

# NON-LOCAL ELECTRON HEAT TRANSPORT EFFECTS PROBED BY MODULATED ECH IN THE RTP TOKAMAK

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Non-local electron heat transport effects are commonly observed following a fast, strong perturbation of the electron temperature ( $T_e$ ) in the outer layers of tokamak plasmas [1]. A reaction of the central  $T_e$  opposite in sign with respect to the induced edge perturbation is observed. Two relevant observations that are common to all experiments [1] are a) a strong dependence on plasma density  $n_e$  (the inversion of polarity between edge and centre disappears at high  $n_e$ ), and b) a correlation between the non-local transient and changes in the sawtooth activity.

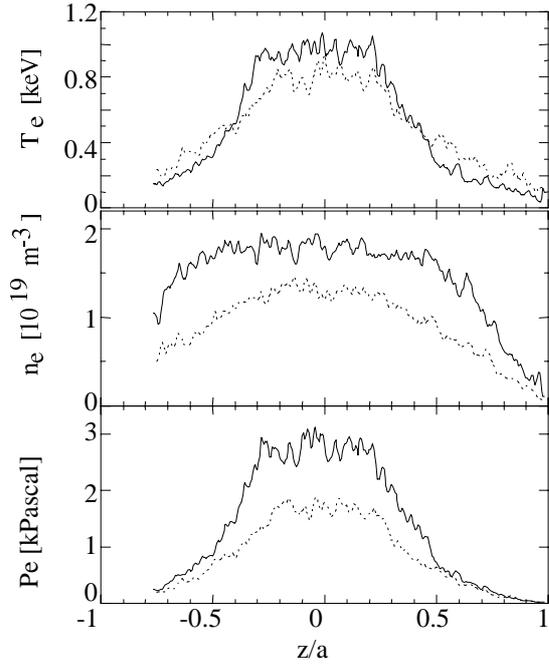
In RTP, fast cooling or heating of the plasma peripheral region was induced respectively by oblique injection of frozen  $H_2$  pellets, or either modulated ECH with very external resonance location or fast  $I_p$  ramps. First results were presented in [2].

The non-local  $T_e$  response has been interpreted as due to changes in  $\chi_e$  taking place in the central plasma region in the absence of a variation in the local thermodynamic quantities. However such interpretation has always been based on a negative argument: excluding all other possibilities, this is left as the only explanation of the observations. Direct experimental information on the mechanism underlying the phenomenon would be required.

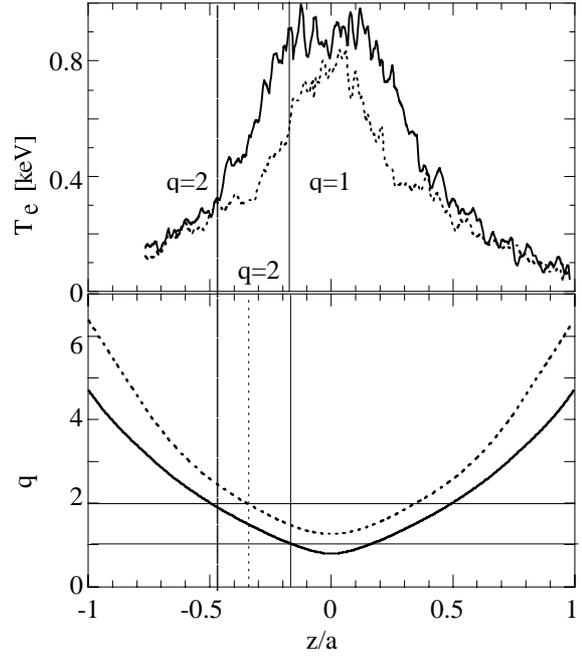
In this paper, we report new experimental results obtained in RTP. They rely on high-resolution Thomson scattering measurements of  $T_e$  during the cold pulse non-local transient and on the use of high frequency modulated ECH (MECH) superimposed on cold pulses. This allows to probe the changes of diffusive transport induced by the cold perturbations. These experiments provide evidence that the non-local  $T_e$  rise in the core is due to the formation of a large temperature gradient (thermal barrier) in a narrow plasma layer. This barrier acts as a layer of transiently increased thermal resistivity when probed by MECH.

