

'Cold Pulse' Experiments in RTP Ohmic and ECH Plasmas

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Oblique pellet injection (OPI) has been used in the RTP tokamak as a means to cool the plasma periphery. In Ohmically heated low density plasmas, the resulting 'cold pulse' triggers a large T_e rise in the plasma core [1,2]. The rise has been ascribed to a significant transient drop in electron thermal diffusivity (χ_e) in the region $1 < q < 2$. Conclusive evidence on the χ_e drop from Modulated ECH (MECH) experiments is reported below. We also report new evidence on OPI experiments in plasmas with dominant ECH heating. The ECH power was provided by a 110 GHz, 350 kW gyrotron (2nd harmonic X-mode injected from the low field side).

Fig.1 shows experimental T_e time traces together with a transport simulation. In the experiment, a pellet is injected obliquely (impact parameter $\rho_p=0.7$) in a plasma with modulated ECH ($\omega/2\pi=750$ Hz, duty cycle $d_c=0.3$, $P=120$ kW). The ECH resonance is at $\rho_{dep}=0.15$. The T_e traces for $\rho < 0.2$ feature the typical rise following OPI. At the same time, the amplitude of the T_e modulation at $\rho \approx 0$ drops substantially without any observable change in the modulation in the other ECE channels. The drop in modulation amplitude is a direct demonstration that a change in transport is indeed occurring in the plasma. In fact Ohmic power redistribution alone would not affect heat wave propagation. Moreover, the change must involve diffusive rather than convective transport, for two reasons: i) high frequency MECH is rather insensitive to convective heat flux components; ii) a transient heat pinch, as would be required to explain the core T_e rise, would not cause an amplitude drop in the plasma centre.

In order to quantify the change in χ_e required to explain at the same time the central T_e rise and the central amplitude reduction, time dependent simulations have been performed using the ASTRA [3] transport code. The code solves the coupled force balance and transport equations of tokamak plasmas. Of relevance for these experiments are the electron heat transport and the current diffusion equations. Electron-ion energy exchange is negligible in RTP at these low densities. Neoclassical resistivity and bootstrap current are taken into account. The main plasma parameters (including the density (n_e) time evolution) are taken from experiment.

The model assumed for electron heat transport is described in Fig.2a. During the steady state before OPI, the model features a radially increasing diffusivity and a small heat pinch component. This allows good reproduction of the time averaged T_e profile (Fig.2b) and of the amplitude and phase profiles of the T_e perturbation at 1st harmonic (Fig.2c-d). The heat pinch component is introduced in order to model consistently steady-state T_e profile and MECH heat wave propagation (due to the well known discrepancy in tokamaks between power balance and perturbative χ_e values, see [4] and [5]). Following OPI, a uniform reduction by a factor 2.2 is applied to χ_e in the $1 < q < 2$ layer (Fig.2a). The heat pinch component is constant throughout the cold pulse. The time averaged T_e profile at the top of the rise is shown in Fig.2b, the amplitude and phase of the heat wave corresponding to the 5 cycles during the rise are shown in Fig.2c-d.

The T_e time traces corresponding to this simulation are superimposed to the experimental T_e time traces in Fig.1. The agreement with experiment is quite satisfactory. In accordance with earlier work on RTP [6,7] also a model featuring thin barriers located near low order rational surfaces which were enhanced during OPI was tested. This gives equally good reproduction of the present data [5]. However, the resolution of the present data is insufficient to resolve the finer barriers, and hence in this paper only the coarser χ_e model is discussed.

As a final remark, we note that the physical mechanism triggering the measured χ_e drop is still not understood. Here we only note that, owing to the delay between the core T_e rise and the diffusive propagation of the inward cold pulse, a non-local dependence of transport is not required to explain the observations [8].

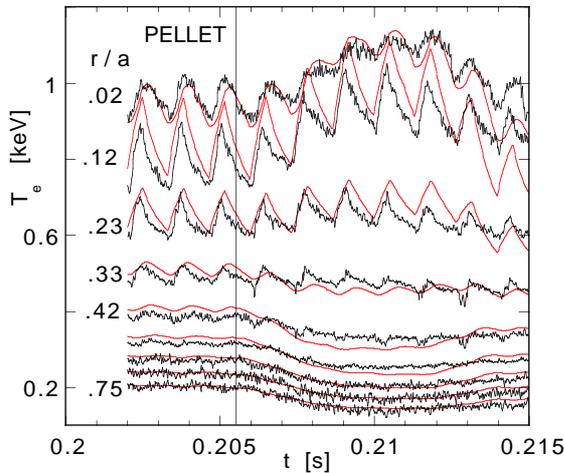


Fig.1. Experimental (black) and simulated (red) T_e time traces for a discharge with combined pellet injection and MECH (discharge $r19970522.020$, $q_a=5.3$, $\bar{n}_e=1.77 \cdot 10^{19} \text{ m}^{-3}$). MECH resonance at $\rho=0.15$. The simulation was performed with the model illustrated in Fig.2a.

