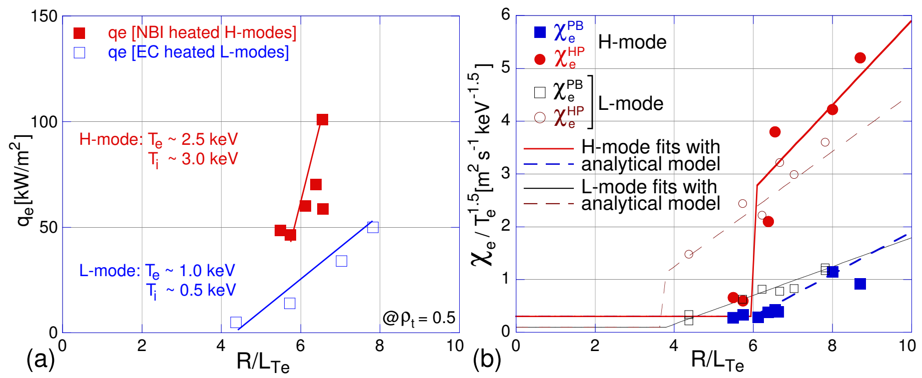

Figure 3: Comparison of the R/L_{T_e} dependence of (a) q_e and (b) $\chi_e^{PB,HP}/T_e^{3/2}$ between pure EC-heated L-modes and NBI-heated H-modes in ASDEX Upgrade. The measurement points are taken at $\rho_t = 0.5$. The two outer most in (a) at 0.6.

between the pure electron-heated L-mode plasmas (here called "eL-modes") presented in [8] and the NBI-heated H-modes ("iH-modes") presented in this work. In figure 3 (a) the resilience behaviour of the electrons is given by the slope of the line connecting the points. For a similar variation of q_e ($\sim +50kW/m^2$), the corresponding variation of R/L_{T_e} is different: in the eL-modes it is varied by a factor of 2, while in the iH-modes it is increased by not more than 20%. Consequently, it results that the iH-modes are apparently 4 times more resilient than the eL-modes. In figure 3 (b) the data is fitted using the critical gradient length model previously introduced. The model is used to fit the experimental profiles of T_e, amplitude and phase of the modulation using ASTRA. As a result, the dimensionless stiffness factor χ_s [2], corresponding to the slope of the curve above κ_c, is determined and used for comparisons. The computation of χ_s for the eL-modes and iH-modes in ASDEX Upgrade results in comparable values, with $\chi_s = 0.1 - 0.25$. The reason for this apparent contradiction lays in the $T_e^{3/2}$ dependence of transport driven by micro-turbulence. The temperature in the iH-modes is 2.5 times larger than in the eL-modes, resulting in a factor of 4 due to the $T_e^{3/2}$ term, which therefore explains the apparent inconsistency.

We are very grateful to the whole ASDEX Upgrade Team. The main author acknowledges financial support from EURATOM in the form of a Marie Curie Individual Fellowship.

References

[1] F. Imbeaux *et al*, 2001 *Plasma Phys. Control. Fusion* **43** 1503
[2] P. Mantica *et al*, O3.1A, 30th EPS Conference (2003), St. Petersburg, Russia
[3] F. Ryter *et al*, 2001 *Plasma Phys. Control. Fusion* **43** A323.
[4] F Ryter *et al*, 2001 *Phys. Rev. Lett.* **86** 2325
[5] F Ryter *et al*, 2001 *Phys. Rev. Lett.* **86** 5498
[6] G T Hoang *et al*, 2001 *Phys. Rev. Lett.* **87** 125001
[7] A Jacchia *et al*, 2002 *Nuclear Fusion* **42** 1116
[8] F. Ryter *et al*, 2003 *Nuclear Fusion* **43** 1396.
[9] C. C. Petty *et al*, 1999 *Phys. Rev. Lett.* **83** 3661.
[10] J. C. De Boo *et al*, 1999 *Nuclear Fusion* **39** 1935.
[11] F. Leuterer *et al*, 2000 *Fus. Eng. Des.* **56-57** 615
[12] N. J. Lopes Cardozo *et al*, 1995 *Plasma Phys. Control. Fusion* **37** 799
[13] A. Jacchia *et al*, 1991 *Phys. Fluids* **B3** 3033
[14] F. Jenko *et al*, 2001 *Phys. Plasmas* **8** 4096