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** See Annex*

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Heat transport with strong off-axis heating

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A clear understanding of the transport of heat in a tokamak has continued to allude workers in the field for many years. One problem that has given particular cause for concern is the apparent insensitivity of the electron temperature profile in some experiments (1) (2) (3) to changes in the heating profile. Various concepts have been put forward to try and explain this apparent insensitivity, such as profile consistency (4) and resiliency (2), inward heat flows (pinches) (5), (3), and, more recently, a suggestion that the variables that describe local transport are not just gradients of temperature and density but some other so far unidentified variable (6).

In this paper it will be shown for the particular conditions of an off-axis ICRH experiment on JET that the temperature does respond to the heating profile and that the total heat flux can be adequately described by Fick's Law $q \;\; \alpha \; -n\nabla T$. In this particular case there is no need to invoke any additional heat flow of a non-diffusive nature to explain the transport of heat. The experiment involves the production of both positive and negative heat flux q and in both cases Fick's law is a reasonable representation of the data.

One significant difference between these experiments and other experiments with off axis heating is that there is a clear thermal response of the plasma to the off axis heating in that initially the temperature profile is peaked off-axis in accord with the heating profile. One other important feature of this pulse is that it is completely sawtooth free and there is no significant MHD during the full 5 second duration of the heating phase. The lack of sawteeth MHD activity simplifies the calculation of the power deposition profile, since there is no possibility of the redistribution of the minority fast ions due to these non classical effects.

The strong negative (inward) heat flux is achieved by heating off axis using hydrogen minority ICRH. Since it is observed in most tokamaks that the thermal diffusivity in the plasma centre is very small compared to its value in the outer region it is essential to have a large heat sink in the plasma centre, and this is achieved by the injection of a 4 mm pellet just prior to the application of the off-axis heating.

The main plasma parameters are shown in Fig. 1. A 4 mm pellet is injected at 3.8 secs after the commencement of the discharge just after the current reaches its flat top, this causes the central temperature to drop by approximately 2 KeV giving a fairly flat temperature profile (see Fig. 2a). Following the injection of the pellet 8 MW of ICRH (hydrogen minority) is applied such that the resonance is ~ 50 cms off axis. Throughout the whole 5 second heating period q(o) obtained from the Faraday rotation measurements is above unity which explains the lack of sawteeth in these discharges.

The time development of the electron temperature profile is shown in Fig. 2a. Immediately after the start of the heating it can be seen that on off-axis peak in the temperature is formed at the resonance position. Some 0.2 secs later the profile has become profoundly hollow and remains hollow for a further 1 sec. In fact the profile only becomes really peaked some 4 secs after the start of heating. The reason for the peaking being the ohmic heating which is peaked on axis 2 secs after the start of heating (see Fig. 2b).

An almost identical pulse with the same heating power but on axis has a very different temperature behaviour being peaked on axis at all times.

A complete transport analysis has been made of the off-axis heating pulse using the TRANSP code. Both the ICRH model in TRANSP (7) and the PION (8) model have been used. The two models give very similar heating profiles and a typical example using TRANSP is given in Figure 2b. The bulk of the power is of course deposited off-axis there is however a small amount deposited on-axis from TTMP as well as the ohmic input.

The power balance consists of five significant terms, the ICRH (P_{ICRH}) and ohmic (P_{OH}) input terms, the thermal inertia ($\dot{W}$) and radiation (P_{rad}) loss terms and the conductive heat flux, the convected heat flux is very small. The equation for the total (ion + electron) conducted heat flux q has the form

$$qS = \int_o^\rho P_{ICRH} + \int_o^\rho P_{OH} - \int_o^\rho \dot{W} - \int_o^\rho Prad \quad , \qquad (1)$$

where S is the surface area of the flux surface ρ.

Due to the high density ($n(o) > 5 \times 10^{19}\ m^{-3}$) in this particular pulse it is not possible to separately evaluate the heat flux in the ion and electron channels. The ion temperature profile was not measured, however the peak ion temperature measured by the X-ray crystal spectrometer closely follows the central electron temperature (Fig. 1). Therefore in the transport analysis T_i was assumed to be equal to T_e everywhere.

