Studies of Energy and Particle Transport in JET

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ABSTRACT

Investigation on H-mode transport has concentrated on pulses where elevated confinement can be achieved. At the time of the L-H transition a prompt transport reduction in the core (as well as at the edge) of the discharge is observed. Poorly performing, higher-Z_{eff} discharges appear to have substantially the same core transport as record achieving pulses. New H-mode power threshold data were acquired in 1994, with ion B drift of both signs, confirming P_{th} to increase with B_t and n_c. The transport of injected impurities indicates that, in L-mode discharges, the outer region of strong anomalous transport more or less coincides with the region of high shear ($s > 1/2$). Analysis of inward propagation of cold pulses supports the hypothesis that, when the edge temperature is perturbed, transport across the discharge suffers a prompt modification.

1. INTRODUCTION

The study of energy and particle transport at JET was mainly devoted, lately, to two basic activities: the further analysis of the database acquired in the experimental campaigns held until 1992 and the comparison of new observations from the present campaign (1994) with those made in the past. For the sake of conciseness the paper is organised in two sections dealing with the high and low confinement respectively. Where possible, reference is made to JET papers, recently published or submitted for publication, that will supply more extensive descriptions of phenomena illustrated here.

2. H-MODE AND ELEVATED CONFINEMENT

Investigation on transport in the H-mode regime has recently concentrated on pulses where elevated energy confinement can be achieved. In **hot-ion pulses,** enhancement factors for the energy confinement time (compared with the JET/DIII-D H-mode scaling) up to 2 are observed. The maximum kinetic energy that can be stored in these plasmas appears limited at a normalised beta $\beta_N \sim 2$ [1] suggesting that the deterioration of transport observed at the highest levels of stored energy may be due to MHD instabilities [2]. This empirical constraint results in a favourable scaling of confinement with the toroidal magnetic field.

Local power balance analysis performed with the TRANSP code on these discharges shows that a marked improvement of transport occurs in the bulk of the plasma immediately after the transition from L- to H-mode. At that time the effective thermal diffusivity χ_{eff} is seen to drop by a factor ~ 3 in the core of the discharge, before the pressure and temperature profiles suffer locally any significant modification, and then to remain at the new reduced level as the stored energy increases by a factor ~ 4 until a sudden termination occurs which often leads to a carbon bloom making recovery impossible [3]. JET pulses run in the new experimental campaign with higher Z_{eff}, broader density profiles and different edge fuelling rate appear to have, over the whole radial range where the local energy transport analysis is reliable ($\rho \approx 0.2 - 0.75$), the same χ_{eff} as higher performance pulses performed in the previous campaign (fig. 1).

High β_p discharges [4,5] are another well-known example of high confinement at JET. Global confinement time is shown in fig. 2 for one such pulse to exceed by ~ 75% times the ITER93H-P scaling in the phase following the end of the ELMs. The dimensionless physical parameters of this discharge are quite different from other confinement regimes, e.g. the safety factor q is 4 times higher and the normalised ion gyroradius ρ_i^* is 2 times smaller than in typical hot-ion H-modes. One of the highest JET values of β_p (~ 2.1) and the largest bootstrap fraction of f_{BS}~ 70 % were achieved in the ELM-free phase. The estimated experimental errors on energy content and on the bootstrap current are rather large (± 20%) due to relatively large uncertainties on measured profiles near the plasma edge and to the lack of space resolved information on the ion temperature. A heuristic transport model [6] that aims to account for the effects of the short- and long-scale turbulence as well as of neoclassical mechanisms has been applied to simulate this pulse using the transport code JETTO. The same model has also been successfully applied for the description of transport in a variety of L-modes as well as a number of H-modes including hot-ion H-modes [7]. The same numerical coefficients used in [7] for ELMy and ELM-free phase have been used for the corresponding phases in this simulation. The time evolution of the energy content is reproduced within the experimental uncertainty. The bootstrap current is also computed predictively by the code and agrees, within error bars, with the experimental value of the non-inductively driven current (fig.2).

