A Numerical Simulation of the L-H Transition and Heat Pulse Propagation in JET with Local and Global Models of Anomalous Transport

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I. ABSTRACT

A numerical study of the dynamics of L-H transition [1] and heat pulse propagation in JET [2] and TFTR [3] was done using local and global models of anomalous transport. Comparison with experimental results shows that the best agreement is achieved when using a global model in accordance with which [4] plasma turbulence is linked due to toroidal effects so that even very localised perturbations of the plasma parameters results in a practically instantaneous change of the anomalous transport coefficients everywhere outside the q = 1 surface.

II. LOCAL AND GLOBAL MODELS

It is commonly believed that plasma turbulence and anomalous transport coefficients in particular depend mainly on local plasma parameters (such as T_e, n_e, $s \equiv \frac{d\ln q}{d\ln r}$). It means that if this turbulence is suppressed by any means in a certain region of plasma column (say near plasma edge) turbulence in all other regions will recognize it only through the evolution of the plasma parameters on the transport time scale. We will refer to such a model of anomalous transport as to a local one. On the contrary, it has been shown by theoretical [4] and by numerical simulations [5] that plasma turbulence in tokamaks could be linked due to toroidal effects so that characteristic radial extension of such a turbulent convective cell would be much bigger than the ion Larmor radius ρ_i up to $(\Delta r)^2 = L\rho_i$ where L is the characteristic length of density or temperature inhomogeneity. In accordance with this model, a modification of plasma turbulence in a certain region of plasma column will almost instantaneously propagate over the entire plasma volume (instantaneously means within $\Delta\tau = \frac{\Delta r}{v_{gr}}$, where v_{gr} is the radial group velocity of the wave, usually $\Delta\tau \ll \tau_E$). This difference between local and global models of anomalous transport manifests itself very clearly in the dynamics of the L-H transition. In this case anomalous transport diffusivities are suddenly reduced only near plasma edge in the local model, whilst in the global model the coefficients are instantaneously reduced over almost the entire plasma volume.

The characteristic radial distributions of electron thermal diffusivity in L mode and H mode assuming local and global model of anomalous transport are shown in Fig. 1. A comparative study of the plasma response to either a local or global modification of the electron thermal diffusivity is the main goal of present work. Two particular situations will be analysed - the L-H transition 0 [1] and the so called "cold pulse" propagation [2, 3] where trace impurity injection produces a rapid cooling of peripheral plasma, the perturbation of electron temperature then propagates towards plasma centre.

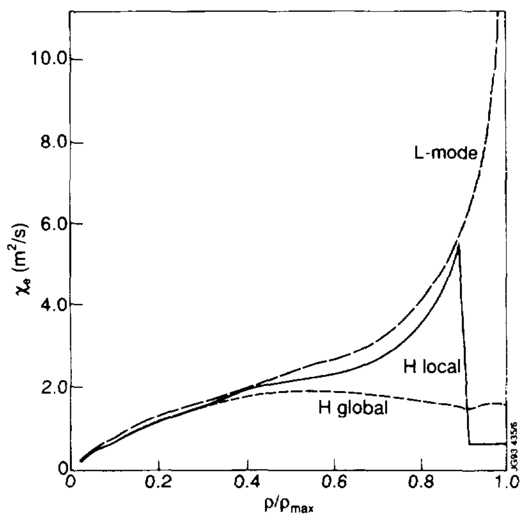


Fig. 1: Radial distribution of electron thermal diffusivity for L-mode (L), local model of H-mode (Lo) and global model of H-mode (G).

We will use a simple model for electron thermal diffusivity in the present work. This is because we will not pay so much attention to the dependence of χ_e on plasma parameters but try to find out the difference in plasma response to the local or global model for χ_e and then compare the results with the experimental data. Specifically we will assume that electron thermal diffusivity consists of two terms

$$\chi = \chi_1 + \chi_2 \qquad (1)$$

where $\chi_1 \sim \frac{1}{n_e}$ is responsible for Ohmic confinement and is not affected by L-H transition (see (5) for details). The second term in (1) is responsible for confinement degradation in L-mode (and improvement in confinement after L-H transition). We assume that χ_2 is reduced everywhere after L-H transition in the global model (see Fig. 1) and χ_2 is reduced only near plasma edge in the local model. A similar assumption about χ_2 is made in the cold pulse propagation study (see part 4).

