Heat wave propagation experiments and modelling at JET: L-mode, H-mode and ITBs

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Introduction

Extensive investigation of electron heat transport mechanisms by means of heat wave propagation techniques has been carried out in JET plasmas. Electron temperature (T_e) modulation experiments were made possible by exploiting the direct, localized and tunable electron power source provided by mode conversion of the launched ICH power to short wavelength waves at the ion-ion hybrid layer [1,2]. In addition, cold pulses from the edge have been launched using Ni laser ablation or shallow pellets. The experiments have been carried out in L- and H-mode plasmas in order to explore the issue of stiffness in the electron channel, and in plasmas with internal transport barriers (ITB) in order to probe the transport in the ITB layer. Theoretical modelling of the results using empirical models and turbulence simulations has been performed. In particular, the use of an empirical model based on a critical temperature gradient length has allowed quantification of stiffness and comparison between stiffness in different machines.

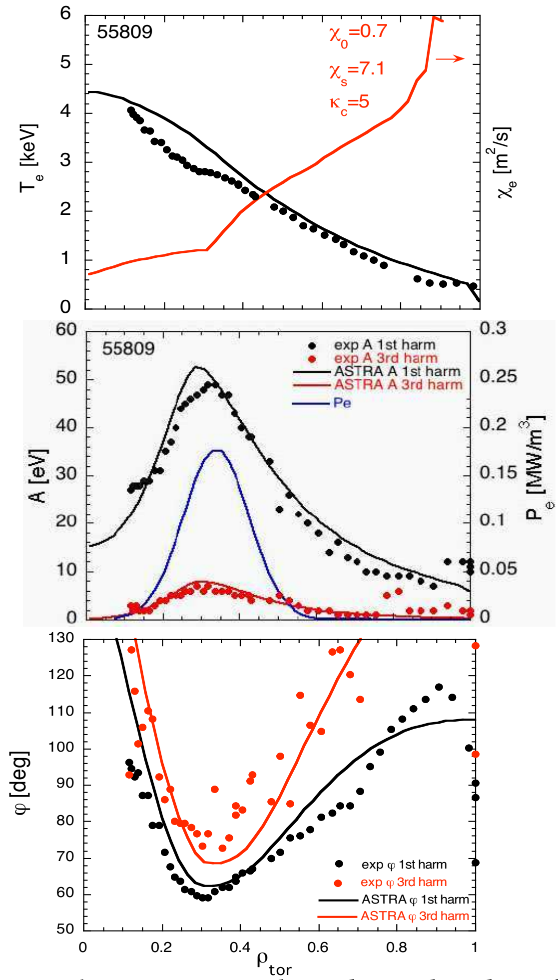
L- and H-mode plasmas

Results from T_e modulation and cold pulse experiments in JET L-mode plasmas have been reported in [3]. Following previous work on AUG [4,5], it has been shown also in JET that from modulation there is evidence for the existence of a threshold in the inverse electron temperature gradient length R/L_T ($1/L_T=-\nabla T_e/T_e$) above which the onset of turbulent transport causes an increase in the power balance χ_e and, even more detectable, in the perturbative χ_e. Recent work on JET electron stiffness has covered two further points.

On the analysis side, an empirical critical gradient length model for χ_e of the type [6]:

$$\chi_T = \chi_s q^{1.5}\,\frac{T}{eB}\frac{\rho_s}{R}\left(\frac{-R\partial_r T}{T}-\kappa_c\right)H\left(\frac{-R\partial_r T}{T}-\kappa_c\right)+\chi_0 q^{1.5}\,\frac{T}{eB}\frac{\rho_s}{R} \qquad (1)$$

