Transient Heat Transport Studies in JET Conventional and Advanced Tokamak Plasmas

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Abstract. Transient transport studies are a valuable complement to steady-state analysis for the understanding of transport mechanisms and the validation of physics-based transport models. This paper presents results from transient heat transport experiments in JET and their modelling. Edge cold pulses and modulation of ICRH (in mode conversion scheme) have been used to provide detectable electron and ion temperature perturbations. The experiments have been performed in conventional L-mode plasmas or in Advanced Tokamak regimes, in the presence of an Internal Transport Barrier (ITB). In conventional plasmas, the issues of stiffness and non-locality have been addressed. Cold pulse propagation in ITB plasmas has provided useful insight into the physics of ITB formation. The use of edge perturbations for ITB triggering has been explored. Modelling of the experimental results has been performed using both empirical models and physics-based models. Results of cold pulse experiments in ITBs have also been compared with turbulence simulations.

1. Introduction

The understanding of heat transport remains a high priority area in thermonuclear fusion research. Transient transport studies have proved to be powerful tools for separating different transport mechanisms and testing the validity of physics-based transport models [1-3].

In this paper, results from transient heat transport experiments in JET and their modelling are presented. The perturbative techniques consisted of a) cold pulses using Ni laser ablation or deuterium shallow pellet injection; b) modulated ICH in the mode conversion scheme. The comprehensive set of JET diagnostics and the long transport time scales make JET particularly suited for such studies, in particular providing the possibility of monitoring the ion component. The experiments have been performed either in conventional L-mode plasmas or in Advanced Tokamak regimes, in the presence of an Internal Transport Barrier (ITB). Modelling of the experimental results has been performed using both empirical models and physics-based models such as IFS-PPPL, MM-95, GLF23. Results of cold pulse experiments in ITBs have also been compared with turbulence simulations using the TRB [4] code.

2. Transient transport in JET conventional L-mode plasmas

In JET conventional L-mode plasmas, the issues of stiffness and non-locality have been addressed by T_e modulation and cold pulse experiments. ICH in D plasma with ~15-20% of ^{3}He results in mode conversion of fast waves into short wavelength waves, thereby providing efficient direct electron power deposition with good localization [5]. A scan of electron heat flux by changing ICH position and NBI power has been carried out. Figs.1-2 show the range of electron power density and heat flux profiles obtained.

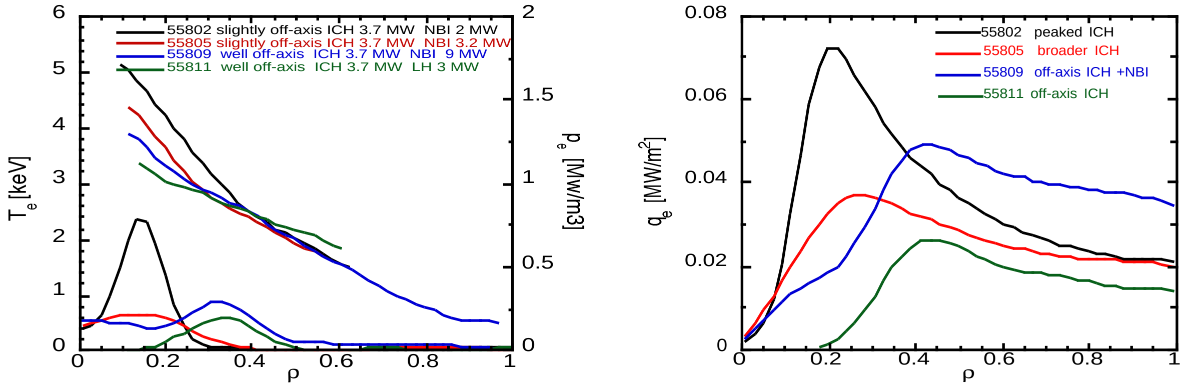


FIG.1. a) power deposition and T_e profiles for 4 discharges from the heat flux scan experiments; b) electron heat flux profiles for the 4 discharges shown in a).