Qualitatively the main difference between the global and local models can be seen by analysing the following simplified situation. Let us assume that the electron temperature (we will speak about T_e evolution for simplicity) came to a steady state L mode profile. The L-H transition occurs at time t = 0 and manifests itself in an instantaneous small reduction of χ_2 on $\Delta\chi_2 << \chi_2$ either only near plasma edge (in local model) or everywhere (in global model). Strictly speaking, the strong inequality $\Delta\chi_2 << \chi_2$ usually can not be applied for L-H transition, we will use it only for illustration. If $\Delta\chi_2/\chi_2 << 1$ we can linearise equation for δT_e evolution ($\delta T_e/T_e << 1$):

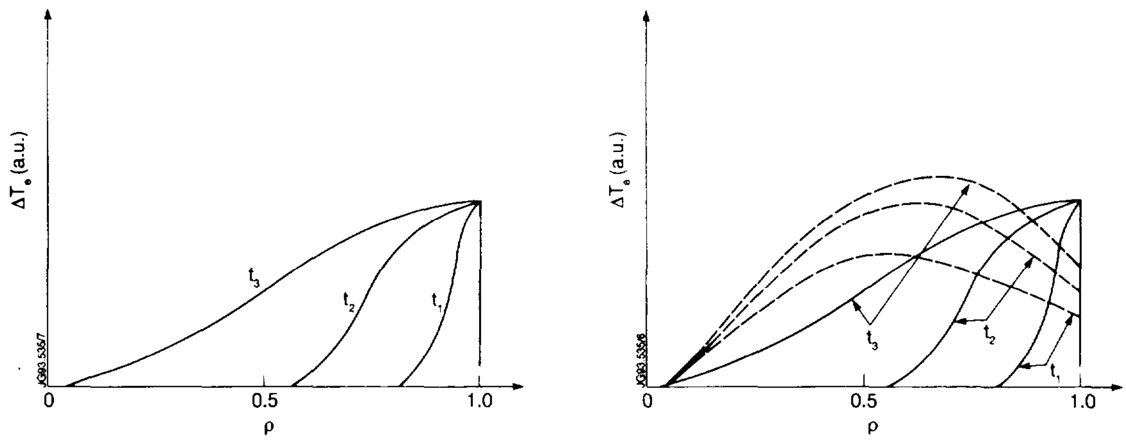
$$\frac{\partial \delta T_e}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r} r(\chi_1 + \chi_2)\frac{\partial \delta T_e}{\partial r} + \frac{1}{r}\frac{\partial}{\partial r} r\,\Delta\chi_2 \frac{\partial T_{eo}}{\partial r}, \quad \Delta\chi_2 < 0. \qquad (2)$$

We assume for simplicity that neither the heat source P, nor nor heat sink Q (like radiation) depends on δT_e.

In the local model, when $\Delta\chi_2$ differs from zero only near plasma edge, we can replace the second term in the right hand side (2) by the appropriate boundary condition like $\delta T_e(\rho = 1) = \Delta T_e$ where

$$\Delta T_e \approx + \frac{|\Delta\chi_2|}{\chi_1 + \chi_2} T_e(\rho = 1) \tag{3}$$

This localized electron temperature perturbation will then propagate toward plasma centre in accordance with (2) with a characteristic time $\tau \sim \tau_E \sim \dfrac{a^2}{\chi_0 + \chi_2}$ (see Fig. 2a).



Figs 2a, b: Temporal evolution of the electron temperature perturbation after L-H transition for local (a) and global (b) models. Dashed lines in (b) correspond to temperature perturbation caused by change of χ_e, solid line by change of the boundary condition.