has been proposed for stiffness analysis. Here $\rho_s=\sqrt{m_i T_e}/eB$, q is the safety factor, χ_0 and χ_s are dimensionless numbers giving respectively the residual and turbulent transport assuming a gyro-Bohm normalization, κ_c is the threshold. The model has the advantage of providing a quantitative definition of stiffness in terms of the parameter $\lambda_0=\chi_0/\chi_s\kappa_c$, and of providing estimates of the dimensionless quantities χ_0, χ_s, κ_c, $\lambda_0$which can then be compared amongst shots with different parameters or between L- and H-modes, and also amongst different machines. The model has been fitted using the ASTRA code [7] to JET profiles of T_e, amplitude (A) and phase (φ) of the modulation at different harmonics, allowing to extract the values of χ_0, χ_s, κ_c. An example of such a fit for an L-mode modulated shot is shown in Fig.1. In this case values $\kappa_c=5$, $\chi_0=0.7$, $\chi_s=7.1$, $\lambda_0=0.02$ are found. This value of λ_0 corresponds to a situation of moderate stiffness, which is found compatible in [6] with the recent ITPA two-term scaling law for energy confinement [8].



On the experimental side, new T_e modulation experiments have been performed in H-mode plasmas (B_T=3.25-3.6T, I_p=1.8 MA, n_{e0}=$310^{19}m^{-3}$, P_{NBI}<16 MW, P_{ICH}~3MW). In order to avoid big ELM crashes that would undermine the quality of the modulation data, H-mode plasmas with small and frequent type III ELMS have been employed. Fig.2 shows a comparison of T_e, A and φ profiles for L- and H-mode plasmas where the RF was modulated at the same position, frequency and duty-cycle. One can see that the spatial derivative of the amplitude logarithm and of the phase are very similar in the two cases, indicating very similar heat wave propagation and therefore core transport properties. The difference in the central T_e values in the two cases can be mainly attributed to the different pedestal temperature. Note that in both cases due to off-axis RF location the stiff region is limited to 0.4<ρ<0.7. There is a hint of flatter slopes in the stiff region in the L-mode case, which, taking into account also the T_e dependence of stiffness as in Eq.1, leads to slightly lower values of χ_s in the H-mode case.

Fig.1: Experimental and simulated profiles of a) T_e (together with χ_e profile, b) A (together with RF P_e profile), c) φ for L-mode.

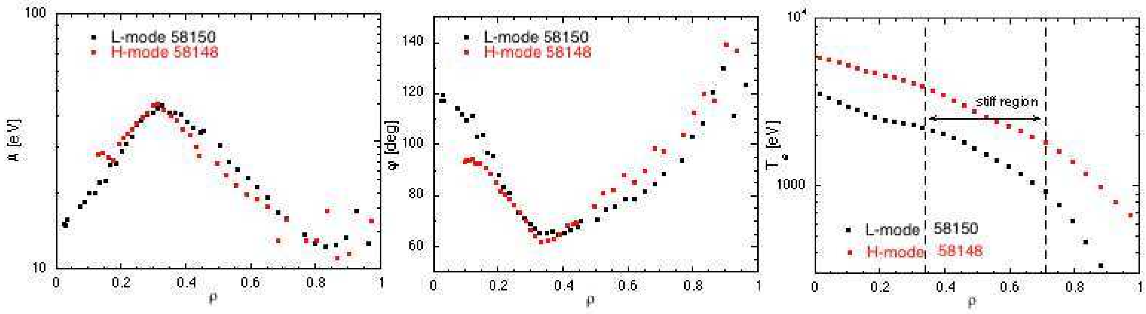


Fig.2:Experimental profiles of A, φ and T_e for L-mode (P_{NBI}=4 MW) and H-mode (P_{NBI}=14 MW) shots. Amplitudes are normalized to the H-mode shot to allow direct comparison.

