Analysis of cold pulses produced by impurity injection in jet

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Introduction

The analysis of the propagation of perturbations of the electron temperature provides a useful means to understand the mechanisms of radial heat transport in a tokamak. The outward propagation of sawteeth, originated spontaneously in the centre of most tokamak discharges, has been used extensively to determine the incremental electron thermal diffusivity $\chi_e^{inc} = \partial q/\partial(n \nabla T)$.

Perturbative phenomena of different origin can be analysed usefully [1], [2] to extend the availability of the method to non sawtoothing discharges and to compare the diffusivities obtained from waves of different physical origin, frequency, direction of propagation etc.

The present work concentrates on the analysis of cold pulses originated by fast cooling of the plasma edge induced by laser- blow off impurity injection in JET.

The inward propagation of these 'cold pulses' and the rapidity of the perturbation allowed to observe marked non-local features of the radial heat propagation which are closely similar to results obtained in the analysis of ELMs in JET[3].

Method

Injection of non recycling impurities (Ni, Mo, Al...) in the JET plasma is obtained by laser ablation of metallic depositions on glass substrates.

Although the Q-switched laser pulse is very short (10 ns), the temporal width of the impurity pulse is of the order of a few milliseconds at the plasma edge, due to the intrinsic velocity spread of the particle beam. This pulse width is still much shorter than typical particle and heat diffusive times so that the impurity source can be considered comparatively fast.

Correspondingly, Abel inverted bolometric signals show that the injected impurities may induce strong radiation cooling which is initially concentrated (i.e. on time scales shorter than the particle diffusive time) outside the surface r/a = 0.9.

It is generally observed in JET that, when the enhanced radiation loss ΔP_{rad} exceeds 2MW, the perturbations of the edge temperature become appreciable. A cold pulse is subsequently generated which propagates toward the plasma centre .

An accurate description of the propagation of the temperature profile perturbation, is obtained by analysis of the experimental data from the high resolution (6kHz sampling rate), 48 channel ECE radiometer.

Results

The time evolution of the electron temperature following the impurity injection in an Ohmic discharge, is shown in Fig. 1 at various normalised radii $\rho = r/a$.

It can be seen that a prompt change of the T_e time derivative, occurs over a wide radial extent. At intermediate radii (near field region: $\rho \approx 0.6$ to $\rho \approx 0.8$) the rapidity of the response to the edge perturbation is seen to decrease moving inwards; while further in (far field region: $\rho < 0.6$), dT_e/dt does not vary appreciably with the radius.

The Fourier analysis of $T_e(\rho,t)$ [4] is reported in (Fig.2 a, b) in terms of the amplitude and phase of three different frequencies against the radial position. One can distinguish three different regions: the outer one ($\rho > 0.8$) is affected by the presence of the radiative losses as demonstrated by the amplitudes decreasing with ρ.

The intermediate region features a normal diffusive behaviour ($|\phi'| = A'/A$), and a value of the thermal diffusivity χ_e^{inc} in accordance with evaluations from the analysis of the simultaneous sawtooth.

Finally, the inner region ($\rho < 0.6$), characterised by a non diffusive phase-amplitude relation, reflects the very fast non-local behaviour indicated by the short propagation time ($\Delta t \leq 4$ms) between the plasma periphery and the centre.

Transport analysis

Simulation of $T_e(\rho,t)$ has been obtained by solving the energy transport equations with the JETTO transport code using the experimental P_{rad}, n_e, profiles and prescribing the dependence of χ on plasma parameters. Impurity deposition and transport are not considered explicitly but through the variation of the Z_{eff} value deduced from spectroscopic data.

Simulations assuming a Bohm-like expression for $\chi_{e,i}$ [5]:

$$\chi_{e,i} = \alpha_{e,i}{}^{L}\, c\, |n\, \nabla Te|\, a\, q^2 / (eBn) \qquad (\alpha_i{}^{L} \approx 2\, \alpha_i{}^{L} \approx 5\ 10^{-4})$$

which is typically satisfactory for JET Ohmic and L discharges, reproduce the stationary temperatures before the cold pulse but show a poor agreement after the perturbation.

Similar results have been obtained with a Rebut-Lallia [6]expression for $\chi_{e,i}$.