Fig. 1 shows Thomson scattering measurements taken in repeated discharges with and without oblique pellet injection. The time of the measurements corresponds the top of the rise for the case with pellet. During the non-local transient the plasma develops a sharp  $T_e$  gradient in the layer  $0.3 < r/a < 0.5$  (the profile remains flat in the region  $r/a < 0.3$ ). Such a  $T_e$  profile in a purely Ohmic discharge directly points to a spatial discontinuity in transport. Apparently thermal transport in the layer is transiently decreased by a factor of two ( $\nabla T_e$  changes from 7 to 14 keV/m).

The position of such a barrier is found to depend on the plasma current, or the safety factor  $q$ . Fig. 2 shows, for two discharges with different  $q_a$  values, the two  $T_e$  profiles at the top of the  $T_e$  rise along with the two  $q$  profiles taken in the Ohmic steady-state phase just prior to pellet injection. They have been computed from the measured  $T_e$  and  $n_e$  profiles assuming neoclassical resistivity and correcting for the bootstrap current. It is seen that in both cases the barrier lies in the  $q$ -range  $1 < q < 2$ . Note that in the discharge with  $q_a = 6.6$  there is no  $q = 1$  surface.



**Fig. 1.**  $T_e$ ,  $n_e$  and  $p_e$  profiles (measured with Thomson scattering) for two low density discharges (r19980303.005-006,  $n_e=0.85 \times 10^{19} \text{m}^{-3}$ ,  $q_a = 4.7$ ) without (dashed line) and with (continuous line) pellet injection.



**Fig. 2.**  $T_e$  profiles (measured with Thomson scattering) and calculated pre-pellet  $q$  profiles for two discharges at  $n_e = 1.4 \times 10^{19} \text{m}^{-3}$  with  $q_a=6.55$  (r19980303.015, dashed line) and  $q_a=4.7$  (r19980303.026, continuous line).

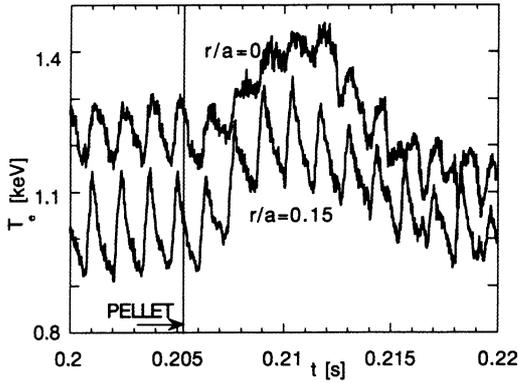
MECH experiments have been carried out to elucidate the transient transport properties of the thermal barrier. Oblique pellet injection was performed on plasmas in which the modulated ECH power ( $f=750 \text{ Hz}$ ,  $dc=0.3$ ) was deposited at different radial locations with respect to the position of the thermal barrier. The inward/outward propagation of the heat pulses and its change during the cold pulse was investigated.

Fig. 3 illustrates the changes in the inward propagating heat pulses for a case where the resonance was set at  $r/a=0.15$  (within the thermal barrier region, near its inner side). A large reduction in the MECH amplitude is observed in the  $T_e$  time trace at the plasma centre on the same time scale as the  $T_e$  rise. The MECH amplitude in the other time trace (representative of the plasma layer where the barrier forms and MECH is deposited) is almost unaffected. The change in heat pulse propagation lasts only for the duration of the thermal barrier, i.e. about four MECH cycles. In cases with resonance at  $r/a=0.33$  (within the thermal barrier region, near its outer side) we observe that the outward propagating heat pulses feature a similar drop while getting out of the barrier region.