In the global model the second term in the right hand side (2) is equivalent to a source of additional heating distributed over those parts of the plasma volume where $\Delta\chi_2 \neq 0$. Qualitatively the solution of equation (2) in this case is a combination of the previous solution (i.e. heat wave propagation toward plasma centre with characteristic time $\tau \sim \tau_E$) and a volume heating term. This case is shown for the L-H transition in Fig.2b. Two main differences can be seen between Figs. 2a and 2b. First, the electron temperature begins to rise instantaneously everywhere in the global model. In the local model the wave of temperature rise propagates toward the plasma centre from the edge with characteristic delay time $\tau \sim \tau_E$ (This time can be shortened if we assume that $\chi_2 \sim |\nabla T_e|^n$ but the delay cannot be taken away completely). The second difference concerns the dependence of the amplitude of the temperature perturbation with radius. It follows from (2) that the amplitude of δT_e should decrease when approaching the plasma centre in local model, whilst in global model δT_e can grow towards the plasma centre.

III L-H TRANSITION

The main plasma parameters for a high power L-H transition on JET are shown in Fig. 3. Fig. 4 shows time traces of T_e for different radii at times close to time of the L-H transition. The most striking feature is the fact that the electron temperature begins to increase everywhere outside q = 1 surface instantaneously after the L-H transition (within experimental time error bar $\Delta t \leq 3$ms). Inside the q = 1 surface the electron temperature is practically unaffected by L-H transition. It increases continuously (together with a rising density) even before transition. This may be due to the fact that transport is already very small in this region even in L-mode when MHD activity (sawteeth or m/n = 1/1) is suppressed. The numerical simulation of such a plasma for both local and global models of anomalous electron diffusivity is shown in Fig. 5. The density evolution was not computed in these calculations but taken from experiment.

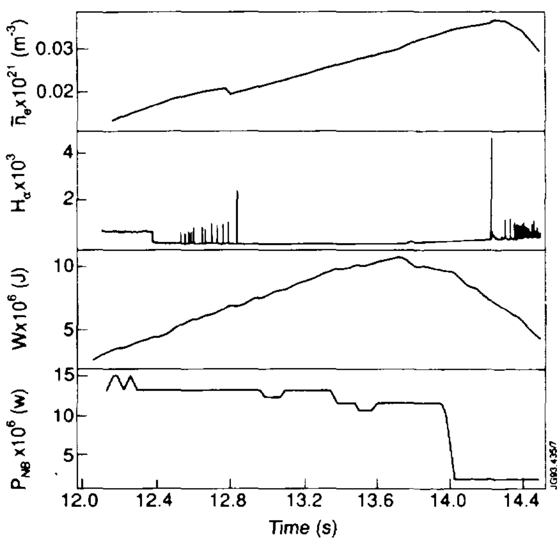


Fig. 3: Main plasma parameters for JET shot #26021: a) - average election density, b) - H_α signal, c) - stored plasma energy and d) - NBI power.

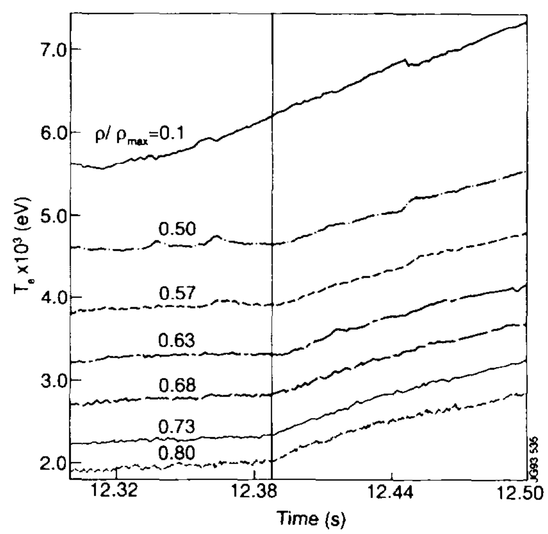


Fig. 4: Temporal evolution of ECE signals (electron temperature) at different radii ρ/ρ_{max} during L-H transition for shot #26021.

