Numerical analysis of the heat pulses in JET

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INTRODUCTION.

Predictive modelling of different kind of heat pulses is a powerful tool to test the validity of transport models. The last experimental campaign in JET gave high quality information of the electron temperature evolution during five types of heat pulses: the L-H transition, sawtooth crashes, giant ELMs, cold pulses triggered by laser impurity ablation and slow roll-over. All relatively strong pulses triggered from the plasma edge show a fast global modification of at least the electron heat conductivity which, in principle, permits different interpretations. A first one involves the idea of a critical temperature gradient (or strong profile consistency) [1-3], an other one uses the idea of a global turbulent structures produced by a toroidal or a non-linear coupling of the unstable modes [4-6]. Numerical analysis of above mentioned heat pulses will be presented to assess which of these models is appropriate.

EXPERIMENTAL OBSERVATIONS.

The 94/95 experimental campaign on JET gave examples of heat and cold pulses which were often initiated in the same shot. Figure 1 shows, for example, the evolution of the electron temperature during a cold pulse and subsequent sawtooth crashes for the H-mode shot #31341. The asymmetry in the speed of pulses which propagate inward and outward is clearly seen - the sawtooth crash heat pulse propagates outward in the usual diffusive way, while the cold pulse changes the behaviour of the electron temperature almost instantaneously in the whole outer half of the plasma column. The evolution of electron temperature during giant (type I) ELMs on JET, after a very short MHD phase, was shown to be very similar to that of the cold pulses [7]. Figure 2 shows temporal evolution of the main plasma parameters during the so called slow roll-over, the event which often terminates high performance phase of the hot ion H-mode on JET. All these transient phenomena were analysed in a semi-predictive way with the transport code JETTO, using either a "global" or a critical temperature gradient model of anomalous transport.

TRANSPORT MODELS.

In our analysis we used a modified version of the RLW [2] critical temperature gradient model with:

$$\chi_{e,i}^{anom} = \alpha_{e,i}\chi_{RL}(\nabla T_e - \beta\nabla T_{crit})\theta(\nabla T_e - \beta\nabla T_{crit}) \tag{1}$$

as an example of a critical marginality model. Here T_{crit} defined by $T'_c = \left(\frac{6}{q}\frac{hjB3}{nT1/2}\right)1/2$, $\chi_{RL} = 2(1 - \sqrt{\frac{r}{R}}\sqrt{1+Z_{ef}}\sqrt{\frac{T_e}{T_i}}\left[\frac{\nabla T_e}{T_e} + 2\frac{\nabla n_e}{n_e}\right]\frac{q^2}{\nabla q B_T\sqrt{R}}$ and numerical coefficients $\alpha_{e,i}$ and β were varied in order to test a different degree of profile consistency. The original RLW model has soft profile consistency with $\alpha_{e,i} = \beta = 1$. Analysis shows however that we should increase $\alpha_{e,i}$ up to ten times in order to be able to get fast propagation of the cold pulses (which corresponds to a strong profile consistency transport model). Simultaneously we should increase coefficient β to reproduce experimental temperature profile.

Our "global" model is based on the assumption that due to either toroidal or non-linear coupling plasma turbulence organises long correlated structures (with the radial correlation length being proportional to the plasma minor radius). In this case the magnitude of the transport coefficients depends not only on the local plasma parameters but also on the source of the turbulence near plasma edge (we will assume that plasma turbulence emerges near the separatrix due to either temperature or pressure gradients and propagates inside with the group velocity of the unstable waves). In order to reproduce such a behaviour, in further analysis we will assume that both electron and ion thermal diffusivities consist of a local gyrobohm term (which could be produced by the ITG instability, for example) and a global bohm-type term (produced by either ballooning or interchange instability near the separatrix) which depends on the relative electron temperature or pressure gradient near the separatrix [7]:

$$\chi_{e,i} = \alpha_{e,i}^{GB}\rho_i\left|\frac{\nabla T_e}{B_T}\right| + \alpha_{e,i}^{B}\left|\frac{\nabla nT_e}{nB_T}\right|a^2q^2\left|\frac{\nabla T_e(r \approx a)}{T_e(r \approx a)}\right| + \chi_{e,i}^{ncl} \tag{2}$$

where $\alpha_{e,i}^{GB}$, $\alpha_{e,i}^{B}$ are numerical coefficients. In a sense the global model is similar to the critical marginality one because the global confinement in both models depends on the plasma quantities near the separatrix. The main difference between the models is that transport properties of the global model are not symmetrical but depend on whether the transient phenomena are initiated near the edge or near the centre of the plasma column. Indeed, if we assume for simplicity that only the electron temperature is perturbed in the course of the heat pulse and that this perturbation is small $\delta T_e/T_e << 1$ we obtain the following equation for the evolution of δT_e:

$$\frac{\partial \delta T_e}{\partial t} \approx div\left\{ \chi_e^{(0)} \frac{\partial \delta T_e}{\partial r} + \frac{\partial \chi_e^{(0)}}{\partial \nabla T_e} \nabla T_e \frac{\partial \delta T_e}{\partial r} + \frac{\partial \chi_e}{\partial T_e(r \approx a)} \nabla T_e \delta T_e(r \approx a) \right\} \tag{3}$$

The first two terms in the right hand side of equation (3) describe the usual diffusive propagation of the heat pulse independently of the localisation of the pulse origin. The last term emerges from the global model and only if the heat pulse is initiated near the plasma edge. It works as a perturbation of the heat source and is distributed over the whole plasma volume. As was discussed earlier, the characteristic time of propagation of such a heat source inward is controlled by the group velocity of the turbulence and it is much faster than the typical transport time $\tau \approx a^2/\chi$.

