Radiation Phenomena and Particle Fluxes in the X-Event in JET

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Introduction

The highest fusion yield of $\Gamma_n \approx 4 \times 10^{16}$n/s has been observed in JET in hot ion H-mode discharges at a heating power of $P_{heat} \approx 15$ MW with average electron densities of $\bar{n}_e \leq 4 \times 10^{19}$ m^{-3}[1,2,3]. The energy confinement during the H-mode was typically 3 times better than in the L-mode. The final termination of the high confinement regime can take place within milli-seconds. The sudden loss of stored energy then causes an intense heat-flash on the divertor dump plates, accompanied by a dramatic increase of divertor particle fluxes (X-event).

Several typical patterns of the H-mode termination have been observed, showing different dynamic and radial range of the confinement deterioration, as reflected in the response of stored energy, W_p, the total neutron rate, Γ_n, and the electron and ion temperature profiles:

The diffusive decay: Γ_n and W_p degrade gradually on a time scale of up to several hundred milli-seconds. The plasma temperature starts to decrease from the edge. A 'cold wave' appears to travel towards the plasma centre.

The fast edge, diffusive core decay: The core ($r \leq a/2$) confinement degradation takes place on a diffusive time scale, while the outer half is deteriorating fast.

The sudden decay: Core and edge confinement decay simultaneously on a sub milli-second time scale.

A final power flash, dumped on the divertor target plates, resulting from the final fall-back into L-mode, can reach more than 100 MW and is observed in all three types.

Experimental:

The radiation build-up and the particle fluxes in the phase, immediately preceding the X-event, has been studied with bolometry and spectroscopy. Only the D_α data have a time resolution (≈ 2 ms), which comes close to the dynamic of the X-event itself. Bolometry, spectroscopy and the infrared diagnostic have resolution in the 20 to 100 ms range.

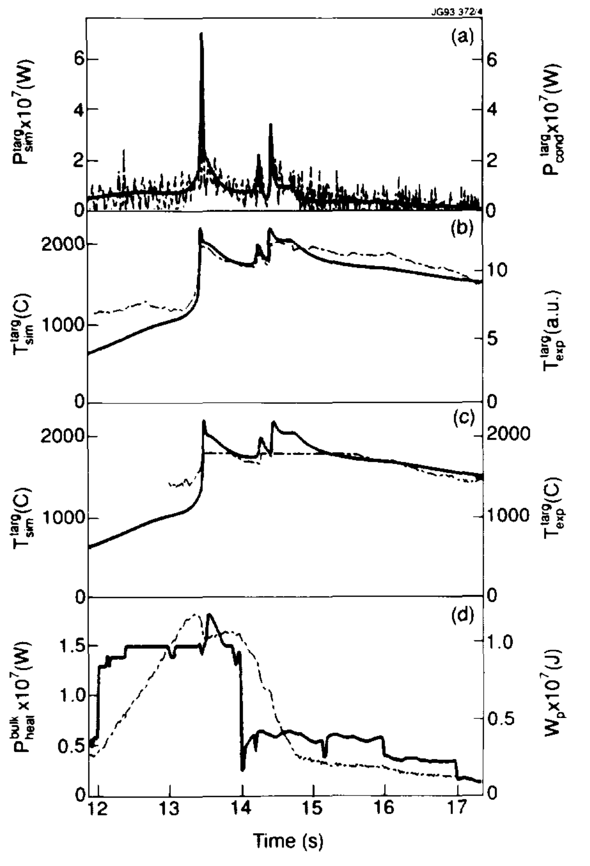

Fig. 1: a: Total heating power (solid) and stored energy; b+c: Fitted temperature (solid) and measured one; d: Fitted (solid) and measured target power.