Pellet enhanced performance (PEP) **discharges** [8] also attain enhanced energy confinement both in L- and H-mode, due to an improvement of the thermal diffusivity in the plasma centre. In that region several unusual conditions are produced during the PEP phase, including high densities, high pressure gradients and negative magnetic shear. This makes it difficult to validate different possible theoretical explanations for the observed improved performance, such as those related to access to the second stability region or stabilisation of ion temperature gradient driven modes [9].

In PEP pulses, depending on the degree of peaking of the n_e and T_e profiles, the shape of the q profile and the amplitude of MHD activity, strong accumulation of light impurities in the plasma centre can occur, occasionally leading to severe depletion of the main plasma ions ($n_D/n_e \leq 30$ %) on the magnetic axis [10]. Impurity accumulation appears however to have only marginal influence on the abrupt collapse of the PEP configuration. The phenomena observed are consistent with the effect of neoclassical forces associated to the logarithmic derivative of the deuterium ion density $\nabla n_D / n_D$ and of the ion temperature $\nabla T_i / T_i$. In these pulses the light impurities are in the plateau collisional regime and both forces are strong and inward-directed. In contrast, no accumulation of light impurities is observed in the hot-ion pulses mentioned previously, that also have strong pressure gradients in the plasma core, but where those impurities are in the banana regime. Indeed for those pulses hollow carbon density profiles appear to develop. This is also in agreement with the neoclassical theories that for collisionalities lower than unity predict a screening effect associated with the $\nabla T_i / T_i$ force.

New **H-mode power threshold** data over a range of toroidal field and density values have been obtained in the present (1994) JET experimental campaign, with the ion *gradB* drift (IGBD) directed both towards (positive) and away (negative) from the target plates. An earlier, partial analysis of these data [11] revealed a weak positive dependence of the threshold on plasma current, X-point position and distance of the limiter from the last closed flux surface. A more recent analysis has shown that with both positive and negative IGBD the power threshold P_{th} scales linearly with the toroidal magnetic field B_t, although it seems to be slightly higher than that of the older data. A very recent experiment, carefully prepared to verify the dependence of P_{th} with the plasma density and carried out with positive IGBD in the line average density range $2.5 < n_e\ (10^{19}\ \mathrm{m}^{-3}) < 4$, has also shown that P_{th} decreases when n_e is lowered (fig. 3). Further dedicated experiments are planned to verify the scaling of P_{th} with n_e at higher densities and to investigate whether there is a minimum threshold power at lower density below which P_{th} might start to increase for decreasing n_e [12].

Dependence of the threshold on $n_e B_t$ for discharges in the present campaign carried out ***with positive IGBD***, NBI heating and carbon-fibre-composite (CFC) target plates is very close to that found in the previous JET campaign (1991-92) with IGBD of the same sign (on pulses mainly performed with the same heating and another type of CFC plates) and to the scaling proposed by the H-mode Database Working Group [13].***With negative IGBD*** the observed thresholds are twice as high for all the 1994 discharges (all run with counter-injection NBI) and the NBI heated ones of 1991-92 (co-injection). It should be noted, however, that significantly lower thresholds were found in the former campaign with ICRF heating and beryllium dump plates [11].

3. L-MODE AND OHMIC CONFINEMENT

The time scale over which modifications occur across the plasma column at the time of the L-H transition [14], is interpreted as the evidence that non local mechanisms are inherent in the L-mode transport processes. The time evolution of the electron temperature T_e, for example, indicates an almost immediate reduction of the thermal conductivity, following the drop in the D_α signals, over a wide radial domain in the outer layers of the discharge. The affected region only excludes a central core about the magnetic axis, where no appreciable change in the behaviour of T_e is detected. The speed of propagation, from the separatrix inward, of the temperature modulation is seen to be 160 m/s or larger. A similar speed of propagation is also deduced for the drop in the **density fluctuation** level at the plasma edge as **measured by** O-mode **reflectometry**. Recent analysis of data obtained with this technique has shown that a strong reduction in fluctuation power (by up to a factor of 20 in a frequency range extending up to 100 KHz) occurs in a 15 to 25 cm thick radial region next to the separatrix. The sharpest drop in the fluctuation corresponds to the region of the profile where the density gradient is highest.

