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Abrupt Changes in Confinement in the JET Tokamak

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ABSTRACT

Analysis of a high performance plasma in JET has uncovered large abrupt changes in confinement. The change in the plasma configuration at these times is small and it appears that the confinement is not determined by the macroscopic plasma parameters.

INTRODUCTION

We consider here the type of JET[1] discharge with the best performance, having plasmas with the highest confinement and fusion rate. The analysis is carried out using one of the most succesful discharges, JET shot 33643. This shot illustrates two dramatic types of behaviour.

The first is a sudden loss of confinement during neutral beam heating. Application of the heating produces a rapid rise in the plasma energy, W. However after reaching a high value of W this rise is transformed into a rapid fall in a time not longer than tens of milliseconds. The uncertainty as to the processes underlying the behaviour led to the phenomenon being called the X-event. The abrupt change in $\dot{W}$ at this event implies a large fall in the confinement time with almost no change in the plasma parameters.

The second, perhaps more remarkable, result is that when the neutral beam heating is switched off some time after the X-event there is only a small change in $\dot{W}$. Since the energy loss rate from the plasma is $P-\dot{W}$, the removal of P with only a small change in $\dot{W}$ implies that, in apparently the same plasma, the energy loss rate has dropped by an amount P. In the present case this represents a large improvement in confinement.

In both of these cases the abrupt change in confinement time, using the simplest analysis, is around a factor of three. A more detailed analysis would no doubt change this factor somewhat but the basic result is nevertheless clear.

THE X-EVENT

Figure 1 displays the basic information. The application of 18MW of neutral beam heating produces a rise in plasma energy, leading to the X-event and the fall of W following this event. The energy W is measured with a diamagnetic loop and therefore measures the total energy in the plasma.

At the time of the X-event there is a rapid instability of the plasma core which is probably similar to the sawtooth instability. This is shown in figure 2 using a time trace of the central electron temperature (only resolved here to a time of 7ms). At essentially the same time there is a burst of D_α radiation which is usually attributed to an instability involving the edge of the plasma (the so-called ELM or edge localised mode). However the key point here is that these transient and brief instabilities do not explain the subsequent continued loss of performance.

They may provide a cause in the sense of a trigger, but do not offer a cause in the sense of having a direct and continuing role in the deteriorated confinement.

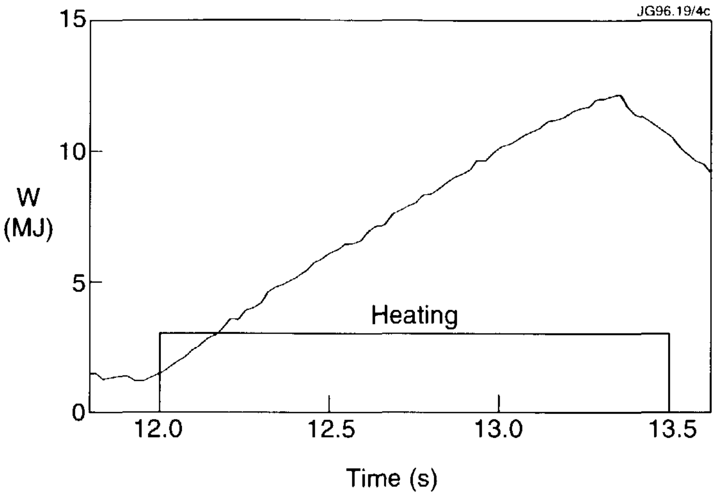

Figure 1. Plasma energy W(t) up to and following the X-event.