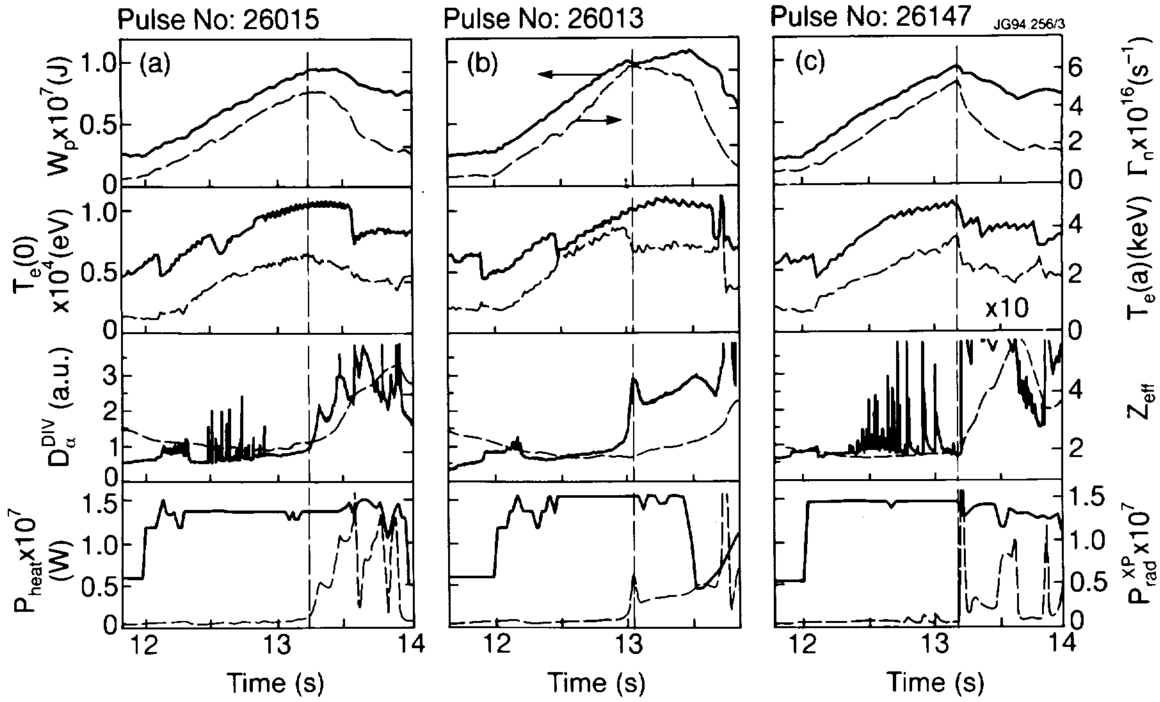

Fig. 2: Three HMI discharges with differing X-event pre-phase. The curves depict (bottom to top, solid refers to left scale): Total heating power and total divertor radiation, divertor D_α-emission and Z_{eff}, central and edge electron temperature, stored energy and total neutron rate, respectively.

The measurement of the target temperature, T_{targ}, was fraught with difficulties. The measuring range of the CCD and infrared cameras did not cover the fast rise of T_{targ} and the temperature pattern was complicated by mechanical alignment errors of the target tiles. For the graphite divertor an attempt had been made [4] to fit the target temparature, calculated from the conductive power into the divertor to experimental data. Figure 1 shows, for a HIM discharge with X-event, the development of the measured and calculated target temperature.

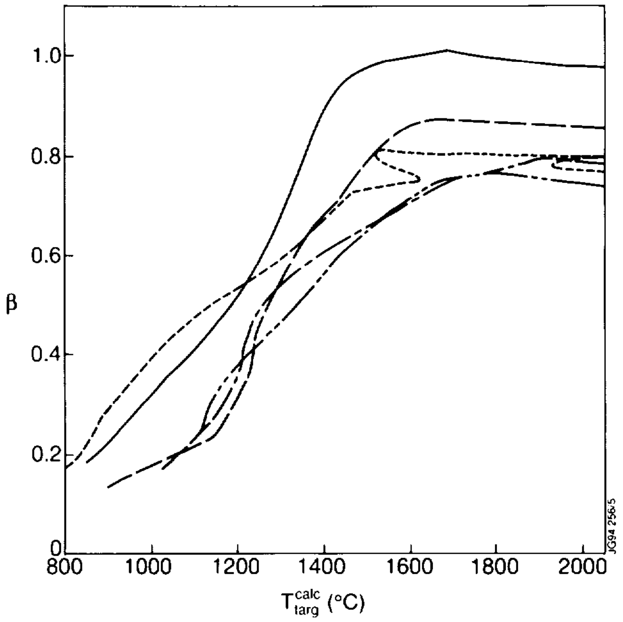

Fig. 3: development of β as a function of the calculated target temperature during the course of the high performance regime of 5 HIM discharges.

Results and Discussion:

Figure 2 depicts relevant plasma parameters during the H-mode of representative hot-ion mode (HIM) discharges for the above classification. The discharges of figure 2a (pulse 26015) and 2b (pulse 26013) show a gradual degradation of the confinement before the actual X-event, which is marked by the sharp drop of the central electron temperature. The edge electron temperature decays well before the central one. Figure 2c (pulse 26147) demonstrates the simultaneous and sudden decay of the electron temperature in the centre and the edge and, not shown, of the ion temperature and, accordingly, the sudden drop of stored energy and total neutron rate.

Although MHD-activities are often coinciding with the termination, there is no clear correlation to a critical β. Figure 3 shows the relation between β and the calculated target temperature during the course of the H-mode for 5 HIM-discharges with similar heating power, $P_{heat} \approx 15$ MW, and electron density, $\bar{n}_e \leq 4 \cdot 10^{19}$ m^{-3}. The run-away target temperature of about 1400 °C is reached at different β-values. The temperature is too low, to contribute through sublimation to the divertor carbon flux. However, any further confinement deterioration increases the power load on the target and can, at this temperature level, lead to run-away conditions:

MHD-activities: A fast loss of stored energy leads to high target surface temperatures, even if ΔW_p is small. If a sawtooth is coupling to an ELM, as in discharge 26147, $\dot{W}_p$ can easily reach 50 to 100 MW.