In the plasma centre for one second after the commencement of heating the heat flux q is negative (i.e. inward) being dominated by the thermal inertia term $(\dot{W})$. Fig. 3a shows the time development of the radial profile of the heat flux. One second after the start of the heating the temperature profile becomes slightly peaked and then the heat flux becomes positive and outward. We find that the changes in sign of the gradient of the temperature approximately (Fig. 3b) match the changes in sign of q in both position and time.

A more conventional method of plotting the data is to exhibit q versus $- n\nabla Te$ at different radial positions as a function of time and this is done in Fig. 4. For the two radial positions close to the plasma centre both q and $- n\nabla Te$ start negative at the beginning of the heating phase, then eventually become positive after passing close to the origin. Moving out further in radius on the outboard side of the resonance the starting point moves further away from the origin but the curves are still approximately straight lines and extrapolate to pass close to the origin. At the outermost radii $0.6 < \rho < 0.8$ there is not a sufficient range in $- n\nabla T_e$ to make a meaningful extrapolation. One other important point to note is that the slope of the lines increases with radius indicating that the χ increases with radius, a feature common to all L-mode plasmas.

Hence we see that a model of the form $q = - \chi n \nabla T$ with χ a function of radius or more likely a function of a magnetic parameter such as q gives an adequate description of the data up to ρ of 0.6. Tests of the sensitivity of this result to errors have been made by varying the input data within its error range and the resulting errors in q and $n\nabla Te$ are shown on Fig. 4. The minority concentration has also been varied between 2.5 and 10%, this has only a small effect on the value of q.

In future studies we will investigate the modelling of the measured χ by functions of temperature T and ∇T and also compare the data with existing transport models such as the one proposed by Rebut, Lallia and Watkins (9) which has a similar structure in q, $-n\nabla T_e$ space to the data shown in Fig. 4.

In summary an example of a pulse in which the temperature profile responds strongly to the heating profile has been presented. Transport analysis of the pulse shows that a model in which the heat flux is a function of the temperature gradient and other local parameters would give an adequate description of the data for both negative and positive heat flux q and no large non diffusive flow terms are required.

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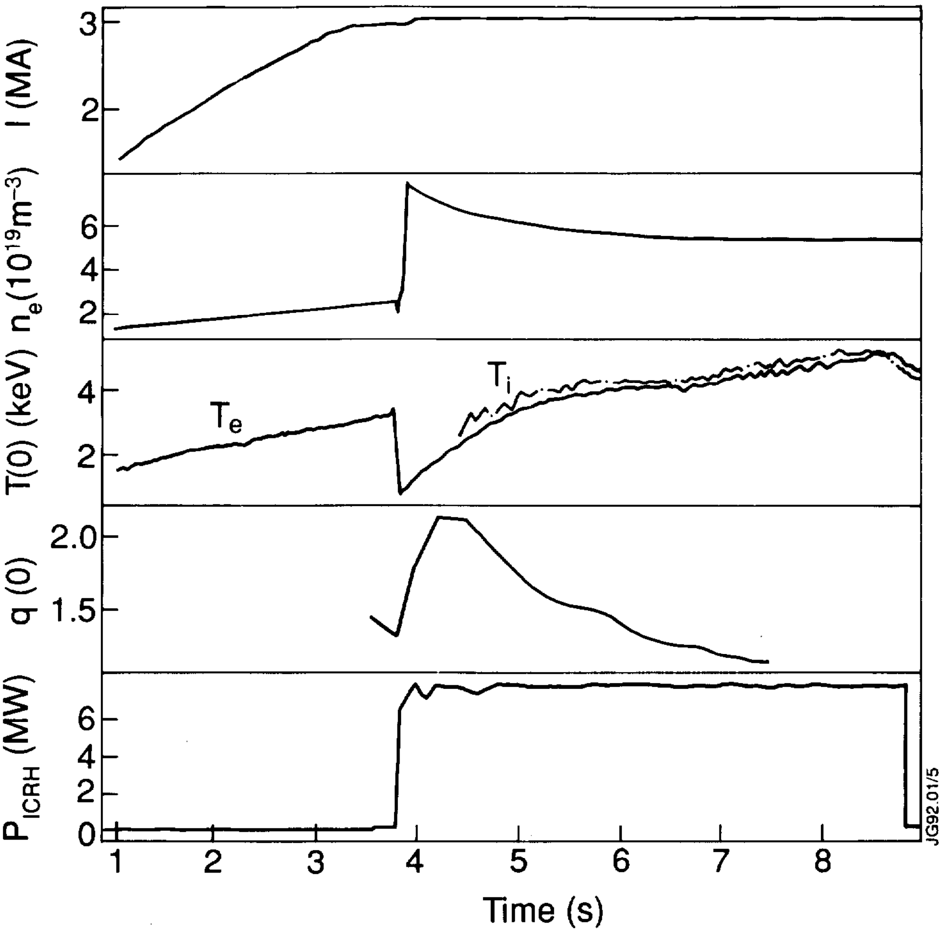

