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ABSTRACT

Transient transport studies have widely been recognised as a valuable complement to steady-state analysis for the understanding of transport mechanisms. Perturbative experiments have therefore been used extensively to investigate conventional plasma regimes in several machines [1]. They have also been used to investigate the nature of transport in the electron barriers observed in the RTP tokamak [2]. This paper presents the first attempt to use perturbative techniques to investigate transport in plasmas characterised by a strong ion and electron Internal Transport Barrier (ITB).

The experiments have been performed in JET plasmas with Optimised Shear (OS) scenario [3] ($2.6T < B_T < 3.4T$, $2.3MA < I_p < 3.1MA$, $210^{19}m^{-3} < n_{e0} < 410^{19}m^{-3}$, $P_{NBI} \leq 12MW$, $P_{ICRH} \leq 8MW$). The perturbative technique used was transient peripheral cooling (Cold Pulse, CP) induced either by Laser Ablation (LA) of metal impurities (mainly Ni) or Deuterium Shallow Pellet Injection (SPI). Both techniques have been tuned in order to provide T_e edge perturbations ~ 200eV. Typically the Prad perturbation caused by Ni LA was ~1MW, localised in the region $\rho>0.8$. Small mass, low velocity pellets (equivalent volume to a 1.72mm radius spherical pellet with a speed of 80m/s) have been used, resulting in a penetration depth < 10cm ($\rho>0.9$) with a 20% perturbation in the ne line integral. The ensuing time evolution of both T_e and (for the first time) T_i perturbations has been measured, using respectively the ECE and the active CX diagnostics. The latter had a time resolution of 50ms. OS plasmas both with and without ITBs have been probed. Core perturbations in P_{rad} and n_e are observed to be small enough on the time scale of heat transport as to not disturb the analysis of the propagating heat wave.

In the case of a CP during the ITB phase, two types of events have been observed: 1) weak ITBs are generally abruptly destroyed by the CP, resulting in a heat pulse being generated at the ITB location and traveling outward (symmetrically, also the birth of an ITB produces a cold pulse at the ITB location, travelling outward); 2) strong ITBs survive the CP and therefore allow to study the propagation of the cold front through the ITB region. Case 2) is the most interesting one and is illustrated in Fig.1 for a JET OS discharge (3.45T, 2MA) with $P_{LH} = 3MW$, $P_{NBI} = 12MW$, $P_{ICRH} = 4Mw$. A shallow pellet is fired at t = 10s, when the ITB is fully developed. The propagation of the induced cold pulse is interrupted at t = 10.8s by a MHD crash associated with double tearing modes, but the amount of time available to study the transient response is sufficient. A similar experiment made with LA in the absence of MHD crashes is shown in Fig.2, however in this case T_i measurements were not available. In both cases one can see a rather unexpected feature in the CP: the amplitude of the CP, both in the electron and in the ion components, instead of being damped to zero when the CP meets the low transport ITB region, is on the contrary strongly enhanced in the outer portion of the ITB region (the part adjacent to its foot), and then damped to zero further inside. The time evolution of T_e profiles during the SPI is shown in Fig.3. The ITB location is $0.3<\rho<0.5$. More clearly, the above mentioned feature is seen in the plot of maximum T_e variation during CP, which is plotted in Fig.4 together with its predicted behaviour in simulations assuming the ITB as a region of (constant) low heat diffusivity or a region of (constant) inward heat convection.

