Sawteeth Induced Heat Pulse Propagation and the Time Behaviour of Electron Conductivity during L-H-L Transition on JET

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SAWTEETH INDUCED HEAT PULSE PROPAGATION AND THE TIME BEHAVIOUR OF ELECTRON CONDUCTIVITY DURING L-H-L TRANSITIONS ON JET.

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1. Introduction Previous methods for the analysis of election transport during sawtooth induced heat pulse propagation (HPP) are valid at radii greater than the mixing radius r_{mix}. This report describes a new numerical technique for the analysis of the decay rate of sawteeth perturbed T_e profiles between the inversion radius r_{inv} and r_{mix} and demonstrates the technique through its application to JET data. The method is a development of the "two-boundaries" method [1]. It was suggested in [2] that the electron heat diffusivity, χ_e, immediately after a crash is strongly enhanced and subsequently relaxes to its original level and that previous heat pulse data could have been distorted by this effect. For this radial zone the influence of χ_e relaxation can be minimised by beginning the analysis a few milliseconds after the crash.

Confinement mode transitions are also investigated. It is shown that during L-H-L transitions the change in χ_e across most of the plasma occurs on a millisecond timescale and is well correlated with the change in the dynamic electron diffusivity $\chi_e{}^{HP}$.

2. Description of the method The evolution of $T_e(r,t)$ observed with 5 ECE grating polychromator channels at $r > r_{inv}$ is shown in detail in Fig. 1. It is seen that within 1 ms from the beginning of the crash, the electron temperature perturbation, $\tilde{T}_e(r, t)$, has spread well away from r_{inv} (in some low q JET pulses it had spread up to $r \approx 0.85$ a). The decay of $\tilde{T}_e(r,t)$ is studied using the usual transport equation for $\tilde{T}_e$.

$$1.5n\partial\tilde{T}_e/\partial t = \nabla(\tilde{Q}) + \tilde{P} = -\nabla(n((\chi_{eo} + \tilde{\chi}_e)\nabla\tilde{T}_e + \tilde{\chi}_e\nabla T_{eo})) + \tilde{P} = -\nabla\left(n\chi_e{}^{HP}\nabla\tilde{T}_e\right) + \tilde{P} \quad (1)$$

Density and particle flux perturbations are ignored. $\tilde{\chi}_e$, $\tilde{P}$, and $\tilde{Q}$ are the perturbations of diffusivity, heat sources and electron thermal flux respectively. The relationship $\tilde{Q}_e = -\chi_e{}^{HP} n_e \nabla\tilde{T}_e$ is used along with the well known relationship $\chi_e{}^{HP} = \chi_{eo} + (\partial\chi_e / \partial\nabla T_e)_o \nabla T_e$. Equation (1) was solved numerically for $\chi_e{}^{HP}$ in the region $r_1 \leq r \leq r_3$ (see Fig. 1) with the initial conditions taken from experimental data 2 ms after the end of the crash. Furthermore, as boundary conditions, the experimental data at $r = r_1$ and $r = r_3$ were used. The optimum value, $\chi_{eb}{}^{HP}$, was determined by minimising the sum of squares of the difference between the calculated and the experimental data from the inner channels $r_1 < r < r_3$ (see Fig. 1). Fig.1 shows examples of the solution of equation (1) with $\chi_e{}^{HP} = (2; 1; 0.5)\ \chi_{eb}{}^{HP}$ (curves c, b, a). The influence of source perturbations and other "convective-like" terms was insignificant for most pulses studied because only "sharp heat waves" with $S = \left|(\nabla\tilde{T}_e / \tilde{T}_e)/(\nabla T_e / T_{eo})\right| > 2$, were analysed. The quantity S is the "quality index" of the heat wave.

3. Results The method was applied to the analysis of HPP in plasmas with additional heating power ranging from 2 to 22 MW in L, H and VH-mode. The relationship between χ_e^{HP} and the effective heat diffusivity from power balance calculations, χ_{eff}, is shown in Fig. 2. There is a close similarity between them. The analysis of HPP in 10 MW on-axis and mixed (on and off-axis) ICRH 3 MA L-mode plasmas together with the χ_{eff} variations in these pulses [3] support a model with a χ_e dependence upon ∇T_e rather than T_e. The same trend was seen for χ_e^{HP} in NBI heated L-mode plasmas.

The evolution of stored energy, W, neutral beam injected power, P_{NBI}, and T_e during different stages of an H-mode are shown in Fig. 3. The first of two sawtooth crashes occurred during a very good confinement hot ion H-mode (VH) and a low value of $\chi_e^{HP} \approx 1.1 m^2 s^{-1}$ was obtained. Three so-called "soft x-events" then occurred. These temporarily cooled the plasma. However, good electron confinement existed between them. The electron heat losses were about 8 MW inside $r \leq 0.6a$ during the cooling. Finally, the second sawtooth crash occurred and χ_e^{HP} was only 1.3 higher than that of the first, indicating that good electron confinement was maintained until the end of the H-mode.