The simplest form of the electron heat flow was used in simulations:

$$Q_e = -n_e \chi_e \nabla T_e. \tag{4}$$

In both local and global models of anomalous transport all transport coefficients depend on local plasma characteristics (such as T_e, n_e, ∇T_e etc.). We chose the following form for the transport coefficients:

$$\chi_e \cong \left(\chi_i - \chi_i^{neo}\right)/3 \cong \alpha_1 \frac{(T_e)^{1/2}}{n_e q R} + \alpha_2 \frac{\nabla(n_e T_e)}{n_e B_T} q^2 \tag{5}$$

where α_1 and α_2 are constants determined empirically from numerical simulations. It is worthwhile mentioning that the second term on the right hand side (5) with $\alpha_2 = 3.3 \times 10^{-4}$ (SI units with T_e in eV) was used in [6] to fit the L mode confinement on JET and corresponds to a model of the Bohm type. The first term in right hand side (5) with $\alpha_1 = 1.2 \times 10^{-19}$ describes ohmic confinement (neo alcator scaling) and is of the gyro Bohm type. It seems reasonable to use a linear combination of these two terms to fit ohmic, L and H modes.

It can be seen from Fig. 5 that local model leads to the usual picture of heat pulse propagation toward plasma centre triggered by sudden change of electron thermal diffusivity near the plasma edge. It is worthwhile to recall that the electron thermal diffusivity in both models contains a term which is proportional to $\nabla(n_eT_e)/n_e$. It means that we have already taken into account the non-linearity which is usually used to explain the experimentally observed factor of two increment in the thermal diffusivity during heat pulse propagation.

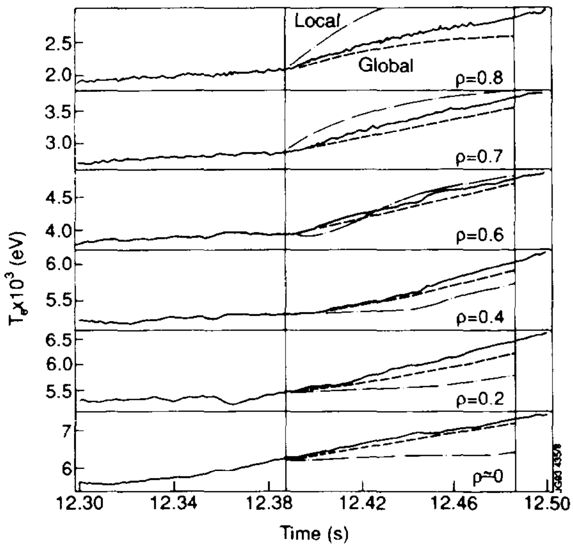


Fig. 5: Temporal evolution of electron temperature at different radii for shot #26021: solid line - experimental data, chain line - local model, dashed line - global model.

The fact that such a non linearity fails to match the experimental results with computed ones implies that a much larger non-linearity (like $\chi \sim T^n$ or $(\nabla T)^n$ with $n >> 1$) would be needed to explain the experimental picture of L-H transition on JET. One should remember however that a stronger non-linearity in χ_e would lead to a stronger degradation of energy confinement time τ_E with the heating power than it is usually seen experimentally.

On the other hand, the global model gives an electron temperature evolution which is very similar to the experimental picture.