Assuming the heat diffusivity constant in time (or also with a simple dependence on ∇T), diffusive propagation can only result in a damping of the CP amplitude, and one would have the necessity to invoke the presence of inward heat convection. However the predicted effect would be much smaller than the observed one for values of heat pinch compatible with the steady-state power balance. Evidently transport in the ITB does not stay constant while the CP propagates through it, but is strongly modified at least in the outer ITB portion. Quantitative empirical simulations have been performed with ASTRA [4] for Pulse No: 53682. Different empirical models have been tested, featuring diffusive or convective barriers moving or shrinking in time at the CP arrival. The best reproduction of the experimental observations was obtained with a model with the following characteristics: the ITB has a diffusive (rather than convective) nature, and its outer part is progressively eroded by the CP, so that the outer foot shifts inward (by about 5cm), while the inner side remains fixed. This implies that χ_e in the outer ITB portion increases back to its pre-ITB value, while χ_e in the inner portion gets slightly lower, in order to compensate for the loss of insulation due to the erosion and maintain the core temperature unaffected as observed in the experiment. The increase of χ_e in the outer ITB portion results in the observed enhancement of CP amplitude, while the inner portion of the ITB has such a low diffusivity as to rapidly damp the perturbation to zero. The resulting time evolution for the simulated T_e variation pro-file during CP is plotted in Fig.5b and can be compared with the experimental one in Fig.5a.

This type of modelling, far from being satisfactory for the understanding of ITB physics, allows us to assess that 1) the ITB is indeed a region well localized in space where transport is reduced, 2) the transport reduction is associated with a reduction of heat diffusivity, while heat convection does not seem to play a significant role (which is normally assumed a priori but can only be experimentally verified using transients), 3) the transport reduction can be rather easily and abruptly destroyed by the negative temperature perturbation induced by the CP, which for weak ITBs results in a loss of the good confinement regime, but for strong ITB is limited to the outer portion of ITBs and does not destroy the confinement performance. The latter observation can be qualitatively associated with the transient increase of temperature gradient induced by CPs, which may bring the outer portion of the ITB above the critical value and therefore cause the loss of turbulence stabilization and transport reduction. However careful and quantitative theoretical modelling is required to assess whether critical gradient models are indeed capable of reproducing the experimental evidence. Also, experiments using modulated ECH instead of CPs would be useful to further test this possible explanation. In fact, in this picture a hot pulse reaching the ITB from the edge should be stopped at the ITB location without inducing any erosion and, more in general, a modulated heat source that can be placed at any location with respect to the ITB position would provide even more stringent experimental evidence for testing ITB transport models.

Cold pulse experiments in OS plasmas were often made in the absence of ITBs (i.e. in pre-or post-ITB phases or in discharges where ITBs did not develop). In this case they are useful tools to investigate the transport mechanisms at work in “conventional” plasmas characterized by low or negative magnetic shear. Issues like stiffness and more generally the testing of transport models can be addressed, with the advantage that, unlike other plasma scenarios, the absence of sawteeth allows to follow fully the propagation of the cold wave from edge to core. Two types of response can be observed: in a limited number of cases the so called "non-local" core temperature rise induced by edge cooling, which is thoroughly addressed in [5], and more usually the propagation of the negative wave which is illustrated in Fig.6. The most striking feature observed in Fig.6 is that the CP amplitude decreases as expected while travelling inward in the region $0.8>\rho>0.4$, but then it starts increasing, reaching large values in the core, which is a clear deviation from a simple diffusive paradigm. This feature is even more prominent in the ion than in the electron channel, suggesting an active role of ions in the process. It is also interesting to mention that such amplitude increase is observed only in plasmas characterized by strong rotation, while it disappears in pure ICRH or normal NBI plasmas. Moreover, the CP propagation is very fast in the region $0.8>\rho>0.4$, while it slows down to "power balance" time scales in the region $\rho<0.4$. This suggests that transport is "stiff" in the region $0.8>\rho>0.4$, while for $\rho<0.4$ stiffness is not observed and a complex mixture of ingredients gives rise to an increase of χ_e and χ_i during the CP propagation, originating the CP amplitude increase. Theoretical modelling of the pulse in Fig.6 in underway. First results using the IFS/PPL model [6] show that the model can indeed reproduce the feature of amplitude increase during CP propagation, however in the simulation the effect is too large and the time scale is too fast in the region $\rho<0.4$ compared to experiment.

In summary, cold pulse experiments have been successfully performed in JET OS plasmas with and without ITBs. The data are powerful tests for distinguishing the validity of different transport models. Results in ITB plasmas seem consistent with the widely adopted picture of a reduction of heat diffusivity in the ITB region due to turbulence stabilization below a critical value of the temperature gradient .