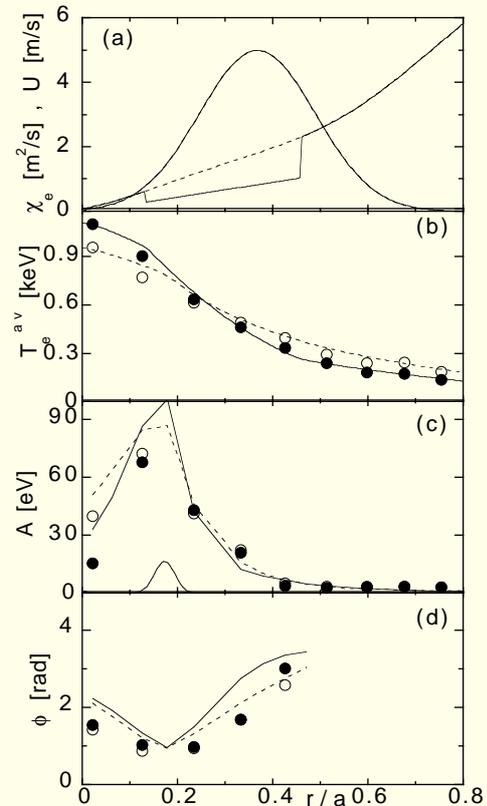


Fig.2. Simulation of the experiment of Fig.1.: a) χ_e and U profiles; b) T_e profile averaged over MECH; c,d) amplitude and phase of MECH wave at 1st harmonic (the ECH power density profile is also indicated). Dashed and continuous lines refer to simulation before and during cold pulse. Open and full circles refer to experimental data before and during cold pulse.

Recent OPI experiments in RTP plasmas with powerful ECH add a number of new features to the picture described above for Ohmic plasmas. The main observations are that (i) the limit density value below which a central T_e rise occurs is larger for ECH than for Ohmic plasmas and (ii) the plasma response to OPI depends strongly on the location of the ECH power.

We recall that previous experiments with strong localized ECH have demonstrated that the T_e profile reacts discontinuously to a continuous change of the resonance location [6]. Fig.3 shows that 5 plateaux can be identified, the transition from one to the next occurring when a

low order rational q surface is lost from the plasma. This evidence has been the basis for the model featuring thin transport barriers located near low order rational surfaces proposed in [7]. For each of the plateaux identified, cold pulse experiments have been performed.

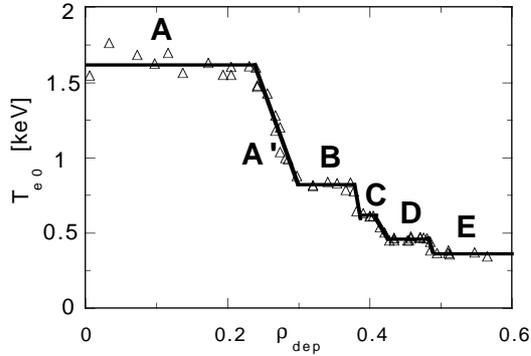


Fig.3: T_{e0} vs. ρ_{dep} in a B_T scan experiment.

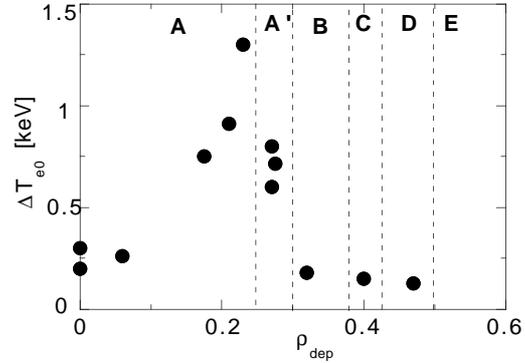


Fig.4: maximum T_e variation during cold pulse as a function of the ECH deposition radius.

Fig.4 shows the magnitude of the maximum T_e variation following OPI as a function of ρ_{dep} for discharges from plateau A to D. We note that for central ECH deposition, the T_e rise is comparable to the rise obtained in Ohmic plasmas. However for off-axis ECH deposition it becomes significantly larger, reaching a record value (T_e almost doubles in the plasma centre) when the ECH is deposited around $\rho_{dep}=0.23$ (i.e. near the edge of plateau A, with ρ_{dep} just inside $q=1$). We also note that while for plateau A and A' (sub-plateau in Fig.3) the T_e rise is maximum at the plasma centre, in plateaux B to D the maximum T_e rise is measured off-axis.