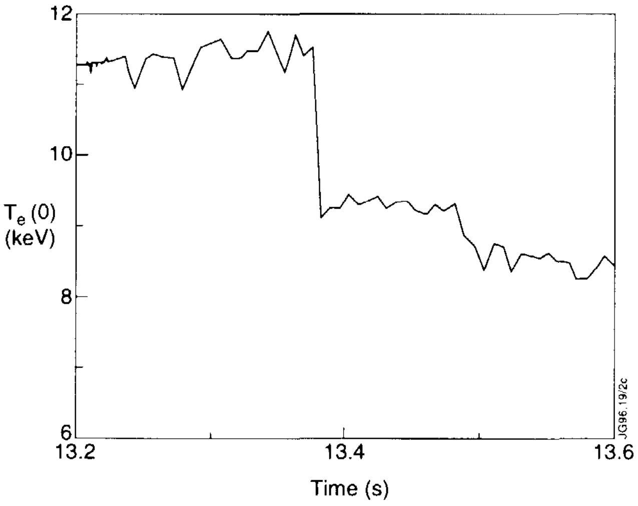

Figure 2. Showing the drop in central temperature at the X-event.

The magnetic fluctuations observed before the X-event fall to a level an order of magnitude lower after the event, and so the deterioration of confinement cannot be attributed to these flunctuations.

To see the problem in a global framework we use the power balance equation

$$\dot{W} = P - \frac{W}{\tau}$$

where P is the heating power and the energy loss is characterised by the confinement time τ, and re-write the equation in the form

$$\tau = \frac{W}{P - \dot{W}} . \tag{1}$$

The power is 18MW and considering times immediately before and after the X-event we find $\dot{W} \simeq 8$MW before and $\dot{W} \simeq -11$MW after. Thus, using equation (1) we obtain the ratio of confinement times before (τ_1) and after (τ_2) to be

$$\frac{\tau_1}{\tau_2} = 2.9$$

Allowance for the effect of Ohmic heating reduces this ratio slightly but leaves the sudden jump in confinement time to be explained. It should be said clearly at this point that no explanation will be offered here, and we shall only be able to describe phenomenologically the way in which the transition occurs.

One rather obvious possible explanation of the results would be that it was a mistake to regard P as constant during the transition. Indeed if the neutral beam were to be extinguished at the X-event, the ~19MW change in $\dot{W}$ would be easily understood as the result of the loss of 18MW of beam power. The difficulties with this explanation are firstly that the loss of beam penetration is calculated to be a slow process rather than the sudden one required, and secondly that there is no obvious physical effect which has been neglected which, if included, could give rise to a sudden beam loss.

A rapid loss of fast ions would not explain the behaviour because W includes the energy of the fast ions, and so the total input is correctly given by P. We note also that the perpendicular energy of the fast ions is approximately 2/3 of their total energy, as with thermal particles.

Another conjecture is that the good "H-mode" confinement before the X-event is due to a transport barrier at the plasma edge, and that this is disrupted by a pressure gradient driven instability at the edge of the plasma. In this case we would expect the immediate effect to be a loss of plasma pressure at the plasma edge. We examine this by looking at measured pressure profiles just before and just after the X-event.

The pressure profiles shown in figure 3 are calculated using $p = n_e (T_e + T_i)$, the density being determined by LIDAR, the electron temperature from ECE and the ion temperature from charge exchange measurements. The correction for $n_i \neq n_e$ through $Z_{eff} \neq 1$ has been examined and does not significantly affect the result.

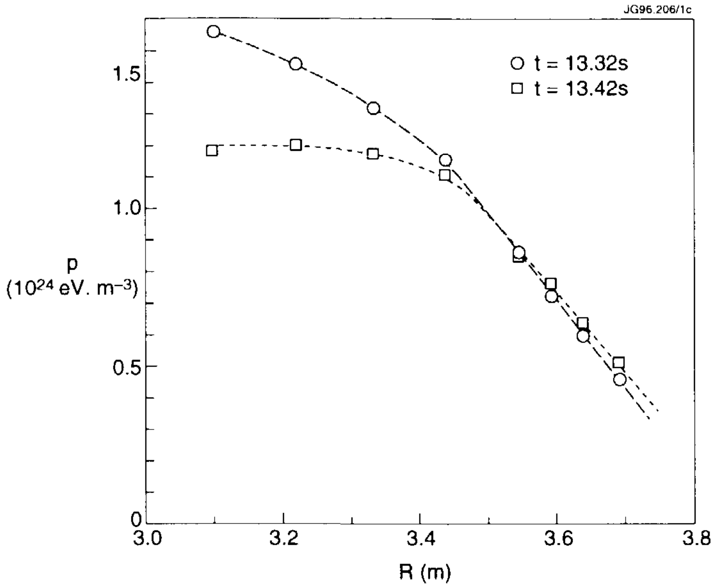

Figure 3. Showing the pressure profile before and after the X-event.