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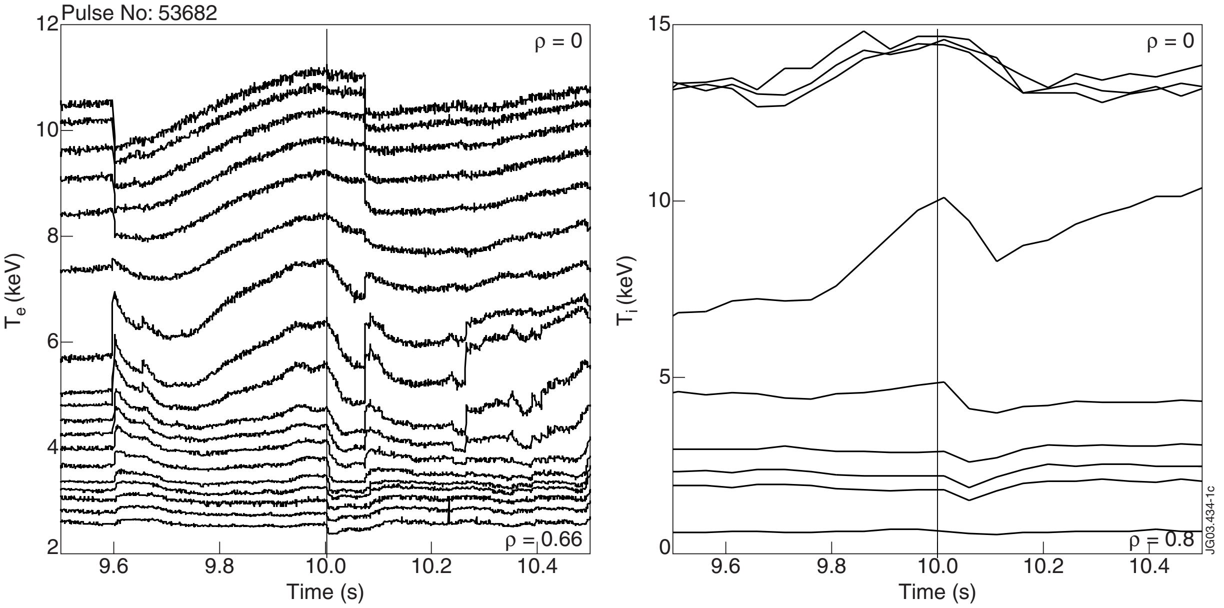

Figure 1: Experimental time traces of electron and ion temperatures in JET Pulse No: 53682 with ITB and SPI at t=10s.

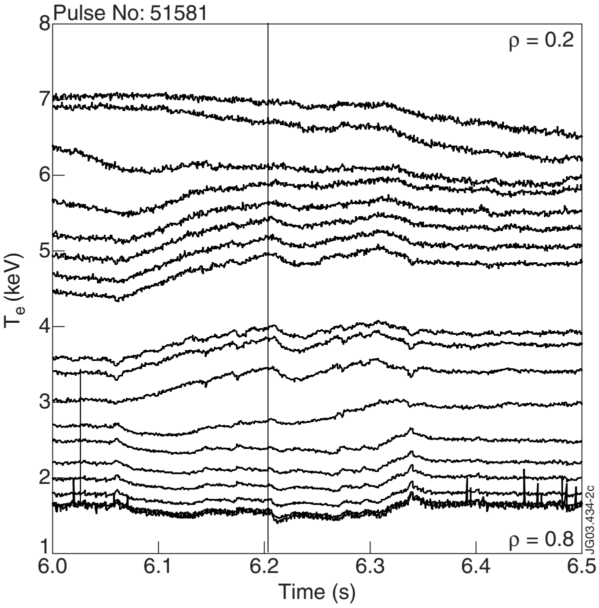

Figure 2: Experimental time traces of electron temperature in JET discharge 51581 with ITB and Ni LA at t=6.2 s.