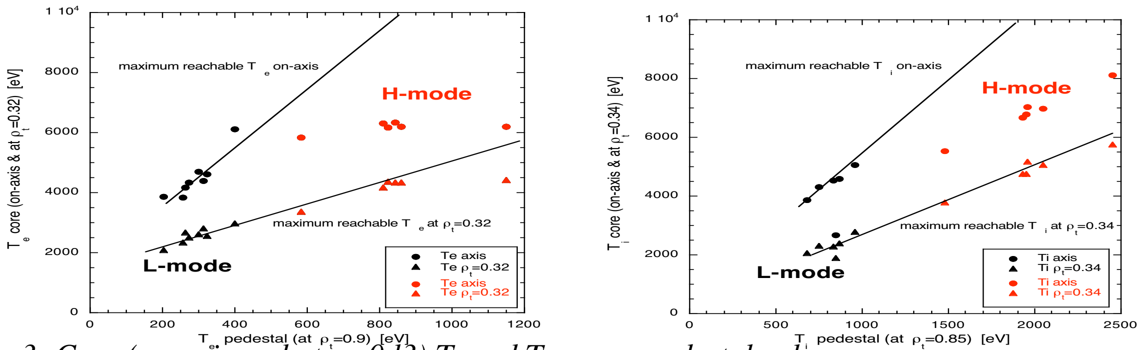


Fig.3: Core (on-axis and at ρ=0.13) T_e and T_i versus pedestal values.

That the main difference in L- and H-mode core temperature values is due to the pedestal, while core transport is similar, is confirmed by plotting the core versus edge temperatures, both for electrons and ions, as shown in Fig.3. A linear correlation can be seen between edge temperatures and temperatures at ρ=0.3, typically the radius at which the plasma goes below threshold. The on-axis values of temperature on the other hand show a bending in the H-mode case, indicating that the inner core is always significantly below threshold due to lack of central power density. The lines in Fig.3 indicate the maximum attainable central temperature if the plasma was close to marginality up to the very core. Similar results were also obtained in ASDEX-Upgrade [9,10] and JT-60U [11].

The analysis using the model in Eq.1 of a number of JET L-mode and H-mode shots with different parameters is summarized in Fig.4, where the electron heat flux normalized as suggested by Eq.1 is plotted versus R/L_{Te}. The dots represent steady-state analysis, while the lines are typical fits to modulation data. On the basis of modulation data it is found that in shots with significant ion heating (T_e/T_i~1, black dots and full line) the electrons are stiffer than in shots with no or small ion heating (T_e/T_i~1.5-2, red dots and dashed line). It is clear from Fig.4 that from steady-state data alone it is impossible due to the experimental uncertainties to identify the amount of stiffness (and consequently to discriminate between transport models with different degrees of stiffness). On the contrary, the fit to modulation data makes it possible to distinguish outside uncertainties cases with χ_s~6 (λ_0~0.02) (black line) from cases with χ_s~1.5 (λ_0~0.07) (red line).

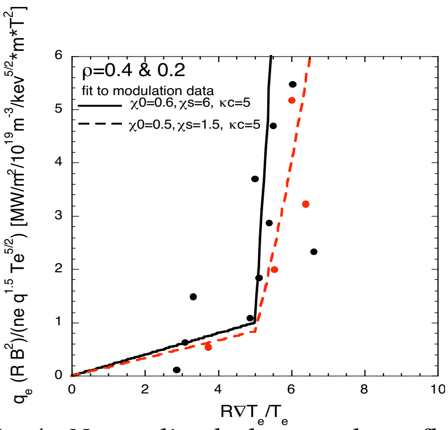


Fig.4: Normalized electron heat flux vs R/L_{Te}.The lines are fits to modulation data.

Inter-machine comparison of electron stiffness

The same kind of analysis has been applied to AUG modulated L-mode shots with pure electron heating [12] and to a FTU steady-state scan of the heat flux profile [13]. Values of χ_s~0.2-1.5 and λ_0~0.1-0.5 were found, which are consistent with the values found in JET dominant electron heating discharges. The details of this inter-machine comparison of stiffness are reported in [6]. Fig.5 summarizes the results in terms of χ_s vs T_e/T_i.

