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# THE PLASMA PROFILE RESPONSE TO VARIATIONS OF THE HEATING PROFILE

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## 1. Introduction

The response of temperature and density profiles to variations in the heating profile shape has been studied on many Tokamaks. The experimental observations and theoretical interpretations have sometimes been conflicting, as claims of “profile consistency” or claims of “local transport controlled by local parameters” have been made. The study in [1] dismissed many of the claims made and it demonstrated how insensitive the temperature profiles are to changes in the heating profile (profile resiliance).

It is essential to distinguish between the following two forms of transport both of which can produce profile resilience but are conceptually different:

1. Plasma transport is governed by a diffusivity $\chi$ which depends on local plasma parameters as in standard thermodynamics.
2. The transport incorporates “action at a distance” features, say coupled turbulence, such that a diffusivity $\chi$ will depend on non-local parameters.

Plasma transport by both forms resulting in profile resilience can arise from various physics processes.

1. A saturation of local temperature T is caused by a strong increase in $\chi$ with temperature, e.g. $\chi \sim T^n$ (or $\nabla T^n$) with n large.
2. A state transition from one form of transport to a new form, e.g. via onset of instability and enhanced turbulence yields a $\chi$ that leads to a hard clamping of $\nabla T$; ITG modes near marginal stability fall into this category.
3. Turbulence with large correlation lengths (streamers) which link transport in the edge region to transport in the centre.
4. The clamping of gradients by MHD instabilities such as sawteeth and ELM’s in different regions of the plasma can give rise to a form of profile consistency.

JET has carried out three series of experiments during 1997, 98 and 99 featuring a total of 19 pulses. These experiments have been dedicated to producing controlled variations in the heating profile shape, all other pulse parameters are held fixed: plasma geometry, current $I_\phi$ = 2.8MA, field $B_\phi$ = 2.8T, density $n_{eo}$ = 3.5 $10^{19}m^{-3}$. The variations of the ICRF heating profile shape result from variations to the resonance position $R_{res}$; in these experiments the resonance position has been moved from inboard $R_{res}$ = 2.4m to outboard $R_{res}$ = 3.7m. A resonance position on the magnetic axis, R = 3.0m, leads to on-axis heating while for $R_{res}$ > 3.0m and R < 3.0m we have off-axis heating. By using more than one ICRH frequency we get a pulse featuring both on-axis and off-axis heating. This arrangement leads to a controlled way of heat deposition; the only lack of control arises from the fact that the spatial hydrogen minority concentration is not well determined. At the edge the $H_\alpha/D_\alpha$ ratio is measured and the value is used as the H/D concentration across the plasma.

**2. Data Analysis**

From the total set of pulses we select pairs of L-mode and pairs of H-mode pulses with matching power levels. For each pulse a time interval ending before the first sawtooth is selected. This is done to ensure that "pure transport and pure heating sources" are studied. Profiles of $T_e$ are from LIDAR and ECE, $T_i$ from CX, $n_e$ from LIDAR and interferometer, $n_i$ ($n_e$, Zeff CX), the ICRH heating rates are from the PION code, NBI heating rates are from the PENCIL code; the profiles are mapped on to EFIT equilibria whose flux surfaces are characterised by a flux surface label $0 \leq \times \leq 1$. All profiles including the EFIT $q_\psi$ are time averaged over 2 to 3 secs. The ion, electron and total fluxes, convective and diffusive parts are calculated as explained in [1], e.g.

$$q_e(x) = \frac{1}{V'(x) < |\nabla x|^2 >} \int_o^x Q_e(x') V'(x') dx' \quad (1)$$

and the ansatz is made

$$q_e(x) = -e\, n_e(x)\, \chi_e(x) < \nabla T_e > + q_{ec} \quad (2)$$

V(x) is volume inside x and $Q_e$ denotes the electron heat source term. From (2) thermal diffusivities are found together with the effective diffusivity

$$\chi_{eff} = \frac{q_e - q_{ec} + q_i - q_{ic}}{-e\left(n_e \nabla T_e + n_i \nabla T_i\right)} \tag{3}$$

**3. Interpretation**

Figure 1 emphasizes how different the heat flux profile shapes at constant total power can be made on JET for the on- and off-axis pulses in both the L- and H-mode cases. In order to illustrate those differences we show the ratios $q_{tot}$ (on-axis)/$q_{tot}$(off-axis); inside x = 0.5, the off-axis resonance position, the flux ratio is 4 in L-mode and 2 in H-mode. These different flux profiles induce a set of different profiles of $\nabla T_e$ and $T_e$. Figures 2 and 3 show respectively the on-axis/off axis ratios for $\nabla T_e$ and $T_e$. Notice that the ratios of $\nabla T_e$ are larger than those of $T_e$; In Figure 4 we show that a local diffusivity profile $\chi_{eff}$ (x) can explain changes to q and $\nabla T$. The $\chi_{eff}$ ratio for H-mode pulses is ~ 1, while for L-mode pulses some T or $\nabla T$ (Figures 2 and 3) dependence of $\chi_{eff}$ is required in the central region.