For the pulses analysed so far, the inner edge of the radial interval where the thermal conductivity drops coincides approximately with the radial position where $q = 1$. The same approximate coincidence is often observed [15], in L-mode or ohmic regime, for inner edge of the region of **high diffusivity for trace impurities** in experiments performed using the laser-ablation injection technique. The analysis of these experiments has now been extended to a wider set of discharges nearly exploring the whole practical ranges of plasma current, magnetic field, density and additional power and including a few cases with evolving current profiles [16]. It appears that a central region of slow transport is always present, even when there is no $q = 1$ resonance in the discharge. Its size, however, is highly variable depending on the shape of the current profile.

The boundary between the slow and fast impurity transport regions is experimentally identified by analysing the radial profiles of the perturbation to the soft X-ray emissivity induced by the injected impurities (fig. 4). After an initial phase of fast propagation in the outer region of the plasma, the inward progression of the maxima in those profiles is strongly slowed down as they reach an intermediate radial position that varies for pulses with different q profiles. Such a position appears to be regularly in very close proximity with the flux surface where the magnetic shear ($s \equiv \rho/q \cdot dq/d\rho$) is equal to 0.5. Within that surface the diffusion of impurities is always moderate, even when the electron temperature gradient is high. The observed shapes and variation trend of the profiles of D_{imp}, the impurity diffusion coefficient, suggest a strong dependence, at intermediate radii, of transport on s and possibly the existence of a threshold condition on that parameter that governs the transition from low to high anomalous transport across the plasma column. These findings appear not inconsistent with theoretical predictions based on the analysis of toroidal coupling of adjacent resonant modes [17] or on the radial distribution of those modes in the discharge [18].

The local values of the D_{imp} in the core region and up to radial positions of about $\rho = 0.6$ is now measured using a recently developed iterative technique [19]. It shows that at the different radial positions the local transport is dominated by diffusion and that the local transport parameters remain the same during several successive quiescent phases between sawtooth crashes, until the injected impurities are lost from the discharge. The measured values of D_{imp} in the plasma core (always between 0.1 m^2/s and 0.3 m^2/s) are generally higher, by a factor of 2 to 10, than the neoclassical predictions. They also do not appear to undergo the strong variation with the magnetic field predicted by the neoclassical theories. In the outer fast-transport region, the effective average level of the impurity diffusion coefficient D_{imp} is seen to increase linearly with ∇T_e (or with T_e), but no appreciable dependence on the plasma density is found when the electron temperature profile is kept constant.

The radiation produced by the injected impurities induces a **cold pulse,** propagating from the plasma periphery inwards, which can be used to analyse the electron energy transport. A prompt change of the T_e time derivative $\dot{T}_e$ is observed over a very wide radial range (fig. 5). This is consistent with the hypothesis that a sudden modification of the electron thermal diffusivity χ_e is occurring practically at once over that radial interval. While at intermediate minor radii ($\rho \approx 0.6$ to $\rho \approx 0.8$) the rapidity of the response to the edge perturbation is seen to decrease moving inwards, further in ($\rho < 0.6$) $\dot{T}_e$ does not vary appreciably with radius. This is also in agreement with the above hypothesis because the rapidity of the perturbation $\tilde{T}_e$ due to diffusive propagation is expected to decrease moving away from the source of the perturbation [20] as observed in the first region; further away and below a certain level the cold wave is mainly consisting of the transient response to the sudden modification of χ_e and its radial variation is much smaller. This is also seen in the radial plots of the Fourier amplitude $A(\omega,\rho)$ and phase $\phi(\omega,\rho)$ of the Fourier transformed temperature perturbation $\tilde{T}_e(\omega,\rho)$ (fig. 6). In the inner region $A(\omega,\rho)$ and $\phi(\omega,\rho)$ do not vary appreciably with the radius while in the intermediate one the normal diffusive behaviour is observed.