IV. COLD PULSE PROPAGATION

Numerical simulations of cold pulse propagation on JET and TFTR were done in a way similar to that used for the simulation of the L-H transition and with similar expressions for electron thermal diffusivity χ_e. Namely χ_e was chosen to fit the experimental T_e profile prior to impurity blow off. The temperature evolution near the plasma edge was used as a boundary condition for equation (2). It was assumed that the local model either is not modified by the cold pulse (if χ_2 = const) or it is modified in accordance with the dependence of χ on the plasma parameters ($\chi_2 \sim \nabla T_e$). On the contrary, it was assumed that in the global model the coefficient χ_2 is influenced by the sputtering of impurities and edge cooling. Namely the following expression for χ_2 was used

$$\chi_2 = \chi_2^{(0)} \rho^2 \left[1 + \frac{|\Delta T_{edge}|}{T_{edge}(t_o)} e\left(-\frac{t - t_o}{\tau}\right) \right] \tag{6}$$

where $\Delta T_{edge} = T_{edge}(t) - T_{edge}(t_o)$, t_o – time of impurity blow off, τ – characteristic time of χ_e recovery, χ_2^0 = const. The result of numerical simulation for TFTR [3] and JET [2] are shown in Figs. 6-10.

a) TFTR

The experimentally measured time evolution of the electron temperature on different radii is shown in Fig. 6. Fig. 7 shows the radial distribution of the peak value of electron temperature perturbation for same shot. The results of this experiment were compared with numerical simulation done in [6] with assumption $\frac{\delta T_e}{T_e} << 1$ and local model of electron thermal conductivity.

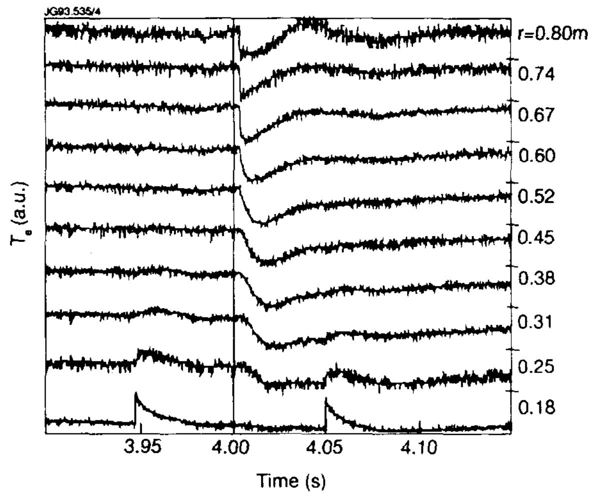


Fig. 6: Temporal evolution of ECE signals at different radii during cold pulse propagation on TFTR.

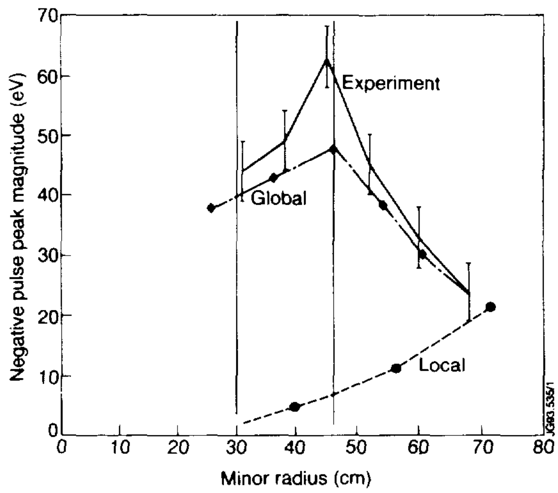


Fig. 7: Radial distribution of the peak value of electron temperature perturbation on TFTR during cold pulse propagation.

The main conclusion of such a comparison were formulated as follows:

1. Cold pulse propagation can be described by a diffusive model only for the region far from periphery ($\rho \leq 0.5$). In outer half of plasma column the amplitude of maximum perturbation δT_{emax} grows toward plasma centre.
2. The transient electron thermal diffusivity in the region $\rho \leq 0.5$ is four times larger than the χ_e which was found from energy balance.

Our numerical analysis (which does not impose any limitation on $\frac{\delta T_e}{T_e}$) confirms these conclusions if the local model of χ_e is used. The dependence of the calculated time-to-peak delay time on effective electron thermal diffusivity is shown on Fig.8 and the "cold pulse" magnitude - on Fig.7.