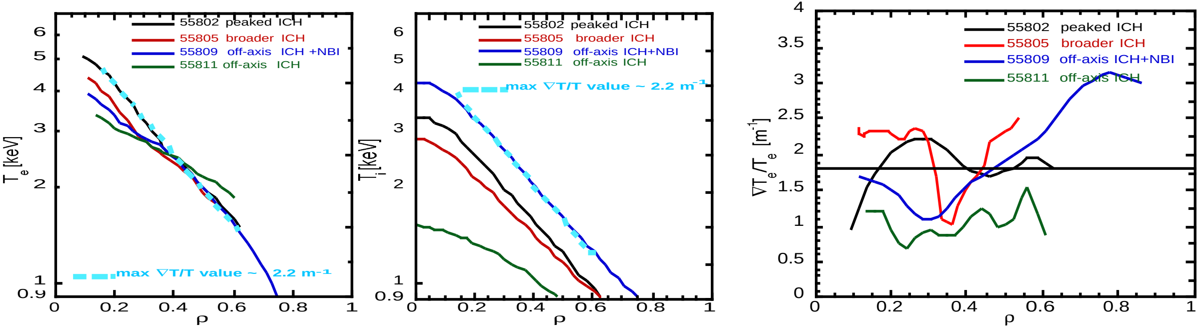


FIG.2. a) T_e and T_i profiles in log scale for the 4 discharges shown in Fig.1; b) profiles of $\nabla T_e / T_e$ for the same discharges.

In Fig.2a the T_e and T_i profiles are plotted in log scale, showing that a maximum value $\nabla T/T \sim 2.2\text{m}^{-1}$ is never exceeded in the core plasma (ρ<0.6). In Fig.2b the profiles of $\nabla T_e/T_e$ are shown. Assuming a critical value $\nabla T_e/T_e \sim 1.8\ \text{m}^{-1}$ as the threshold for the onset of stiff transport (this is justified below), one can see that in shots 55802 (black) and 55805 (red) $\nabla T_e/T_e$ is above threshold in the whole region ρ>0.1 (except for a small region around ρ~0.4 in shot 55805 where an MHD island flattens the profile). In shot 55811 (green) $\nabla T_e/T_e$ is below threshold throughout the plasma, while in shot 55809 (blue) it crosses the threshold value.

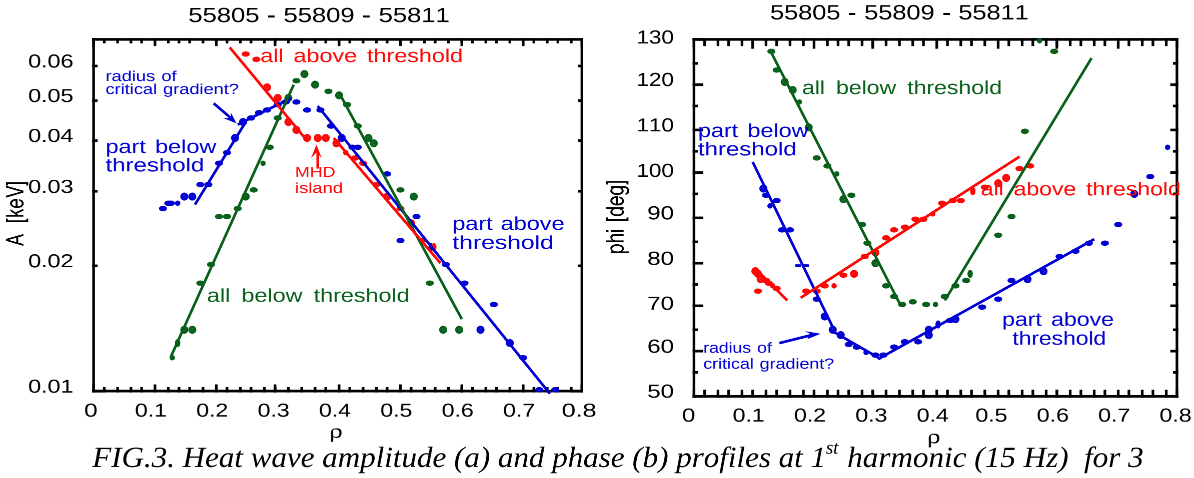


FIG.3. Heat wave amplitude (a) and phase (b) profiles at 1^{st} harmonic (15 Hz) for 3 discharges from the heat flux scan experiment