These simulations suggest that following the initial edge perturbation there is a rapid increase of the thermal diffusivity also at radial positions where no appreciable modifications of the local plasma parameters have yet taken place [7].

The simulation of Fig. 3 assumes that the thermal diffusivity is a function of the edge temperature:

$$\chi_{e,i}(\rho,t) = \chi_{e,i}(\rho,t_{injection})\ [T_{e,edge}\,(t)\ /\ T_{e,edge}(t_{injection}]^{-0.6}$$

It appears that for Ohmic pulses the large modification of χ at the plasma centre is essential for a consistent interpretation of the experiment.

Such a strong modification of the diffusion coefficient is not strictly necessary at intermediate values of the normalised radius to reproduce the experimental data.

This is confirmed by analysis performed by means of a linearised transport code, where only the perturbation $\Delta T_e(\rho,t)$ to the T_e-profile is modelled in terms of a time dependent incremental electron heat diffusivity $\chi^{inc}(\rho,T)$. Such analysis confirms the evidence that a prompt increase in χ^{inc} is taking place at large distance from the source of the perturbation.

H-mode

Laser induced cold pulses in H modes were more difficult to study due to the non stationarity of the discharges and to the higher experimental uncertainty on the edge temperatures.

However also in these cases clear evidence of a global modification in the heat transport parameters was observed. The diffusively propagating component of the temperature perturbation appeared to decay more rapidly moving away from the perturbed plasma edge. This behaviour is consistent with the lower values of χ^{inc} in H modes.

Fig. 4 reports the simulation of an H mode cold pulse obtained by assuming that after the pulse the thermal diffusivity increased instantaneously by a factor ~8 over its stationary value (corresponding to the transition from a typical $\chi_{H\text{-mode}}$ to a typical $\chi_{L\text{-mode}}$) for 5 msec. The same dependence of χ_{inc} on T_{edge} as in the Ohmic discharge was not acceptable in this case because it resulted in a reaction in the electron temperature that was too slow in the plasma centre.

The comparison of a giant ELM and a laser induced cold pulse shows that the propagation to inner radii is very fast in both cases even though the perturbations at the plasma edge can be quite different: the strong variations in the H_α signal, typical of ELMs, are not usually observed during the laser induced cold pulses; the Abel inverted bolometer profiles are more concentrated in the external periphery in the ELM case and also the edge perturbation of the electron temperature can be much smaller following laser blow off injection than following an ELM.

Conclusions

Generation of cold pulses by laser ablation of impurities has proven as a useful tool for studying heat transport in JET plasmas.

Although more precise assessment of the behaviour of the electron heat conductivity requires further experimentation, it emerges clearly that the propagation of the pulse is accompanied by a simultaneous fast increase of χ^{inc} over a large radial extent.

Similar features in the propagation have been also observed in perturbations produced by ELMs which are produced spontaneously in the plasma edge of H mode discharges. Conversely, laser cold pulses have been observed on any confinement regime.

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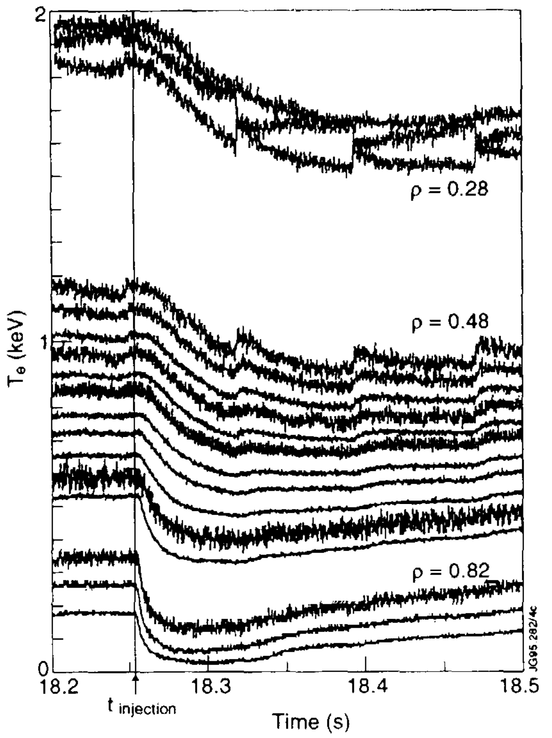