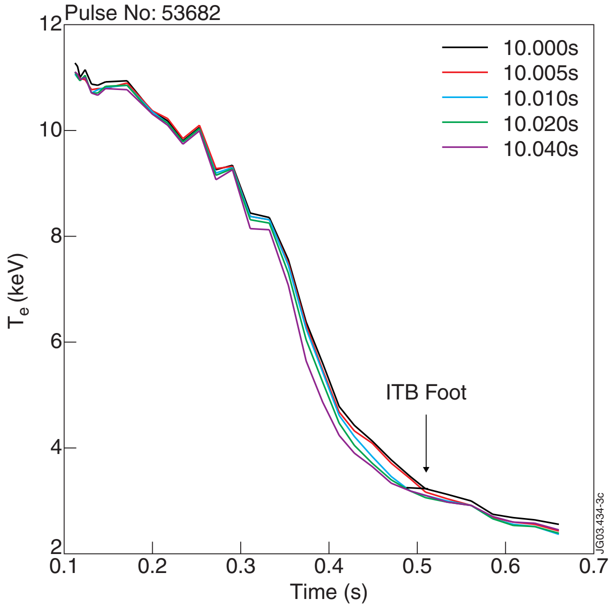

Figure 3: Time evolution of experimental T_e profiles during CP in JET discharge 53682.

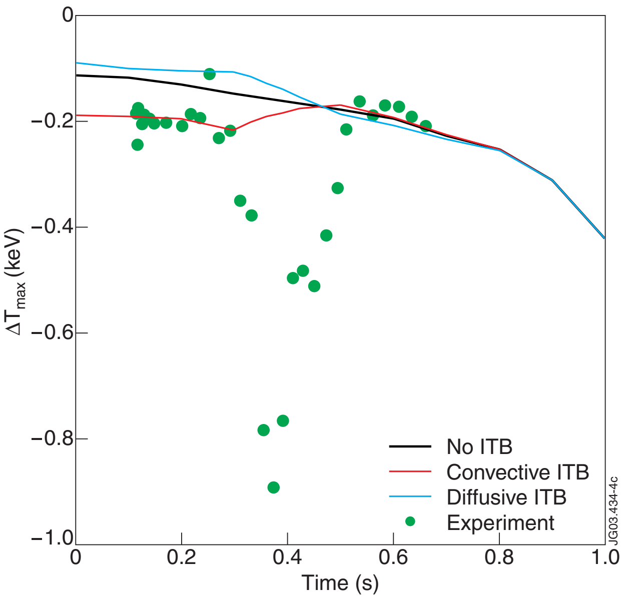

Figure 4: Radial profile of CP maximum amplitude compared with simulations using simple diffusive and convective models for the ITB region.