**4. Discussion**

The JET ICRH experiments with on and off-axis heating feature pairs of pulses with large difference in the heat flux profile but at fixed total power. Such differences and the absence of sawteeth (and ELM's L-mode) yield large and systematic differences to $\nabla T_e$ and $\nabla T_i$ (not shown); these in turn result in systematic profile differences to $T_e$ (and $T_i$). [In NBI only heated pulses it is not possible at fixed total power to change the heat flux profile such as that shown in Figure 1 with ICRH.] The changes to q and hence $\nabla T_e$ are smaller and less systematic; when $\nabla T_e$ is integrated for two similar pulses a much reduced difference $\Delta T_e$ is obtained and this has lead to the interpretation "profile consistency".

In these JET experiments we note that the total stored energy W and the internal inductance $\ell_i$ are both slowly increasing over a period of 8 sec. for both L and H-mode pulses. Such an increase is consistent with results from current ramp experiments on JET. Prior to the onset of sawteeth, i.e. after the end of the time interval chosen for analysis, an accelerated peaking of $T_{eo}$ and $T_{io}$ takes place. This observation appear to show that as the axial $q_\psi$ tends to unity there is a reduction of ion and electron transport.

[1] J.D. Callen et al., Nucl. Fusion 27 (19871857)

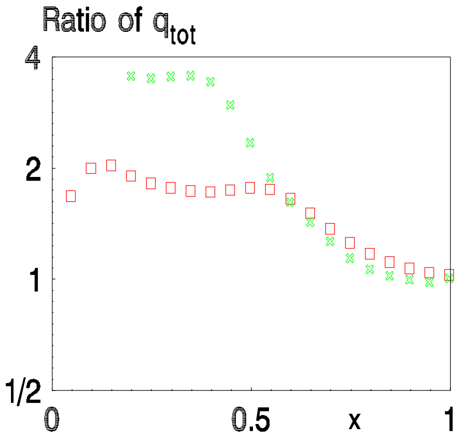


*Fig.1 Ratios of total heat flux. Legend :*

*L–mode 46824 on–axis/46826 off–axis*

*H–mode 43633 on–axis/43634 off–axis*

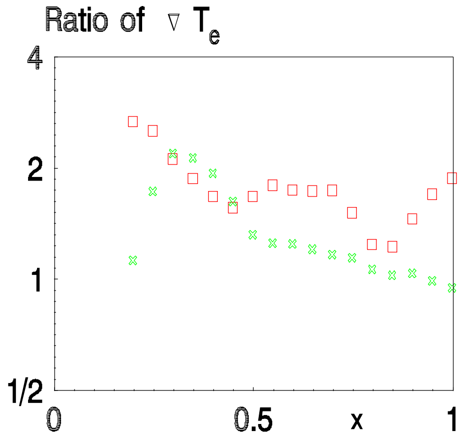


*Fig.2 The profile response to changes in heat flux*

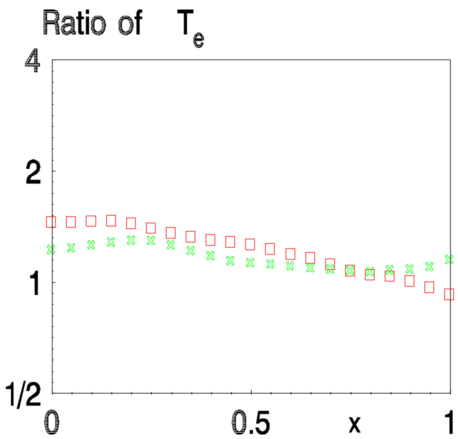


*Fig. 3 The change to temperature is less pronounced than that of the gradient.*

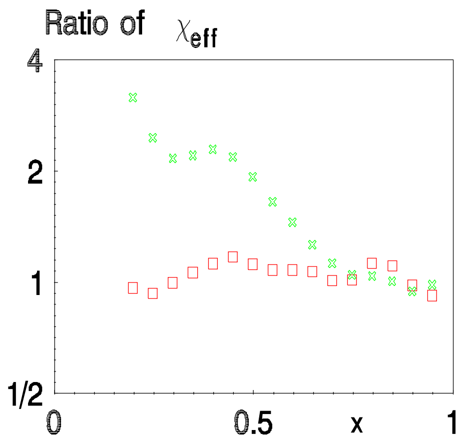


*Fig. 4 The H–mode diffusivity on–off–axis is unchanged. The L–mode requires some T or ∇T dependence to make the ratio 1*