The relaxation of χ_e^{HP} in time can be studied by varying the time delay between the crash and the start of HPP analysis (for figures 2 - 3, t_o was about 2 ms). The decay of χ_e^{HP} with time has been determined. For most pulses studied, the χ_e^{HP} values calculated had to be reduced by 20 - 30%. The reduction was larger in VH-modes.

4. The χ_e Time Behaviour During L-H-L Transitions The time behaviour of the L-H-L transition varied. An example of a rapid H-L transition is shown in Fig. 4. The transition is seen as a sudden change in $\partial T_e / \partial t$, approximately equal in value across the region $0.3 \leq r/a \leq 0.6$, i.e. $\nabla\tilde{T}_e(r,t) \approx 0$. The observed behaviour of T_e is governed by a rapid change in χ_e. The heat source term, $\tilde{P}$, is not believed responsible. The value of the conductivity jump $\delta\chi_e \equiv \tilde{\chi}_e$ can be obtained by integrating Eq. (1) taking $\partial T_e(r,t)/\partial t$ from the experimental data. The value $\delta\chi_e \approx 0.8\ m^2s^{-1}$ at $r = 0.5a$ was determined. A sawtooth crash occurred later during the L-mode and a value of χ_e^{HP} of $3.6\ m^2s^{-1}$ was obtained. This is 1.5 higher than that found for a previous crash during the H-mode.

The decay of T_e after the crash was modelled with $\chi_e \propto \nabla T_e$ and $\chi_e \propto \nabla T_e^4$. The results are shown as the sets of curves 1 and 2 respectively in Fig. 4. The H-L transition was analysed as a "cooling wave" propagation with the same $\chi_e(\nabla T_e)$ dependencies as the sawtooth crash. Equation (1) was solved numerically with the boundary condition taken from experimental data at $r = 0.57a$. The sets of curves 1 and 2 were our solutions and clearly represent a poor fit to the data. We are unable to deduce any linear or non-linear $\chi_e(T_e, \nabla T_e)$

dependence which can describe both the $T_e(r, t)$ evolution during an H-L transition and its evolution after the crash. A similar picture of the $T_e(r, t)$ evolution, with the "appearance" on a millisecond timescale of equal values of $\partial T_e / \partial t$ at various radial positions and therefore with $\nabla \tilde{T}_e(r,t) \approx 0$, was seen also in a limited space-time region after L-H transitions, during "soft-x-events" and strong ELM induced cooling. Typical values of $\delta\chi_e$ at $r/a \approx 0.5$ were about 2 m^2s^{-1} for X-events and $\sim 0.6\ m^2s^{-1}$ for L-H transitions.

5. <u>Discussion and Conclusions</u> We have demonstrated that the $\tilde{T}_e(r,t)$ decay in the spatial zone $r_{inv} \leq r \leq r_{mix}$, a few milliseconds after a sawtooth crash, behaves in an almost diffusive manner and can be studied with the new technique presented. The ratio χ^{HP}/χ_{eff} generally varied between 0.8 and 2 for 1.5-5 MA plasmas with additional heating power ranging from 2 to 22 MW. Variations of χ_e^{HP} due to plasma parameter changes were generally consistent with variations of χ_{eff} The analysis of HPP in L-mode plasmas support a model with χ_e dependant upon ∇T_e rather than T_e. The value of χ_e^{HP} drops during the transition from a low power L-mode to a VH-mode, while the local temperature can increase by a factor of four. The low values of χ_e^{HP} ($\sim 0.7 m^2s^{-1}$) in VH-modes represent good electron confinement without significant convective heat fluxes (the convective velocity is less than $0.4 ms^{-1}$).

During L-H-L transitions, "soft X-events" and ELM induced cooling, the change in χ_e across most of the plasma column occurred on a millisecond timescale and usually together with changes in H_α radiation. The values of the observed jumps in χ_e were in reasonable agreement with the normal L-mode trend, i.e. the jump in χ_e is larger when (T_e, ∇T_e) increases. No dependence $\chi_e \propto f(\nabla T_e, T_e)$ or "heat pinch model" can describe the χ_e^{HP} data in all regimes L, H and VH together with the observed jumps in χ_e during confinement mode transitions.

We suggest that all events described represent a "switching on or off" of the anomalous L-mode transport. These jumps in χ_e could be qualitatively understood if a part of anomalous transport is controlled by "noise pumping" created by the strong peripheral turbulence [4].