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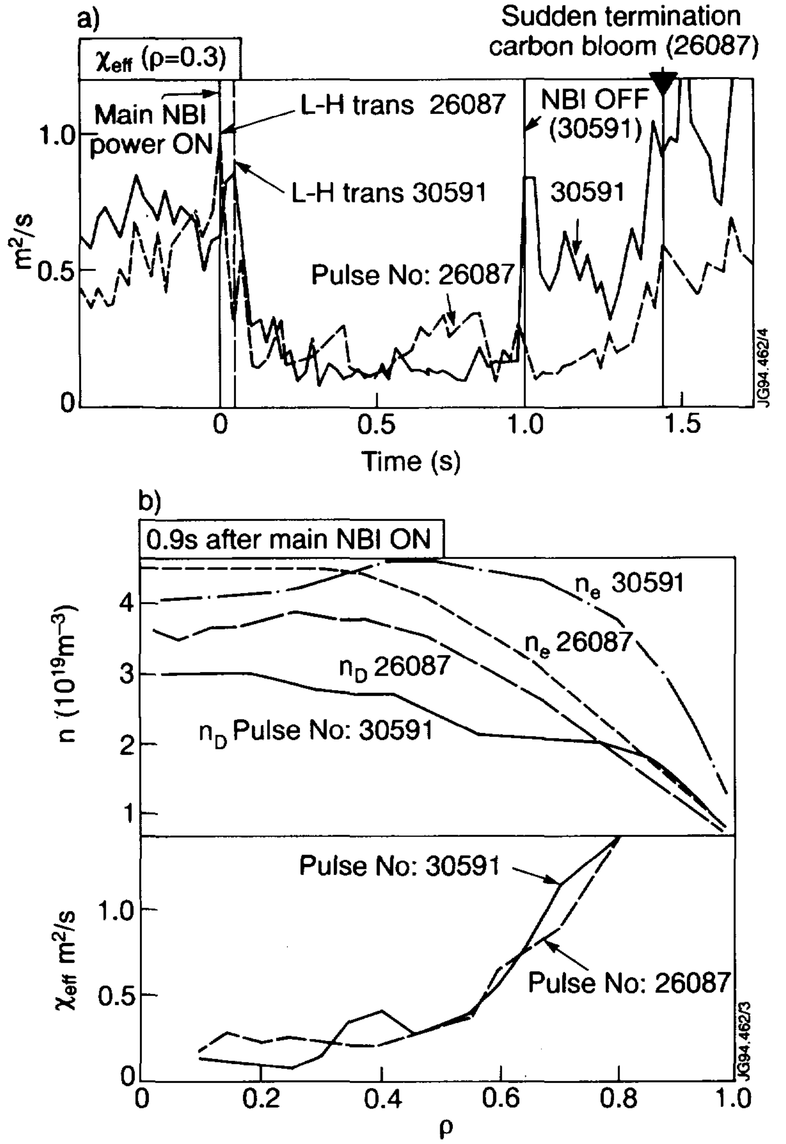

Fig.1 *Time evolution of $\chi_{eff}(\rho = 0.3)$ for two hot-ion JET discharges. Time is measured starting from the application of the main neutral beam power (a). Electron and deuteron density profiles during the ELM-free phases for for the above discharges; also shown are the profiles of χ_{eff} during the ELM-free phase (b).*