RESULT OF NUMERICAL ANALYSIS.

We have performed a predictive numerical modelling of selected JET discharges with different kind of the pulses. The selection covers both the heat pulses, initiated near the plasma centre (caused by the sawtooth crash) and pulses initiated near the plasma edge (cold pulse, ELMs, L-H transition and slow roll-over).

Figure 3 compares the result of the numerical simulation of the cold pulse and sawtooth heat pulse with the corresponding experimental evolution from shot #31341. Direct comparison of the change in slope of the simulated electron temperature at different radii at the onset of the pulses shows, that the global model (2) can reproduce the observed asymmetry. The critical marginality model with soft profile consistency underestimates the speed of propagation of the cold pulse while the model with strong profile consistency overestimates the speed of the sawtooth heat pulse.However simulation of slow roll-overs seem to indicate that a combination of the global transport and ITG mode might be at work. The result of the numerical analysis of the central ion temperature evolution during the roll-over with different transport models is shown in Figure 4.

CONCLUSIONS.

In summary, even though the critical marginality models considered here can reproduce some of the features of the global and local transport, they seem to fail to reconstruct the asymmetry in the time scales observed during transient phenomena. A "global" model gives a better agreement with experimental results in these situations. However modelling of the slow roll-over indicates that a combination of the global turbulence, which dominates in the outer part of the plasma volume, and of the local ITG mode, which could be important at mid-radius, might be responsible of the variety of phenomena observed.

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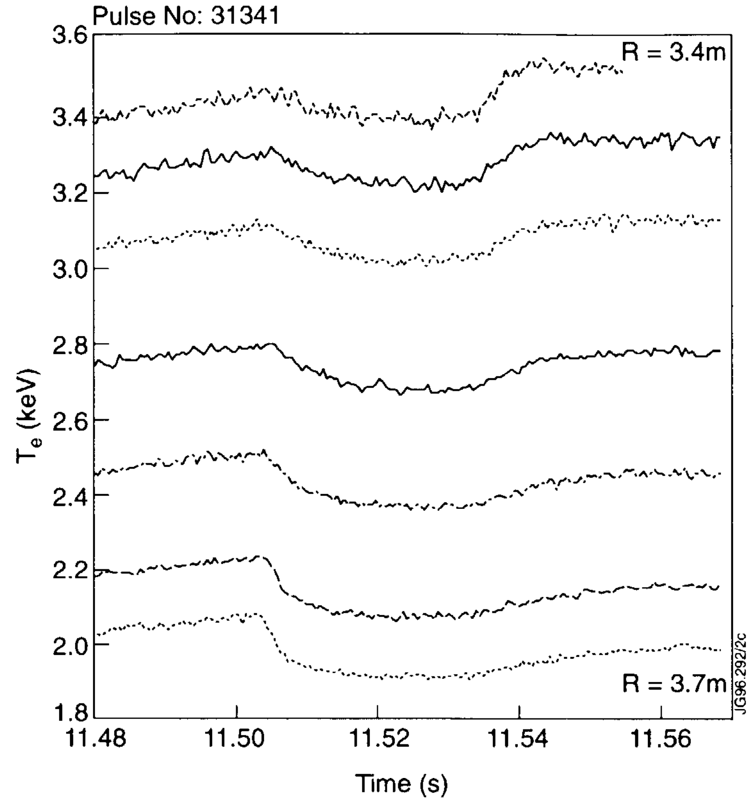

Figure 1. Experimental electron temperature evolution on different radii for the cold pulse followed by sawteeth heat pulses.