Recycling losses: High target bulk temperature can cause a significant release of deuterium, trapped in the graphite and, due to the enhanced recycling, can lead to an effective edge cooling.

Thermally decoupled carbon: Recent NBI test-bed experiments on graphite tiles [5] have demonstrated the existance of a partial coverage of particles without or with reduced thermal contact to the bulk. This carbon can be vapourised and/or ejected into the plasma on a ms time scale, even with relatively small heat pulses, similar to a laser blow-off. The particle coverage can not be removed completely, even at intensive pulsing. Redeposited carbon might also contribute in the same way.

The development of the calculated target temperature T_{targ} and the time-integrated target ower

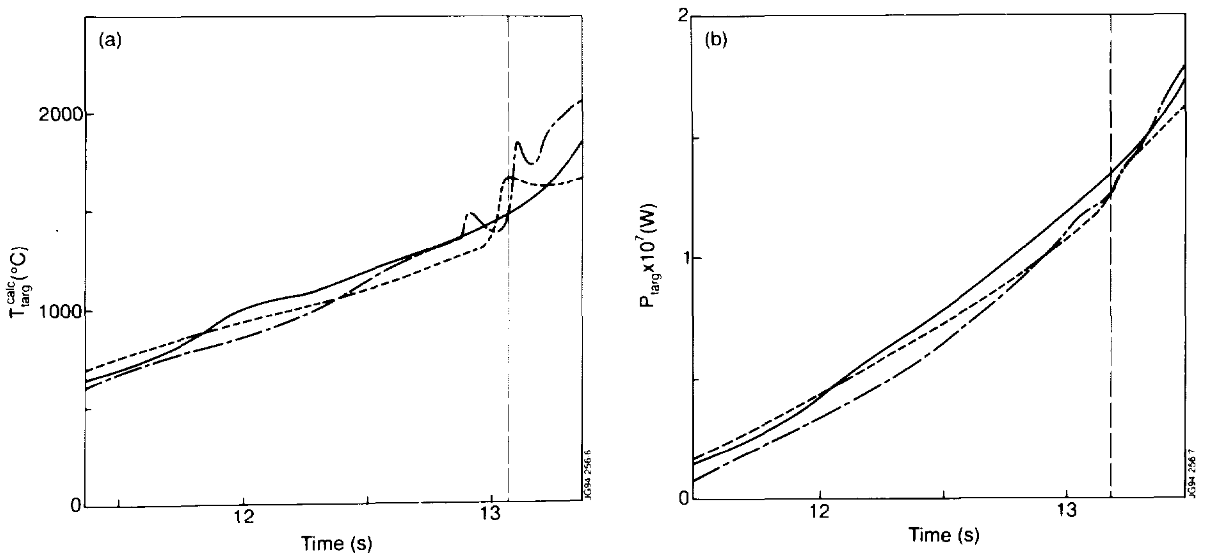

Fig. 4: The development of target temperature (left) and integrated target load (right) during the high performance regime for the 3 discharges of picture 2. The vertical dotted line marks the onset of the X-event, the start of the decline of the total neutron rate.

$E_{targ} = \int_{t_{xp-s}}^{t_0} P_{targ} dt$ are depicted in figure 4 (t_{xp-s}=start of the X-point configuration). At the time of the X-event, marked by the vertical dotted line, typical values are $T_{targ} \approx 1400\ °C$ and $E_{targ} \approx 13$ MJ.

Summary:

- The H-mode phase in high performance discharges tends to collapse irreversibly. The (calculated) target temperature just before the X-event amounts to about 1400 °C. Any deterioration of confinement at this temperature leads to run-away conditions of the target temperature and a final fall-back into L-mode. However, there is no clear of a correlation between a critical β and the H-mode termination.
- Possible causes of the confinement deterioration are:
  1. MHD activitives can cause a fast plasma loss and, hence, a power flash, dumped on the divertor target, leading to a temperature jump of up to 1000 ^{0}C. At a bulk temperature $T \geq 1400\ ^0C$ this leads to run-away conditions of confinement and target surface temperature.
  2. Enhanced recycling, due to thermal release of trapped deuterium from the graphite target plates causes an efective plasma edge cooling.
  3. Loose graphite on the target tiles with virtually no thermal coupling to the target bulk can be sublimated and ejected into the main plasma with even small power levels.
- Apart from major instabilities, the bulk temperature of the divertor dump plates appears to play an important role. Increasing temperature reduces the equilibrium pressure of trapped deuterium in the graphite and leads to higher recycling fluxes and hence, stronger edge cooling, making the discharge vulnerable to any further confinement deterioration. An active cooling, keeping the bulk target at ambient temperature could make the discharge more resilient against even medium MHD instabilities, as e.g. giant ELMs.

References:

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