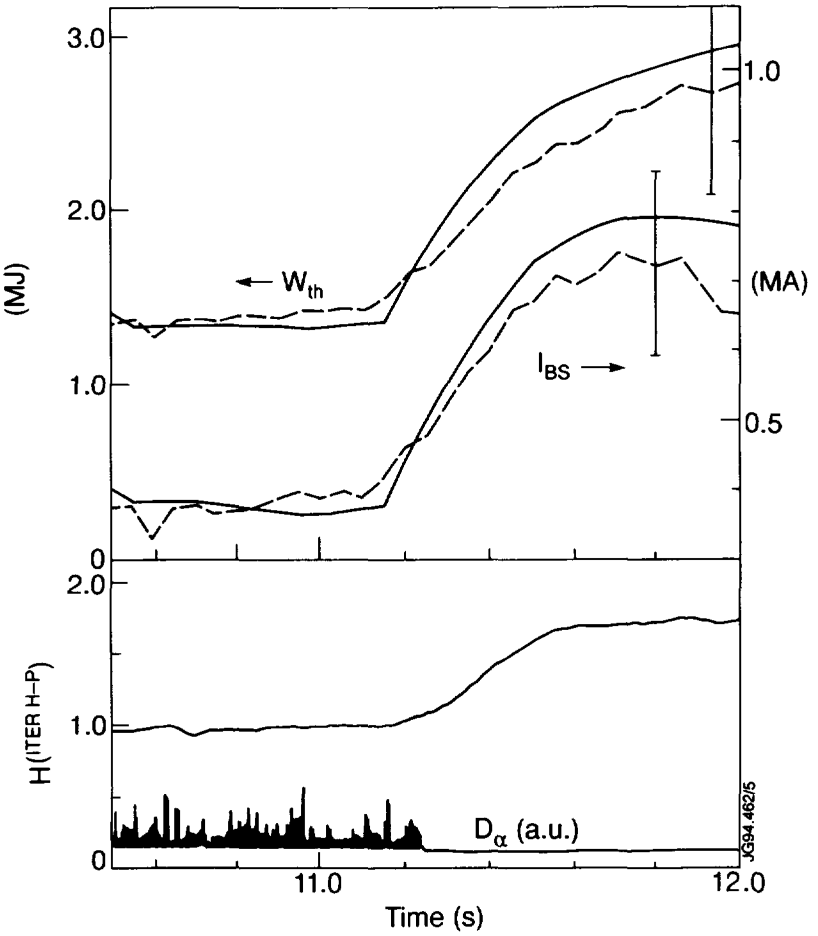

Fig.2 *Time evolution of thermal energy W_{th}, and bootstrap current I_{BS}, in a high β_p discharge (JET pulse 25264) as deduced from the experimental data (dashed lines) and from the simulation performed using the transport model proposed by Taroni, Erba and Parail (see paper A-2-II-3, this Conference). Also shown are the enhancement H(ITERH-P) of the energy confinement time over the ITER93H-P scaling and the D_{α} signal.*