The two pressure profiles show two important features. Firstly the maximum fall in plasma energy density occurs at the *centre* of the plasma, and secondly the pressure in the outer half of the plasma rises rather than falls, contrary to the expected behaviour following from an edge instability.

The plasma is substantially below the β-limit, having β/(I(MA)/aB) = 1.7. Away from the edge, the pressure gradient is well below the ballooning stability limit.

It is also interesting that the pressure gradient in the outer part of the plasma is essentially unchanged although the heat flux, ~$(P - \dot{W})$, through this region has trebled.

The dramatic change in the thermal diffusivity can be illustrated using an effective χ defined by

$$\chi_{\mathrm{eff}} = \frac{q}{n|\nabla(T_e + T_i)|}$$

where q is the heat flux density, and the observed change in χ_{eff} is shown in figure 4. The large increase in χ_{eff} mirrors the confinement time calculation given above.

It is seen from these results that although there was a "sawtooth-ELM" instability at the time of the X-event, the lasting consequence which gives the apparently irreversible loss of performance is a change in the transport state of the plasma. Thus for very similar plasma states shortly before and after the X-event the thermal diffusivity has changed by a factor of around 3. It appears that the plasma is capable of two very different transport states in very similar plasma configurations.

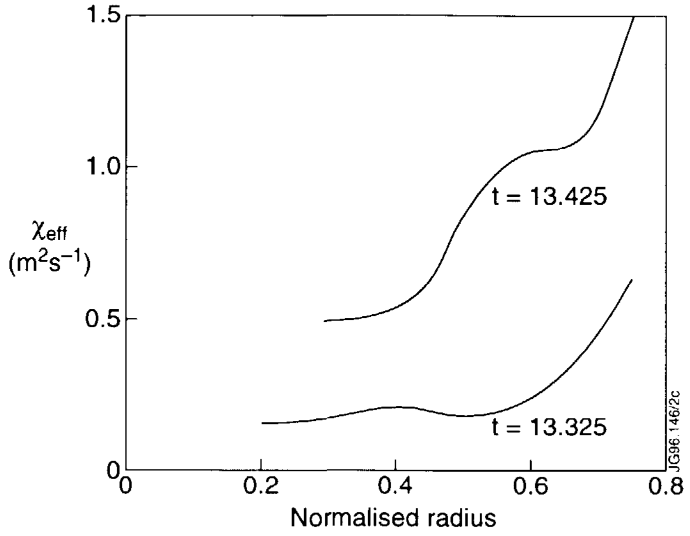

Figure 4. Graphs of χ_{eff} before and after the X-Event

NEUTRAL BEAM SWITCH-OFF

Immediately before switching-off the neutral beam the rate of change of plasma energy is given by

$$\dot{W} = P - \frac{W}{\tau}.$$

Since we would expect it to be the same plasma immediately after the switching-off of the beam power as before, neither W nor τ should change. We would therefore expect that when the power P is switched off there would be change in $\dot{W}$ given by

$$\Delta\dot{W} = -P.$$

A graph of W(t) for the case considered is shown in figure 5. The absence of a significant change in $\dot{W}$ is clear. However we need to examine the behaviour carefully and the figure 6 allows a more precise analysis.

The + signs indicate the data points. To determine the change in $\dot{W}$ we need to identify its value *before* the switch-off. The upper and lower limits of the slope of W are shown by the two straight lines. Now it is seen that 250ms after the switch-off the value of W lies within the band of extrapolation.