The same characteristics were calculated with the global model. It is seen (see Fig. 7, 8) that both time-to-peak delay time and radial profile of "cold pulse" magnitude can be easily reproduced by the global model with $\frac{\Delta\chi_2}{\chi_2} \leq 0.05$.

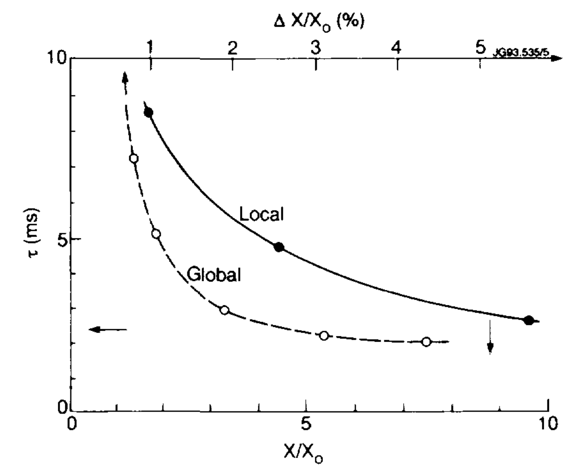


Fig. 8: Calculated time-to-peak delay time for TFTR as a function of effective thermal diffusivity (for local model) and $\Delta\chi_e$ (for global model).

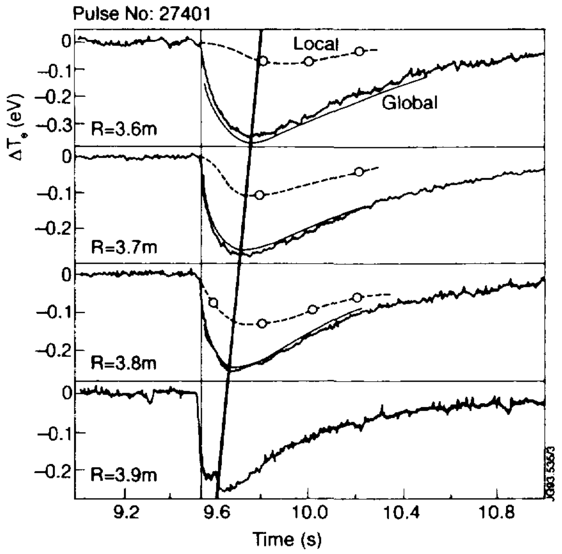


Fig. 9: Characteristic time evolution of measured $\Delta T_e(\rho)$ during cold pulse propagation for JET shot #27401 compared to those with the local and the global model for anomalous electron thermal diffusivity.

b) JET

Detailed information about JET blow off experiment will be presented at this Conference by J.J. O'Rourke. The characteristic time evolution of the experimentally measured T_e profile for Ohmic discharge # 27401 is shown in Fig. 9. Result of numerical calculations with local and global models are shown at the same figure and allow us to conclude that in this case, similar to TFTR, both fast cold pulse propagation and growth of its amplitude in the intermediate part of plasma column can be easily reproduced by the global model of electron thermal diffusivity.

V. SUMMARY

A numerical analysis of the dynamics of the L-H transition and "cold pulse" propagation was done using a local and a global model of anomalous transport. The results of this study lead us to conclude that the L-H transition in JET cannot be explained as a sudden reduction in transport coefficients (formation of transport barrier) limited to the plasma edge only. Much better agreement with the experimental observations is obtained by using the global model, in the frame of which the L-H transition is followed by a sudden reduction of transport coefficients everywhere outside the $q \cong 1$ surface. It was shown also that the dynamics of "cold pulse" propagation both on JET and TFTR could be explained in a much more easy and natural way by employing a global model of electron thermal diffusivity. These results support recent theoretical ideas in which the plasma turbulence in a tokamak forms large linked convective cells with a characteristic correlation length of the order of plasma minor radius. The results indicate also that confinement in L and H modes could be of a different nature and that in the usually used expression $\tau^H_E \cong H \times \tau^L_E$ the enhancement factor H should be not a number but rather function of the plasma parameters [1]

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