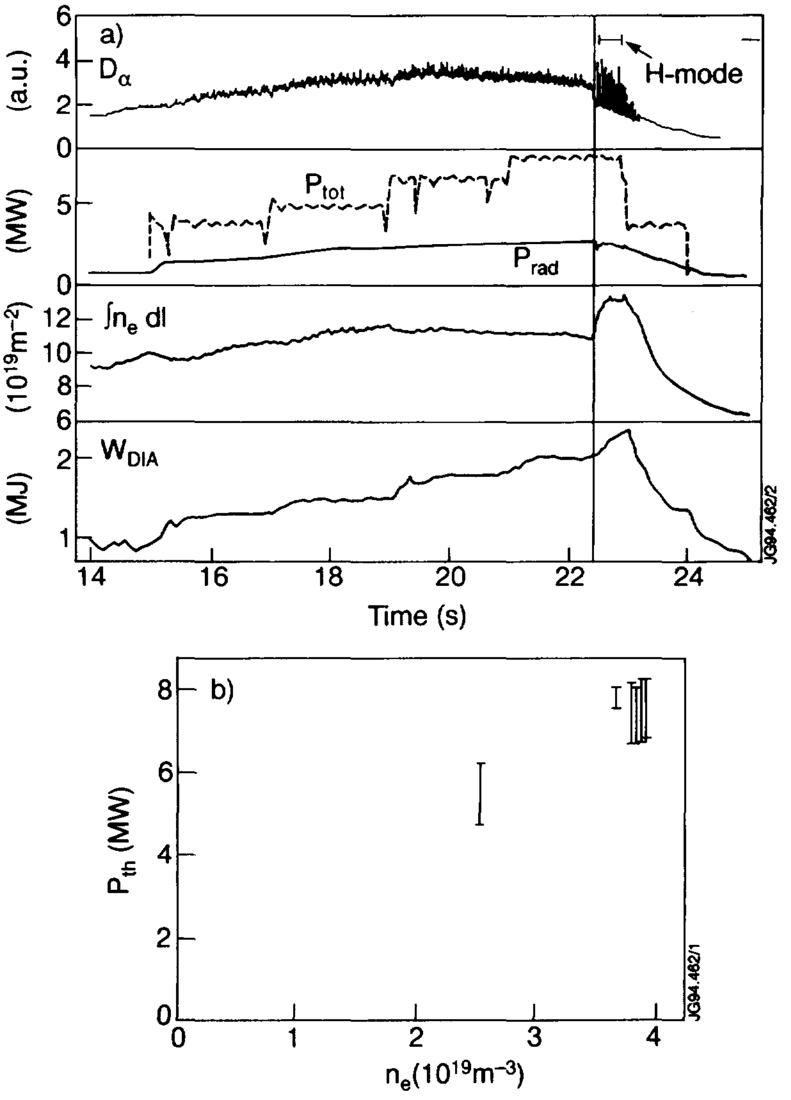

Fig.3 *Time evolution of D_α light, total heating power, total radiated power, line integrated electron density and stored energy from the diamagnetic loop for JET pulse 31596 ($B_T = 2.4$ T, $I_p = 2$ MA). In the last phase of the discharge, at $t \sim 22.4$ s, the transition to H-mode occurs when the line average electron density, that was slowly decreasing, reaches the value of $3.65x10^{19}m^{-3}$ (a). Power threshold versus line average electron density in a set of discharges run at $B_T = 2.4$ T, $I_p = 2$ MA with ion B drift directed towards from the target plates (b).*