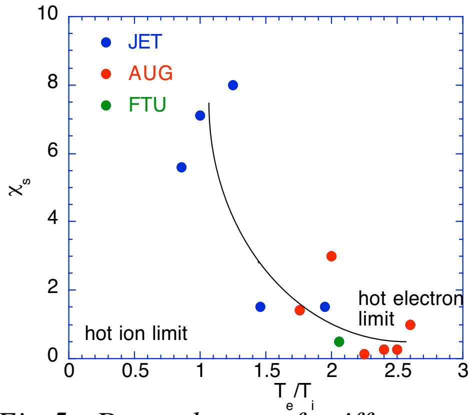


Fig.5: Dependence of stiffness parameter χ_s on T_e/T_i

The dependence of χ_s on T_e/T_i in Fig.5 is remarkably different from results obtained by DIII-D steady-state experiments in [14]. However this does not imply a contradiction, since DIII-D has explored the region $T_e/T_i<1$ while our results concern the region $T_e/T_i \geq 1$. Moreover, in DIII-D steady-state experiments κ_c and χ_s effects may be mixed. We note that at present there are no JET modulation results in the region of strongly dominant ion heating, so we cannot establish whether χ_s has a bell shaped dependence on T_e/T_i or whether at low values of T_e/T_i the dependence of the ITG threshold on T_e/T_i becomes the dominant player in determining the favourable confinement properties of hot ion plasmas. The experimental result in Fig.5 is in qualitative agreement with theoretical investigations of the dependence of stiffness on T_e/T_i by varying either the ion or electron heating using the collisionless Weiland model [15].

Quantitatively however the dependence of stiffness on T_e/T_i found in experiment is much stronger than predicted by theory, which requires further investigation.

ITB plasmas

T_e modulation experiments using mode conversion in ITB plasmas have recently been performed at JET. The data are presently under analysis.

Cold pulse experiments in ITB plasmas have been reported in [2,16]. It was observed (Fig.6a) that cold pulses are amplified by the outer ITB part and strongly damped in the inner ITB part. This would be consistent with ITBs as layers of reduced heat diffusivity, in which however the stabilization of turbulence can be deteriorated by the increase in temperature gradient associated with the cold pulse. This would in turn be consistent with a mechanism based on linear stabilization due to magnetic shear rather than a bifurcation process due to ExB shear. This result has been addressed by turbulence simulations using TRB [17] and CUTIE [18]. Fig.6b,c shows the time evolution of the simulated ΔT_e due to the cold pulse. The enhancement of the cold pulse when meeting the ITB foot is qualitatively reproduced in both cases

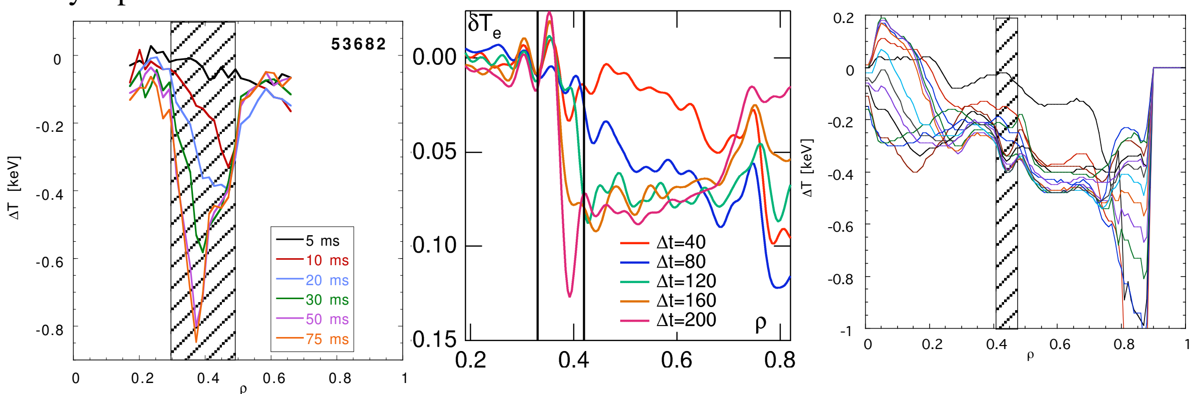


Fig.6: Time evolution of experimental (a) and simulated (b,c) ΔT_e profile following a cold pulse in ITB plasma. (b) with TRB(1 time unit=50 μs; 10 ms after cold pulse are shown), (c) with CUTIE (15 ms after cold pulse are shown).

Conclusions

Modulation of Mode Converted ICH power has been used in JET to investigate electron stiffness and compare with other machines using the same critical gradient length model. A good match between stiffness parameters in different machines is found for pure electron heated plasmas. In JET an increase of electron stiffness for increasing ion heating is observed. L- and H-mode core plasmas show similar stiffness properties. ITBs have been probed by edge cold pulses and results have been reproduced by turbulence simulations.

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