Considering now the modulation data, the issue is to identify whether the heat wave propagates differently in regions above or below threshold. The analysis concerns the electron channel alone, since with mode conversion no significant ion perturbation is excited, as confirmed by active CX spectroscopy. Fig.3 shows profiles of amplitude (A) and phase (φ) of the heat wave at f=15 Hz for 3 of the above discharges. In both A and φ plots, two slopes are observed (the slopes are indicative of the $1/\sqrt{\chi_e^{pert}}$ value [6]). A steeper slope is observed in regions below threshold, corresponding to a low value of χ_e^{pert} which is found to coincide with the power balance value, while a flatter slope is observed above threshold, with a ratio $\chi_e^{pert}/\chi_e^{PB}$ exceeding 10. The transition between the two modes of propagation appears quite sharp, as can be noticed in particular in shot 55809 (blue) where the heat wave is observed to cross the threshold and change abruptly its propagation speed. The data have been modelled using the 1D transport code ASTRA [7] and an empirical model for χ_e featuring the onset of stiff transport above a critical value of the inverse electron temperature gradient length [8]:

$$\chi_e = \chi_0 + \lambda\ T_e^{3/2}\left(\frac{|\nabla T_e|}{T_e} - \kappa\right)^{\beta} H\left(\frac{|\nabla T_e|}{T_e} - \kappa\right) \quad (1)$$

where H is the Heaviside function, χ_0 is the residual (constant) χ value below the threshold κ, λ and β quantify stiffness.

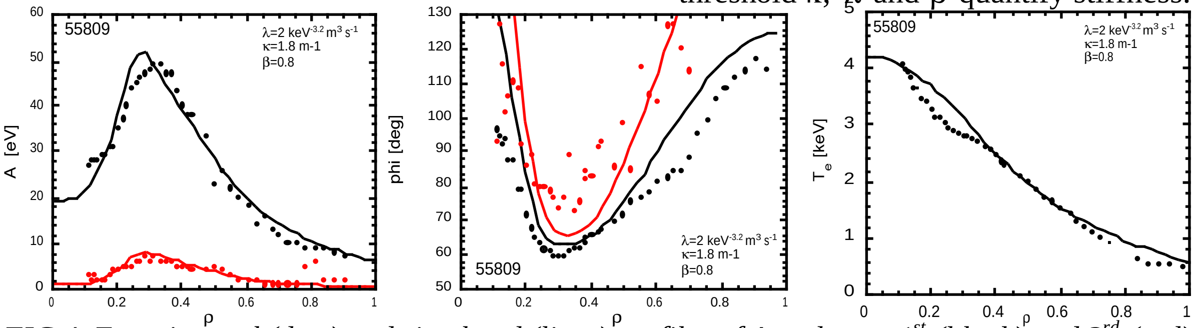


FIG.4. Experimental (dots) and simulated (lines) profiles of A and φ at 1st (black) and 3rd (red) harmonics and steady-state T_e for shot 55809 using the model of Eq.(1).

Indeed the model reproduces well the observations, with κ=1.8 m^{-1} (R/L_{Tc}=5.4), λ=2 m^{3}s^{-1}keV$^{-3/2}$, β=0.8. The fit in the case of shot 55809 is shown in Fig.4.

In summary, modulation results are consistent with the existence of a threshold in the inverse critical gradient length R/L_{Tc}~5.4, and a "medium" level of stiffness in the electron channel, as shown also in Fig.5. The results are in good agreement with results from AUG concerning electron stiffness [9]. Also, it has been shown [10] that they are not inconsistent with the recently derived ITPA two-term confinement scaling law [11].

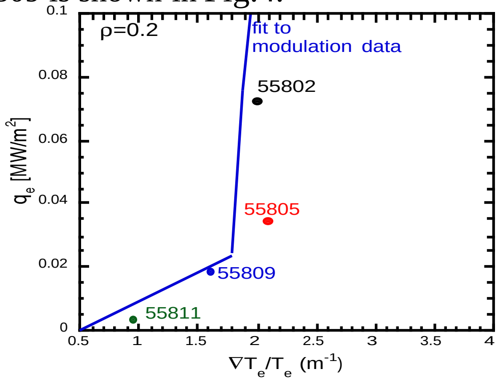


FIG.5. Electron heat flux vs $\nabla T_e/T_e$ at ρ=0.2 for the discharges shown in Fig.1. The line represents the empirical model that fits the modulation data.