For lack of space we shall only report on OPI in plateau A, where the T_e behaviour is most striking. Fig.5 shows T_e time traces at different radial positions for a cold pulse in a ECH discharge with $\rho_{dep}=0.23$. The sensational T_e increase (confirmed by Thomson scattering profile measurements) is the main feature to be explained, also in comparison with the smaller rise for slightly different values of ρ_{dep} . A key observation in this respect is that the T_e profile becomes peaked during the T_e rise in spite of the resonance position being located off-axis. This can be recognised in Fig.5 by the different time evolution of the three innermost channels following OPI. This feature cannot be explained by a pure variation in the heat diffusivity as in the model assumed for Ohmic plasmas (Fig.2a). Dedicated MECH experiments reported in [9] have shown that in off-axis ECH dominated plasmas in plateau A a significant inward convection term is required in the region $\rho < \rho_{dep}$ in order to explain steady-state and MECH observations. This convective term, already present in the steady-state phase before OPI, must be enhanced during OPI in order to explain the observed T_e profile peaking.

A qualitative simulation of the experiment in Fig.5 is shown in Fig.6. The χ_e and U profiles used before and during pellet injection are shown in Fig.7. Besides increasing with radius, χ_e has been given an inverse dependence on n_e to reproduce the LOC scaling of confinement with n_e . During OPI, χ_e is reduced by a factor 1.7 in the region $1 < q < 2$. This drop in χ_e is comparable to that required in Ohmic plasmas (Fig.2a), but in the presence of high ECH power it yields a central T_e rise significantly larger than in the Ohmic case. In addition to this, the strength of the heat pinch in the region $\rho < \rho_{dep}$ is increased by a factor 2.8. This model allows to reproduce the two observations of a large T_e rise and of a peaking of the T_e profile. One could speculate that a record T_e rise is obtained in plasmas near the edge of plateau A because

the heat convection efficiency is maximum when ρ_{dep} is located just inside $q=1$. This point however needs further investigation. On the other hand, we note that the poor T_e rise observed for $\rho_{dep} \approx 0$ may be related to strong $m=1$ activity which occurs under these conditions, although it is not clear how the mode would affect the changes in transport.

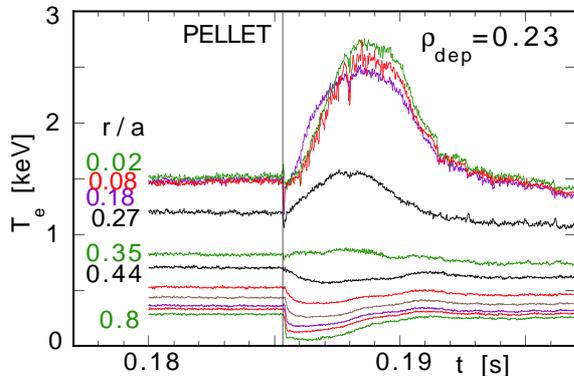


Fig.5: Experimental T_e time traces for a discharge with pellet injection in a plasma with CW ECH off-axis heating in plateau A ($P=280$ kW, $\rho_{dep}=0.23$).

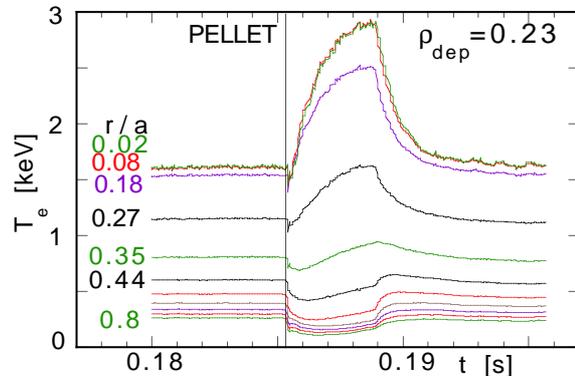


Fig.6: Simulated T_e time traces for the discharge of Fig.5 using the model illustrated in Fig.7.

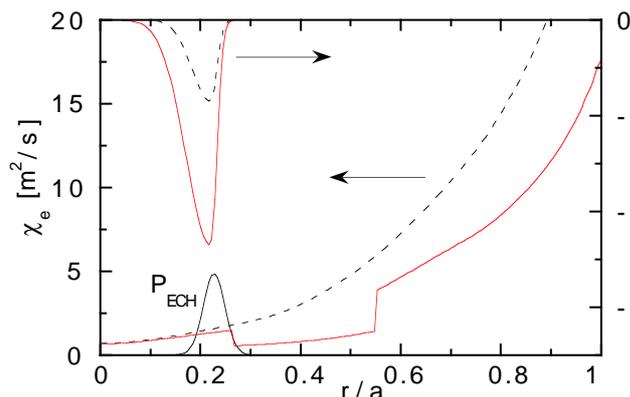


Fig.7: Model used for χ_e and U in the simulation of Fig.6. Dashed line refers to before pellet injection, full line to the top of the T_e rise. The ECH power deposition profile (in a.u.) is also shown.

In conclusion, OPI experiments in RTP ECH plasmas show a marked dependence of the T_e rise on the ECH resonance location. The record T_e rise occurs for ρ_{dep} just inside the $q=1$ surface and seems to be due to an enhanced convective inward heat flux in addition to the reduced outward diffusive heat flux observed in Ohmic plasmas.

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