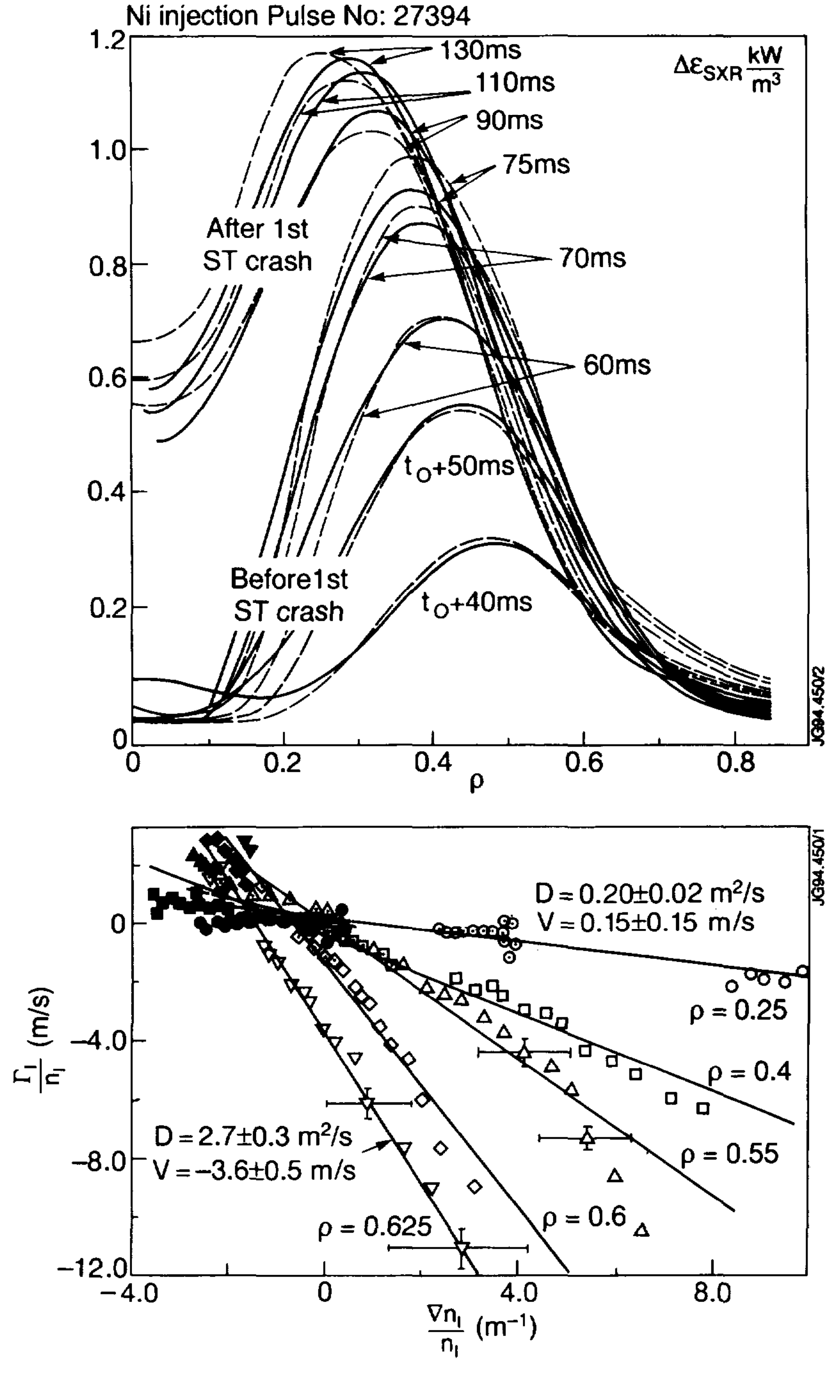

Fig.4 *Measured (solid lines) and simulated (dashed lines) radial profiles of the perturbation to the soft X-ray emissivity $\Delta\varepsilon_{SXR}$ induced by the injection of Ni. Data refer to consecutive quiescent phases between sawtooth crashes (a). Local measurements of the transport parameters are obtained from linear regressions of the normalized Ni fluxes Γ_I/n_I versus the normalized Ni density gradients $\nabla n_I/n_I$. The data points are from the first three quiescent phases between sawtooth crashes (respectively empty, dotted and filled shapes); the different shapes refer to different radial posistions. The Ni density profiles $n_I(\rho,t)$ are deduced from $\Delta\varepsilon_{SXR}(\rho,t)$ using the iterative technique illustrated in ref. [19] (b).*