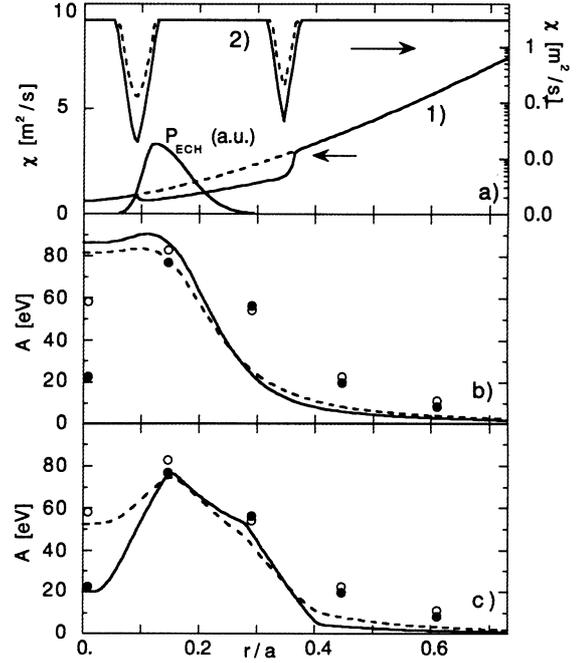
An attenuation of the heat pulse by a factor of two across 2 cm (ECE diagnostic spatial resolution) cannot be explained in terms of changes in current density and Ohmic power deposition profiles. Some change in energy transport must be taking place in a narrow region of the plasma. There are two reasons to ascribe such change to diffusive transport: a) it is observed through high frequency MECH which is not very sensitive to convective components; b) a change in convective transport (which should have the direction of an inward pinch to explain the  $T_e$  rise) would never be able to explain a drop in the MECH signal propagating towards the centre. Fig. 4 shows two qualitative simulations of MECH induced heat pulse propagation obtained by solving numerically the linearized electron heat transport equation

$$\left(\frac{3}{2}i\omega + \frac{1}{\tau}\right)T_\omega - \frac{1}{n_e}\nabla(n_e\chi_e\nabla T_\omega) = p_\omega \quad (1)$$

where  $T_\omega = Ae^{i\phi}$  is the  $T_e$  perturbation at the modulation frequency  $\omega$ ,  $p_\omega$  is the modulated power density and  $1/\tau$  a damping term. Fig.4a shows the  $\chi_e$  and  $p_\omega$  profiles used: in case 1),  $\chi_e$  is taken to decrease during the cold pulse in the whole layer  $1 < q < 2$  (as one may infer from the Thomson scattering observation). This model performs rather poorly (Fig.4b), featuring an amplitude increase in the whole central region, rather than the observed drop in the centre and no change elsewhere. Good agreement with the experimental observations is obtained for case 2) (Fig.4c), where the changes in  $\chi_e$  are concentrated in two narrow layers near  $q=1$  and  $q=2$ .



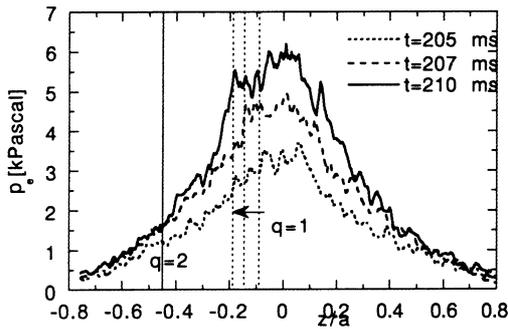
**Fig. 3.** ECE  $T_e$  time traces for a discharge with combined pellet injection and MECH (discharge r19970522.020,  $q_n = 5.3$ ,  $n_e = 1.77 \cdot 10^{19} \text{ m}^{-3}$ ). MECH resonance at  $r/a=0.15$ .