After the switch-off it is expected that the slope of W would be changed by an amount – P, that is – 18MW, and expected slope is indicated by the dashed line. The discrepancy is clear.

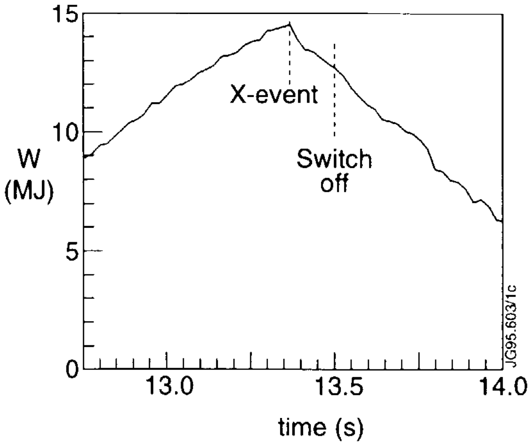

Figure 5. Behaviour of the total plasma energy around the neutral beam switch-off.

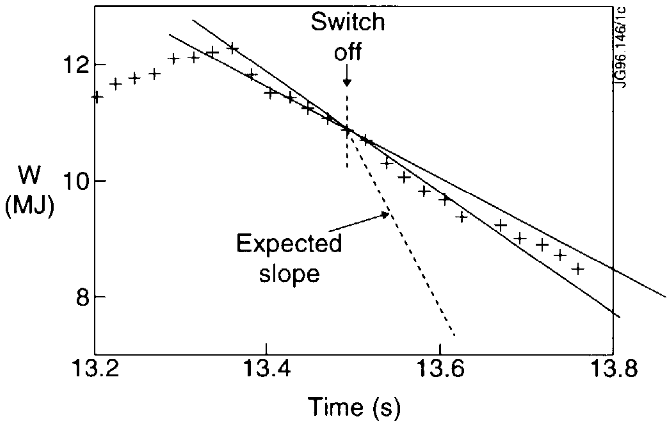

Figure 6. Showing the experimental slope of W(t) after the neutral beam switch-off as compared with the extrapolated slope and the expected slope.

The implication of a constant $\dot{W}$ can be seen from equation (1). The confinement time before the switch-off is

$$\tau = \frac{W}{P - \dot{W}}$$

and after switch-off is

$$\tau = \frac{W}{-\dot{W}}.$$

It is seen therefore that the experimental result implies a change in τ given by

$$\frac{\Delta\tau}{\tau} = \frac{P}{-\dot{W}}. \qquad (2)$$

In the present case $\Delta\tau / \tau \sim 2$, implying an increase in τ by a factor 3.

The value of W is obtained from the diamagnetic signal and this includes the energy of fast beam ions. However, on the assumption that there is no direct loss of fast-ions, the energy loss from the thermal plasma is still $P - \dot{W}$, where W is the total energy, and equation (2) is unchanged. The conclusion is therefore unaffected by the presence of fast particles.

The plasma has a toroidal rotation driven by the beams. The slowing of this rotation is a source of energy for the plasma even after the beam switch-off. However the rotation energy, which is about 1MJ at the X-event, decays rapidly to half that value *before* the beam switch-off. It is likely that the decay is no faster after the switch- off. If it is characterised by the ion energy confinement time it will be slower. This means that the change in confinement time is even greater than calculated above.

The interpretation of this result would seem to be that the heat flux Q is above a critical value, Q_c, before the power switch-off and that the differential heat flux $Q - Q_c$ sees little or no impedance. Reduction of the heat flux to a smaller value $(\geq Q_c)$ after the switch-off then leads to no change in $\dot{W}$, as observed.

A simple, but partial, analogy is that of pouring water into a bath with an opening to a pipe. The pipe provides an impedance to the flow a provided Q is below the critical value Q_c, at which the bath overflows. The flow $Q - Q_c$ sees no impedance.

CONCLUSION

It has been shown that it is possible for the plasma to have very different confinement in very similar macroscopic states.

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REFERENCE

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