'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 (\( \chi_e \)) in the region \( 1 < q < 2 \). Conclusive evidence on the \( \chi_e \) 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 \( \rho = 0 \) 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 \( \chi_e \) 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 \( \chi_e \) values, see [4] and [5]). Following OPI, a uniform reduction by a factor 2.2 is applied to \( \chi_e \) 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 $\chi_e$ model is discussed.

As a final remark, we note that the physical mechanism triggering the measured $\chi_e$ 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].

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. $\rho_{dep}$ in a $B_T$ scan experiment.](image)

![Fig.4: maximum $T_e$ variation during cold pulse as a function of the ECH deposition radius.](image)

Fig.4 shows the magnitude of the maximum $T_e$ variation following OPI as a function of $\rho_{dep}$ 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 $\rho_{dep}$ 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 $\rho_{dep}$. 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 $\chi_e$ and $U$ profiles used before and during pellet injection are shown in Fig.7. Besides increasing with radius, $\chi_e$ has been given an inverse dependence on $n_e$ to reproduce the LOC scaling of confinement with $n_e$. During OPI, $\chi_e$ is reduced by a factor 1.7 in the region $1<q<2$. This drop in $\chi_e$ 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 \( \rho_{\text{dep}} \) 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 \( \rho_{\text{dep}} \approx 0 \) 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 (\( P=280 \text{ kW}, \rho_{\text{dep}}=0.23 \)).](image1)

![Fig.6: Simulated \( T_e \) time traces for the discharge of Fig.5 using the model illustrated in Fig.7.](image2)

![Fig.7: Model used for \( \chi_e \) 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.](image3)

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 \( \rho_{\text{dep}} \) 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.