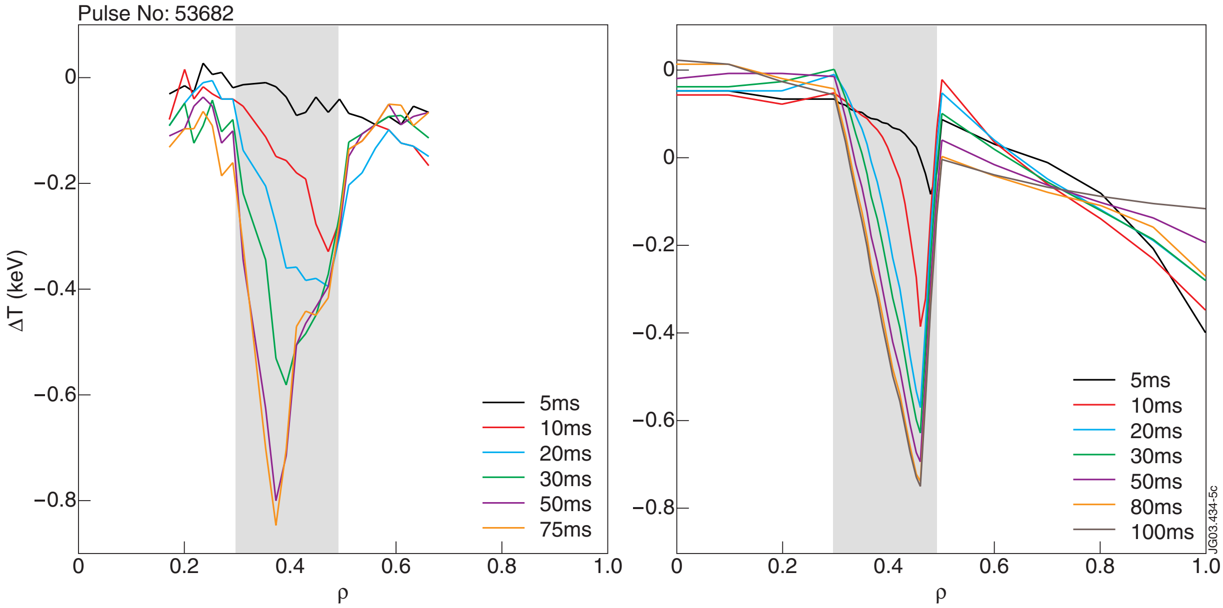

Figure 5: a) Time evolution of experimental ΔT_e radial profile during CP for shot 53682; b) the same for an empirical simulation featuring a diffusive ITB with erosion of its outer portion.

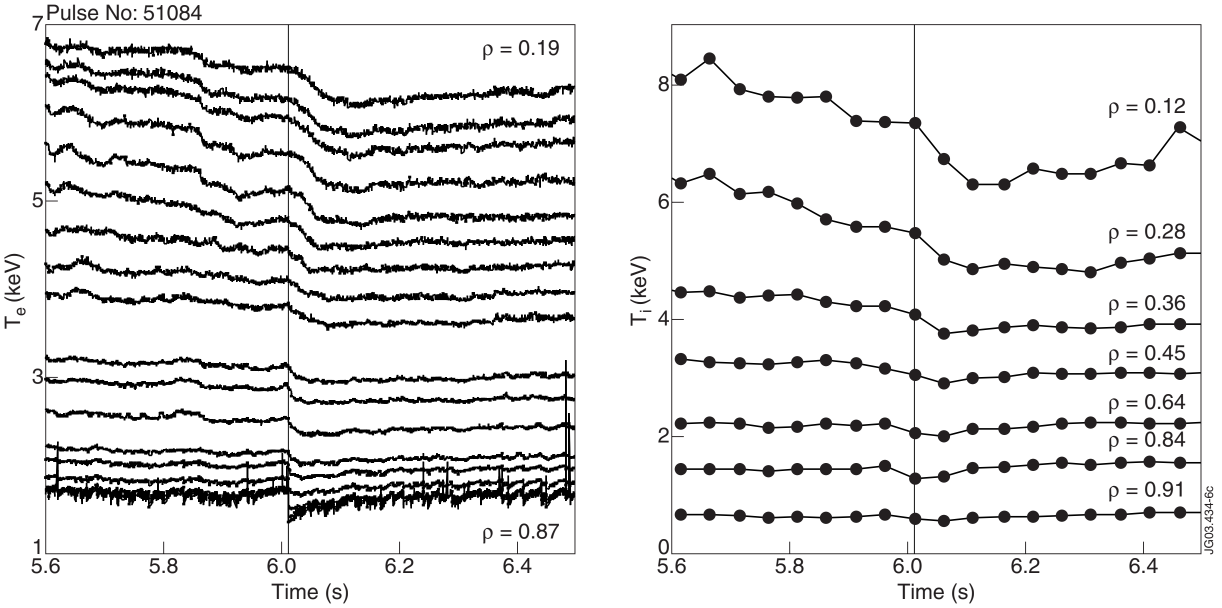

Figure 6: Experimental time traces of electron and ion temperatures for a pellet cold pulse (t=6s) with no core inversion (Pulse No: 51084).