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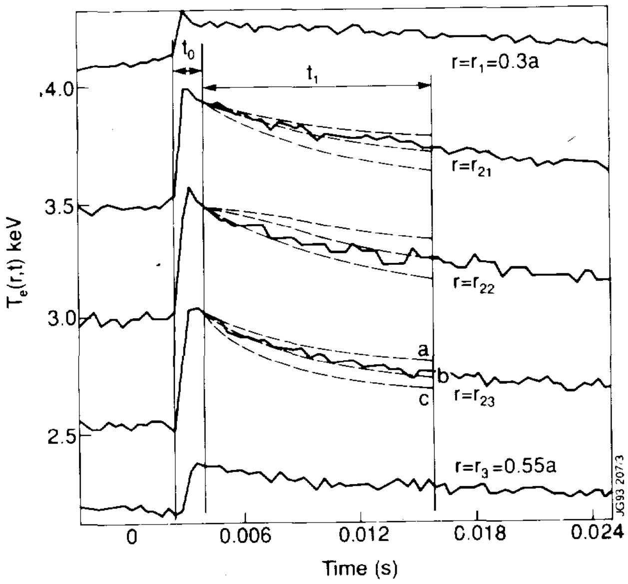

Fig. 1 The evolution of Te (r, t) for # 27578 (10MW on axis ICRH, 3MA).

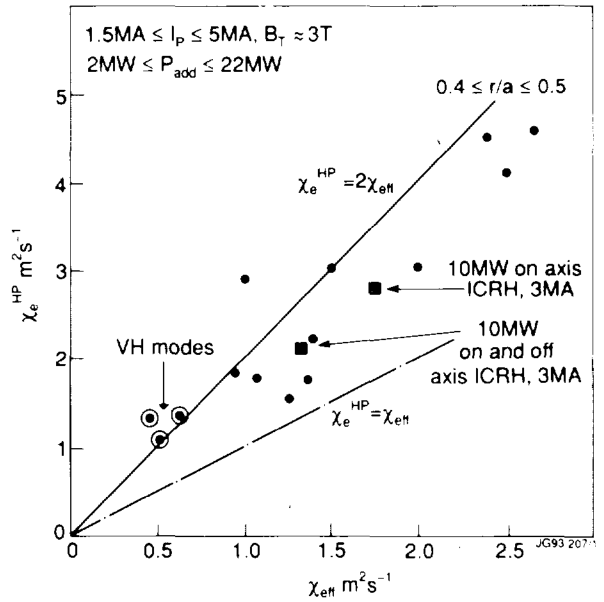

Fig. 2 Comparison of $\chi_e HP$, χ_{eff} for 1.5-5MA plasmas, L, H and VH modes.

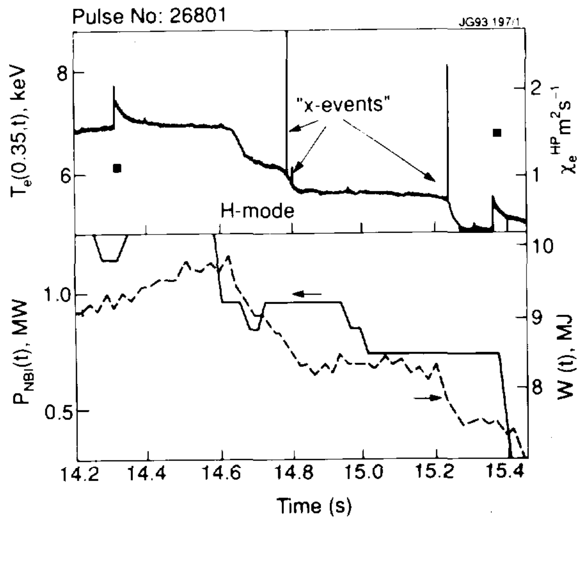

Fig. 3 The evolution of T_e (r, t), PNBI (t), stored energy W (t) and χ_e^{HP} in pulse 26801

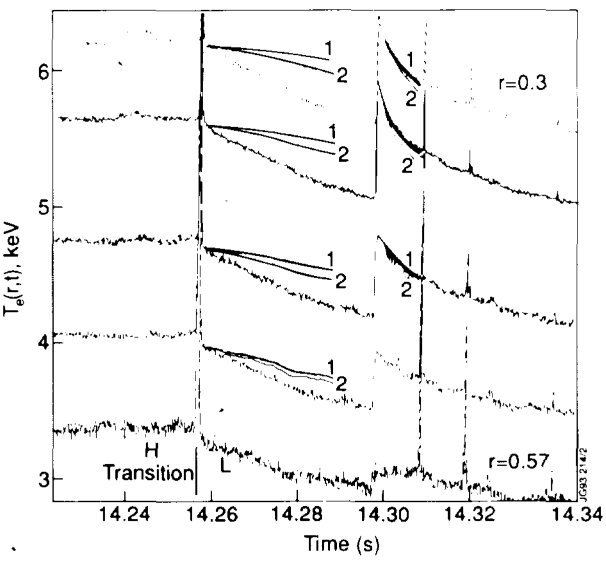

Fig. 4 The evolution of Te(r, t) in pulse 26780. Curves 1 and 2 are calculations made with the $\chi_e \propto \nabla T_e$ and $\chi_e \propto (\nabla T_e)^4$.