Cold pulse perturbations performed in the same shots of Fig.1 are observed to travel almost instantaneously (within the experimental noise level) from edge to core, crossing at high speed also the regions below threshold where the modulation heat wave is observed to propagate slowly and where the simulation with the critical gradient model would predict a measurable delay (Fig.6). Similar observations of prompt responses of the core to edge perturbations were already reported for JET [12,13]. Here this is observed in a plasma without sawtooth activity (easier to diagnose in the core) and together with modulated heat waves featuring slower propagation. The observations suggest that, although stiffness can explain fast propagation in outer regions above threshold, stiffness alone is not enough to explain the fast response of the core to edge perturbations. Alternative explanations are "non-local" transport via the existence of radial structures connecting edge to core or via mode coupling, or avalanche-like processes triggered by the edge cold pulse and carrying with them a fast propagating turbulence front.

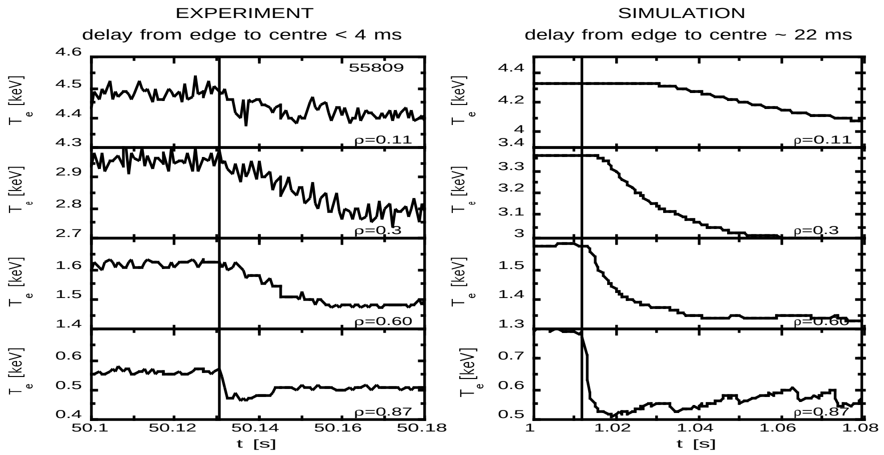


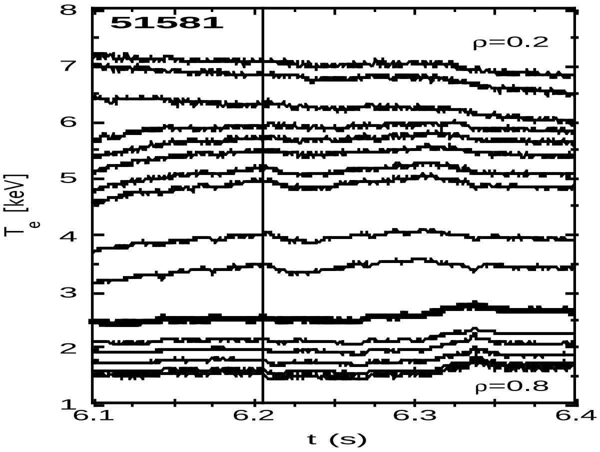
FIG.6. Experimental and simulated (using critical gradient model Eq.(1)) T_e time traces for cold pulse propagation in shot 55809.

3. Transient transport in JET Advanced Tokamak Plasmas

The only cases where a slowing down of the cold pulse has been observed in the core region are Advanced Tokamak plasmas with low or reversed magnetic shear. These observations have been reported in detail in [3], both during an ITB phase and in the absence of an ITB. In the latter case, the cold pulse is observed to slow down in the core, but its amplitude grows (at variance with simple diffusive propagation). Existing first-principles models such as IFS-PPPL, GLF23 and MM95 have been tested against the data and found not able to reproduce the whole set of observations for ions and electrons, although they can reproduce subsets of the observed features. Qualitatively, the observations are consistent with a region of stabilised transport due to low or reverse shear, which slows down the pulse but may be damaged by its arrival, giving rise to an increase in transport leading to an increase of the cold pulse amplitude.