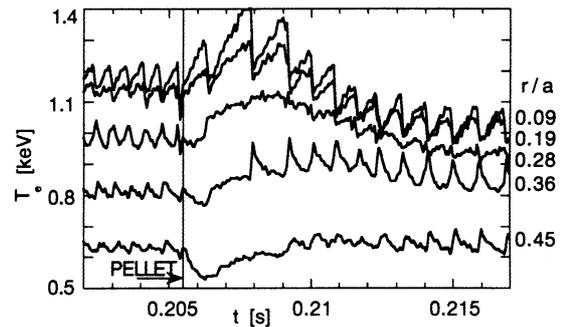
**Fig.4.** Simulations of the MECH A profile before (dashed line) and during (continuous line) a cold pulse. 4a)  $\chi_e$  and  $p_\omega$  profiles used in the simulations: case 1) smooth  $\chi_e$ ; case 2)  $\chi_e$  featuring two barriers at  $q=1$  and  $q=2$ . 4b) simulated A profiles using  $\chi_e$  model 1); 4c) simulated A profiles using  $\chi_e$  model 2). The experimental data of shot r19970522.020 are plotted for comparison (open and full circles refer to before and during cold pulse respectively).

An accurate modelling of the MECH propagation is beyond the scope of this paper. A basic question is however whether the changes in  $\chi_e$  inferred from MECH are enough to explain the observed  $T_e$  increase. Power balance before and during the cold pulse indicates that indeed the change of  $\chi_e$  profile shown in Fig.4 (case 2) is able to account for the observed  $T_e$  increase. We can conclude that MECH experiments provide direct evidence that non-local transients are indeed associated to changes in energy transport, and these turn out to be localized in narrow regions. Steady-state transport barriers have been observed in RTP in a series of dedicated experiments in which the resonance position of the localized ECH was scanned in small steps through the plasma [3]. The observations are described very well by a model featuring a shell structure of alternating layers of high and low diffusivity (barriers), where the barriers are associated with low order rational  $q$  surfaces [4]. The new observations reported in this paper fit very well in this picture. The so called non-local  $T_e$  rise can be explained in terms of a transient strengthening of one or more pre-existing transport barriers.

One could speculate about the mechanism behind the transient strengthening of transport barriers. The time evolution of the  $T_e$  and  $p_e$  profiles during the cold pulse provides some more insight into this. Fig. 5 shows that the location of the discontinuity between flat and sharp gradient regions expands by about 1.5 cm in 5 ms in this case. This is consistent with the expansion normally observed of the sawtooth inversion radius (Fig. 6), and suggests that a peaking of the  $J$  profile takes place during the cold pulse. One can calculate that the current enclosed by the  $q=1$  surface has to increase by 1.5 kA (15%) to expand it as observed. This is compatible with current diffusion from the cooled edge. The increase in central Ohmic power associated to that is not enough to explain the  $T_e$  rise, since it is almost compensated by the decrease in resistivity. In fact the sawtooth reheat rate does not change during the cold pulse. However the  $J$  peaking could be responsible of the observed changes in sawtooth period and amplitude and, most importantly, could be the cause of the change in transport. In fact we know from [3,4] that the width of the barriers may depend in a subtle way on the local value of the shear. Even a small change in  $J$  could then cause the observed strengthening of barriers and be the local mechanism that causes the change in transport. This mechanism may also allow to explain why the  $T_e$  rise increases at low density: in fact due to a larger relative perturbation of the edge density, low density discharges feature a larger  $J$  peaking during cold pulse. This is confirmed by a more pronounced expansion in time of the flat  $T_e$  region (cf. Fig. 2 and Fig. 5). A larger  $J$  peaking induces a stronger effect on barriers, which, associated with the smaller number of particles, causes a larger  $T_e$  rise in low density plasma.



**Fig. 5.** Time evolution of the  $p_e$  profile during the non-local transient (measured with Thomson scattering) for three identical discharges ( $n_e = 1.22 \times 10^{19} \text{ m}^{-3}$ ,  $q_a = 5.05$ ). The pellet enters the plasma at  $t = 205.4$  ms.



**Fig. 6.**  $T_e$  (from ECE) time evolution following pellet injection for a sawtooth discharge (r19970224.021). One can notice an expansion of the inversion radius during the cold pulse.

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