Fig. 1 The current I, central density n_e, central T_e and T_i, q(o) from polarimetry and ICRH heating power versus time. The pellet is injected at t = 3.8 seconds.

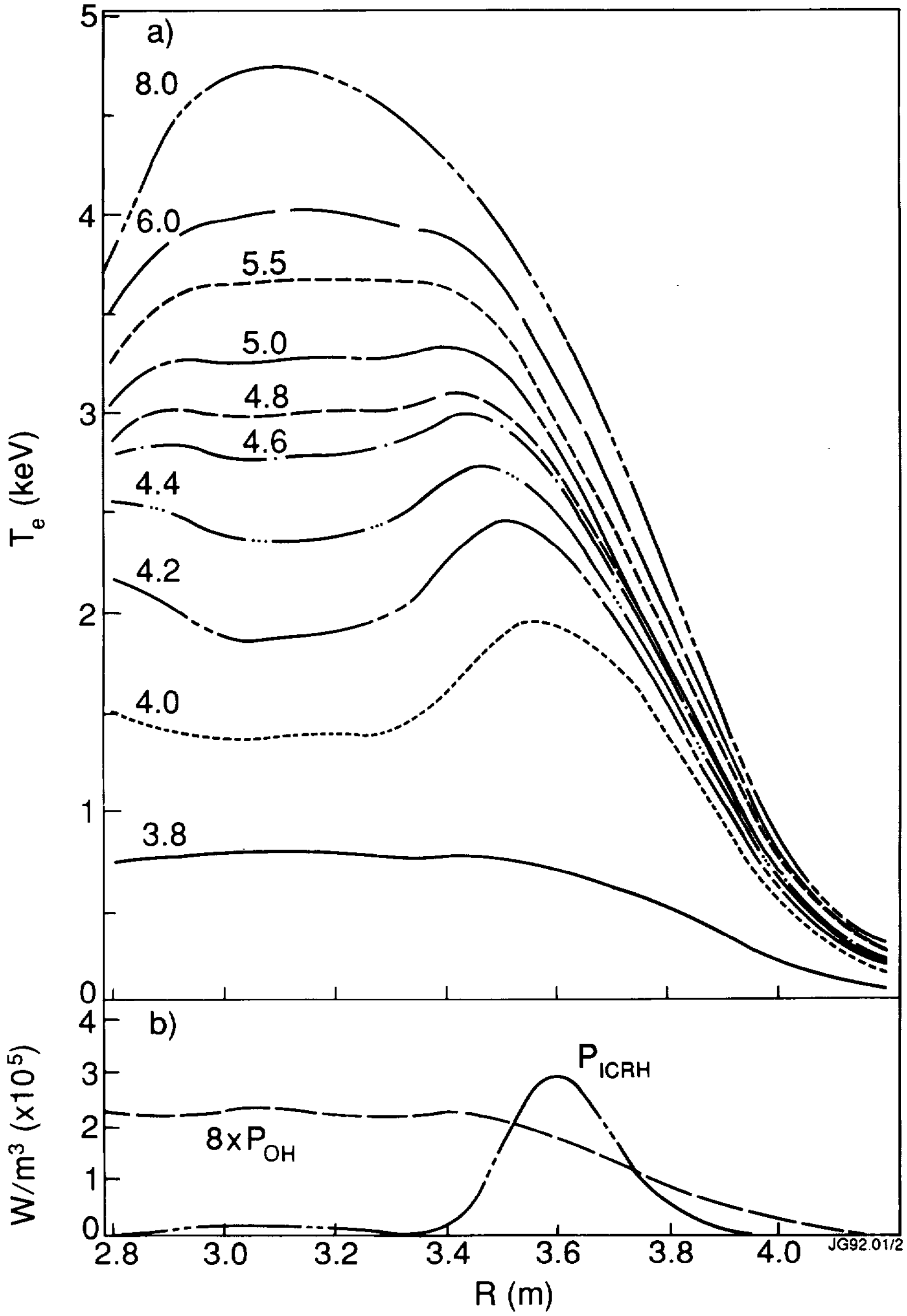

Fig. 2 (a) The radial electron temperature profile at several different times.

(b) The ICRH and ohmic heating profiles at t = 8 secs note the ohmic has been multiplied by a factor of 8.