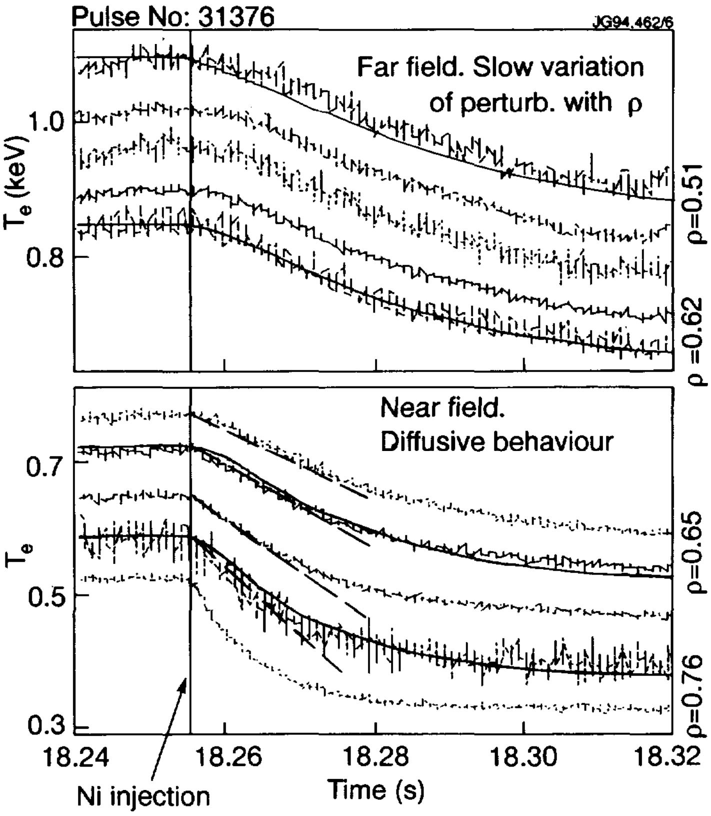

Fig.5 *Time evolution of the electron temperature at different radii following injection of Ni in one ohmic discharge. The solid lines are from the simulation of the phenomenon using the transport model of ref. 7 and a perturbation of the electron thermal diffusivity* $\Delta\chi_e(\rho,t)=\chi_e(\rho,t_0)\xi H(t-t_0)\xi exp(-t/0.15\,s)$.

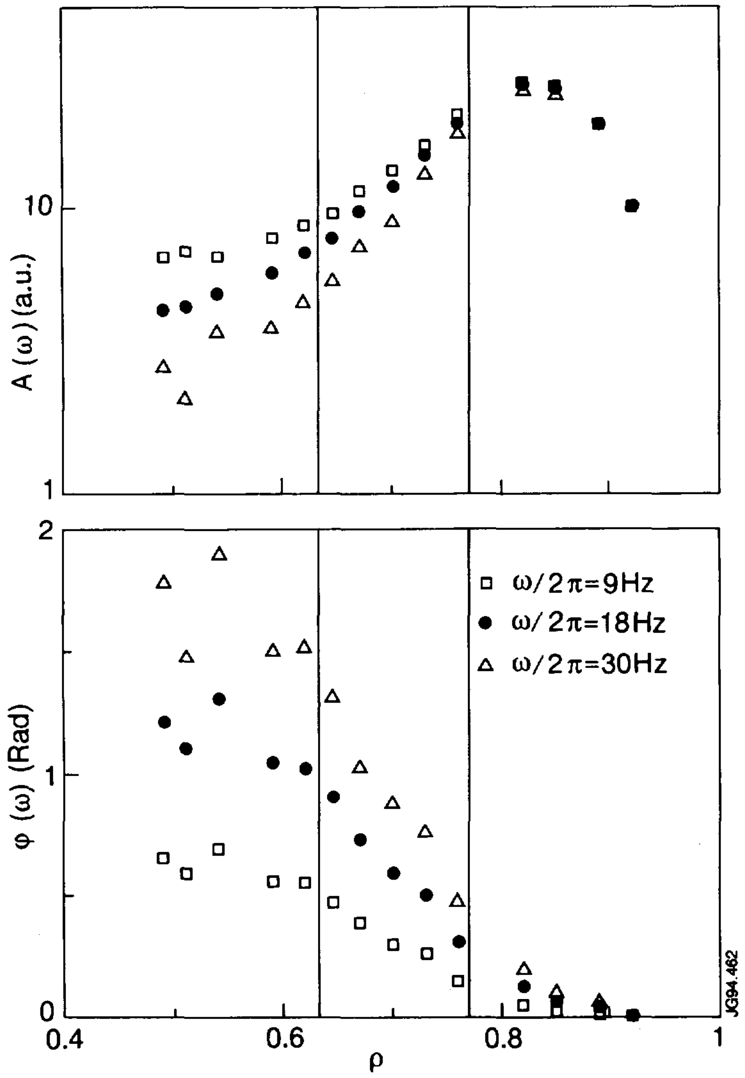

Fig.6 *Amplitude $A(\omega)$ and phase $\varphi(\omega)$ of the Fourier transformed temperature perturbation induced by laser blow-off injection of Ni in the discharge illustrated in fig. 5. At values of the normalised minor radius above $\rho = 0.77$ the propagation is affected by the modulation of the radiated power induced by the injected impurity; within that radius, the influence of the radiated power on the radial profiles of A and φ is negligible. For $0.63 < \rho < 0.77$ those profiles are consistent with a diffusive propagation characterized by a value of the incremental electron thermal diffusivity χ_e^{inc} 2.5 m^2/s For $\rho < 0.63$ the propagation is much faster and consistent with the expected transient response of the plasma to a sudden modification of χ_e.*