Consistent with these observations, but possibly more dramatic in their consequences, are the observations of cold pulse propagation in the presence of an ITB. Fig.7 shows T_e time traces for one case with laser ablation, Fig.8 shows T_e profile evolution in a similar case with shallow pellet. The profiles of T_e variation for both cases are shown in Fig.9. One can notice that when the cold pulse meets the ITB foot its amplitude is enhanced in the outer ITB part, and is then damped strongly in the inner ITB portion. This suggests that the ITB is indeed a region of reduced heat diffusivity, which is however easily deteriorated by the increase of temperature gradient driven by the cold pulse. In the cases shown the ITB was strong enough to maintain its confinement capabilities in spite of the outer erosion. Weaker ITBs are however easily killed by cold pulses, and presumably the same type of phenomenon underlies the dramatic effect observed with ELMs, which lead rapidly to the loss of the ITB [14]. These observations bring additional elements for the understanding of ITB onset mechanisms, in particular regarding the issue whether experiments support more a 1st order or 2nd order type of transition, as discussed in [4]. In fact erosion due to transient enhancement of temperature gradient would be more easily compatible with a 2nd order transition scheme. Theoretical modelling of cold pulse propagation in ITB plasmas is being addressed via turbulence simulations. First results using the 3D ITG/TEM fluid turbulence code TRB are reported in [4] and are indeed in good agreement with experimental observations.

Finally, the issue of triggering ITBs by means of edge cold pulses has been investigated. Although in some cases an apparent coincidence in time has been observed [15], ITB triggering in JET is more strongly connected with the appearance of rational surfaces [15,16]. When the cold pulse is fired far from suitable conditions in terms of rational locations, it causes at most a weak increase in central T_e which does not develop into a proper ITB [3].



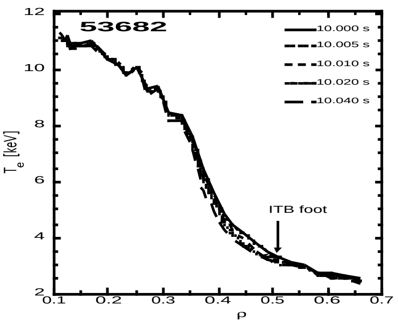


Fig.8: Time evolution of experimental profiles of ECE T_e following the cold pulse in ITB in shot 53682.

Fig.7: Experimental time traces of electron temperatures for a Ni laser ablation cold pulse (shot 51581, t=6.2 s) in a strong ITB. The channel at ITB foot is marked thick

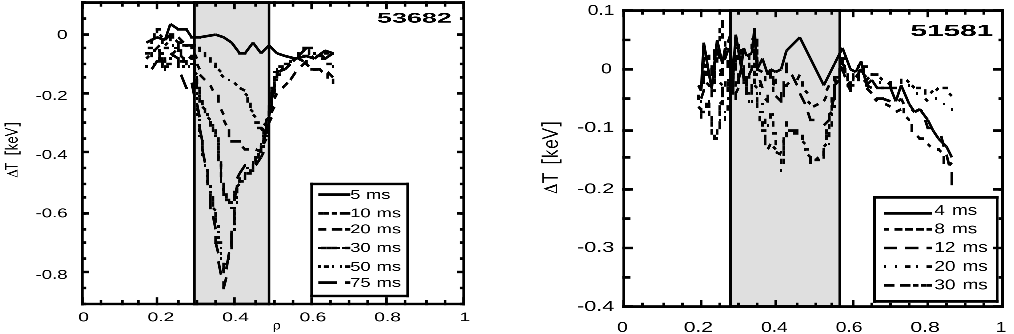


FIG.9: Time evolution of experimental profiles of ECE ΔT_e following (a) a shallow pellet cold pulse in shot 53682 and (b) a laser ablation cold pulse in shot 51581. The ITB region is shaded.

4. Conclusions

T_e modulation experiments in conventional L-mode plasmas show the existence of a threshold above which electron transport is characterised by a "medium" degree of stiffness. The results are not inconsistent with ITPA global confinement scaling laws. Cold pulse experiments show fast propagation from edge to core, requiring additional mechanisms than stiffness alone to be explained. Cold pulses are slowed down in regions of low or reverse shear. Physics based models have been tested against cold pulse data with non satisfactory results. Cold pulses in ITBs induce an erosion of the ITB outer edge and are damped further inside. The result is well reproduced by ITG/TEM turbulence simulations. Cold pulse induced ITB triggering decoupled from the role of rational surfaces could not be obtained.

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