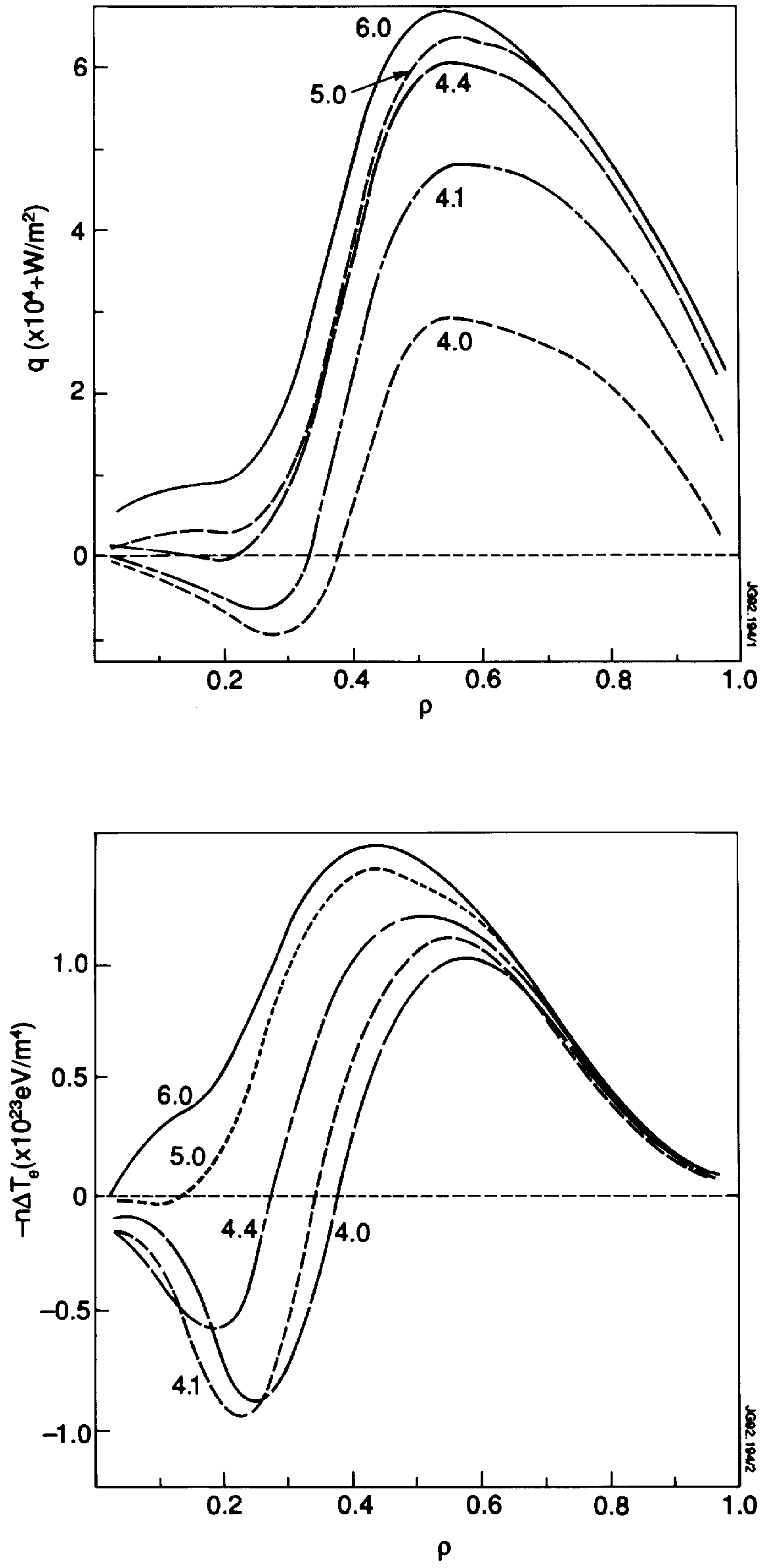

Fig. 3 (a) The total heat flux q defined by equation (1) versus radius. (b) $-n\nabla T_e$ versus radius.

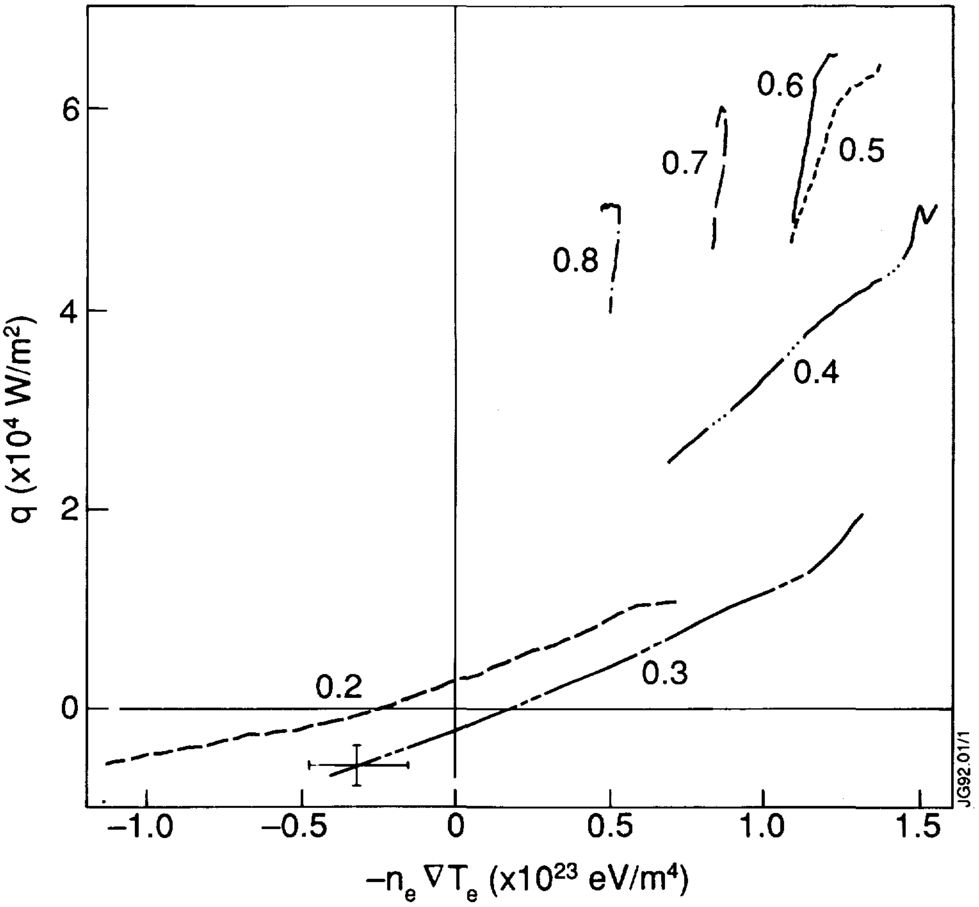

Fig. 4. The total heat flux q versus -n∇T_e at different values of the normalised radius ρ.

ANNEX

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