Fig. 1 Time traces of T_e at various ρ=r/a positions

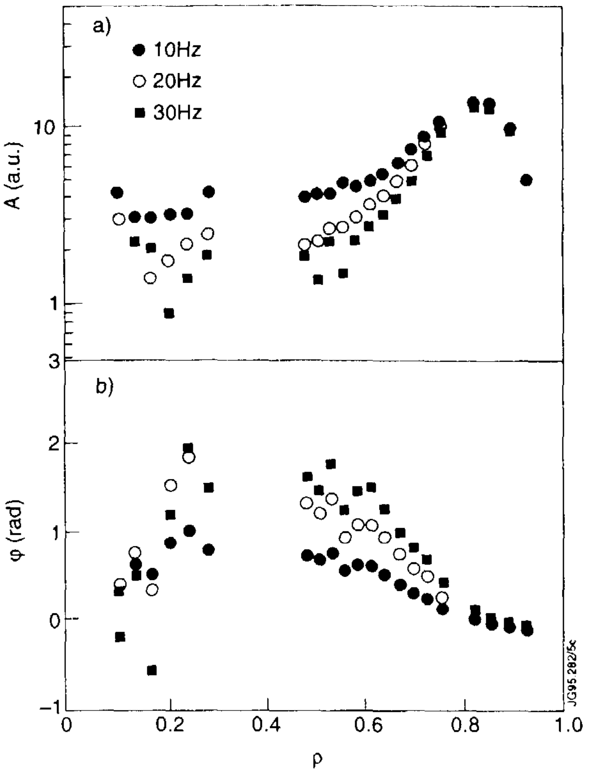

Fig. 2 Fourier analysis of $T_e(\rho,t)$ a) amplitude, b) phase

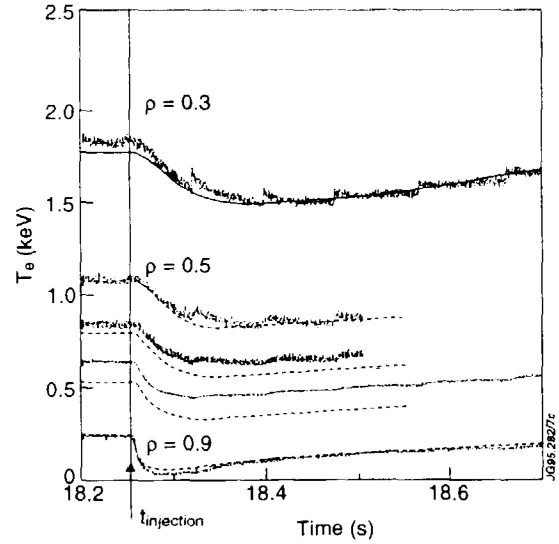

Fig. 3 Simulation of $T_e(\rho,t)$ using a non-local thermal diffusivity dependent on edge temperature

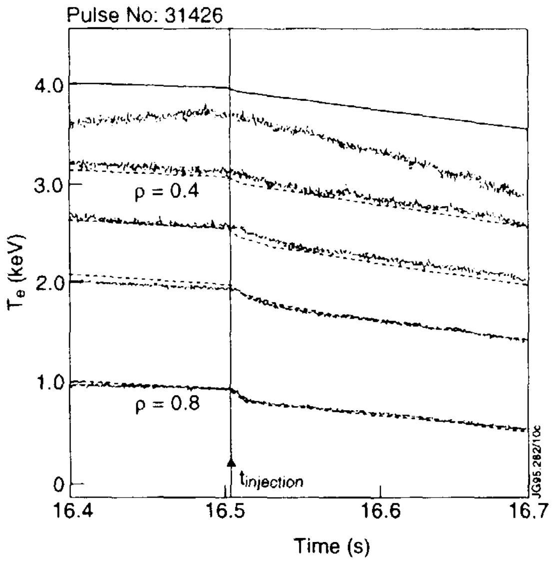

Fig. 4 Simulation of $T_e(\rho,t)$ for an H mode obtained using an instantaneous variation of χ ($\chi^{H\text{-mode}}$ to $\chi^{L\text{-mode}}$ for 5 msec)