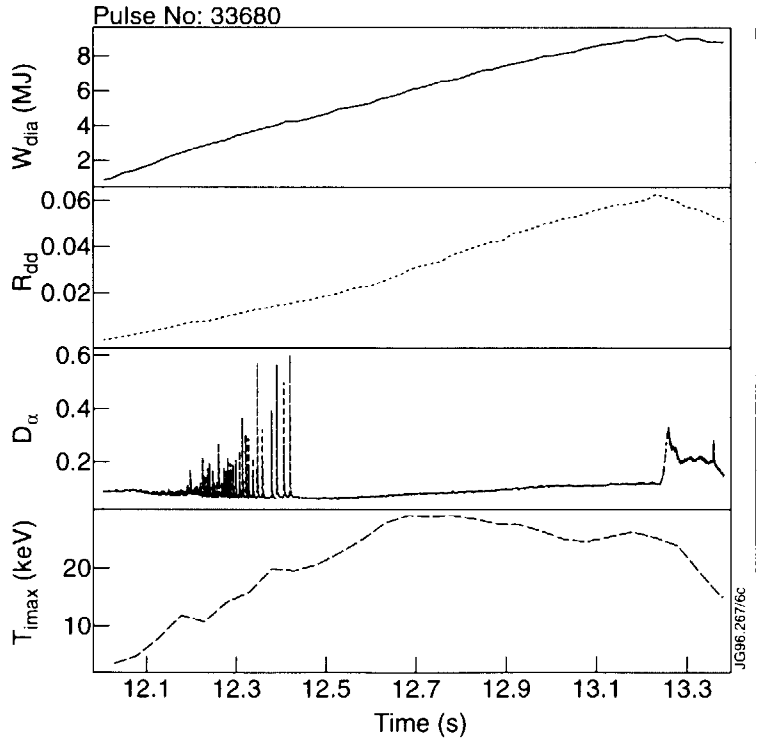

Figure 2. Evolution of the main plasma parameters in the hot ion H-mode which is terminated by the slow roll-over.

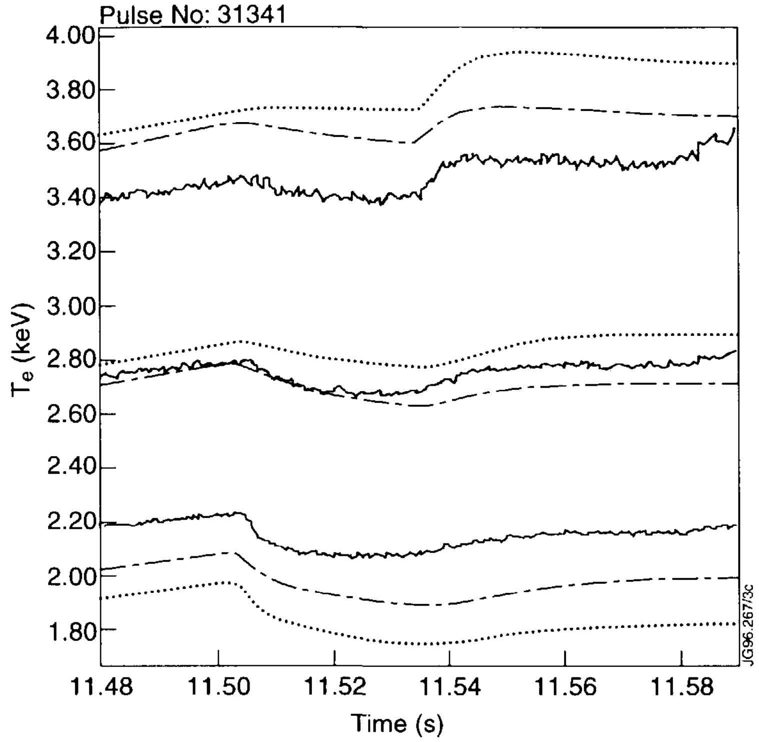

Figure 3. Comparison of the experimental electron temperature evolution (solid lines) with the simulated one: global model- chain, soft profile consistensy - dotted.

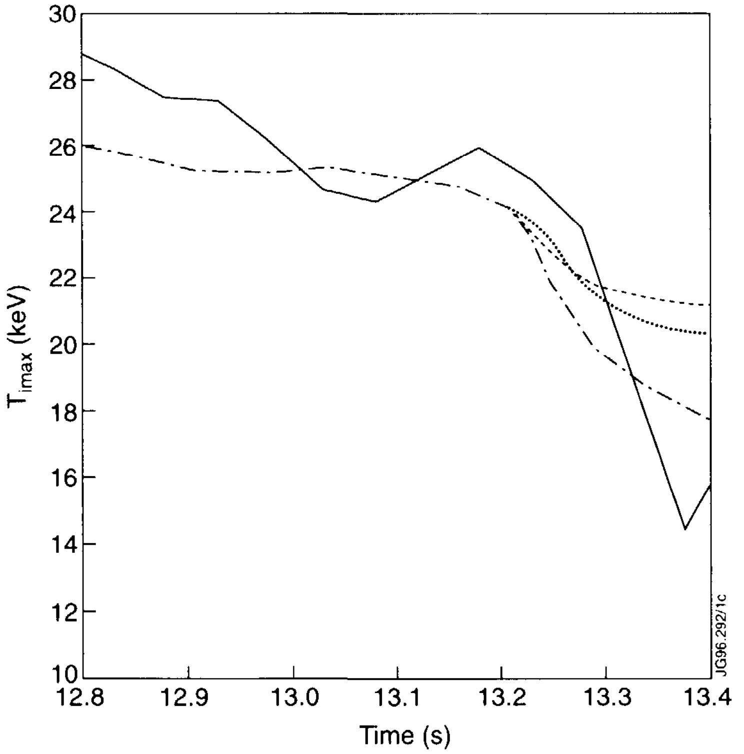

Figure 4. Temporal evolution of the central ion temperature during roll-over: solid- experiment, dashed - global model, dotted- ITG model, chain - combination of global and ITG models.