

Divertor radiation distribution during ELMs in JET

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Introduction. The Type I ELMy H-mode regime is the baseline scenario for operation of ITER in high fusion gain regimes ($Q_{DT} \geq 10$) with high density plasmas ($\langle n_e \rangle \geq 10^{20} \text{ m}^{-3}$) and with high plasma energy ($\sim 350 \text{ MJ}$) [1]. The major drawback of this operating regime is the ELM-associated periodic power loading of plasma-facing components which can lead to high target erosion and a significant reduction of component lifetimes. In present tokamaks, the plasma energy drop normalised to the pedestal energy, $\Delta W_{ELM}/W_{ped}$ during a Type I ELM is typically 3-10%. A significant part of this energy can be found in form of plasma radiation, located mostly in the divertor region (in the present contribution, it is integrated over $\sim 2 \text{ ms}$, which is considerably longer than the ELM target power deposition of several $100 \mu\text{s}$). Systematic studies of the distribution and magnitude of this radiation are required in order to understand and predict the energy deposition by ELMs on plasma-facing components in larger devices such as ITER, where even the smallest Type I ELMs will considerably exceed the maximum energies currently accessible.

Experimental set-up Dedicated experiments aiming at the characterisation of transient loads during large Type I ELMs have been performed during the 2007 JET campaigns at high plasma current and input power: $I_p=3.0 \text{ MA}$, $B_T=3.0 \text{ T}$, $q_{95}=3.2$, $\delta_u \sim 0.22$, $\delta_l \sim 0.28$, $\kappa=1.73$, 19 MW NBI and 1.4 MW ICRH power. The JET bolometer camera system has recently been substantially upgraded, allowing significantly improved spatial and temporal resolution of the radiation distribution, particularly in the divertor region [2]. This allows a greatly improved tomographic reconstruction of the radiation pattern on a timescale of the order of the typical duration of a Type I ELM cycle ($\sim 1 \text{ ms}$). In addition, the new system permits for the first time on JET an accurate analysis of the total energy radiated by any particular ELM, even in the case of smaller, higher frequency Type III ELMs.

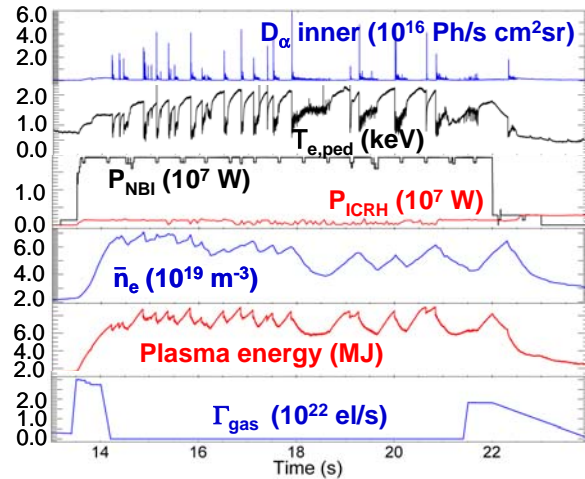


Fig.1 #70226: discharge overview: $I_p=3.0 \text{ MA}$, $B_T=3.0 \text{ T}$, $\delta_l \sim 0.28$, vertical target

Results and Discussion The gas fuelling has been varied in a series of repeated 3.0 MA discharges to produce Type I ELMs of different sizes ($\Delta W_{ELM}/W_{ped}$ increases with decreasing gas fuelling) in the ELM energy range $\Delta W_{ELM} = 0.2 \rightarrow 0.9 \text{ MJ}$. Fig. 1 shows typical time traces of the parameters of an ELMy H-mode discharge in JET with strike points located on the lower vertical tiles of the MkII-HD divertor for a discharge without gas fuelling, with large (giant) ELMs ($\Delta W_{ELM} \approx 0.9 \text{ MJ}$). Such ELMs

are often followed by a phase of Type III ELMs or even a brief return to L-mode confinement. The “global energy balance” for this discharge (energy balance integrated over the entire discharge) reads: total injected energy of $E_{in}=177\text{MJ}$, radiated energy $E_{rad}=82.4\text{MJ}$, $E_{rad}/E_{in}=0.47$ and deposited energies onto inner and outer divertor targets of 24.6MJ and 70.9MJ respectively. Despite

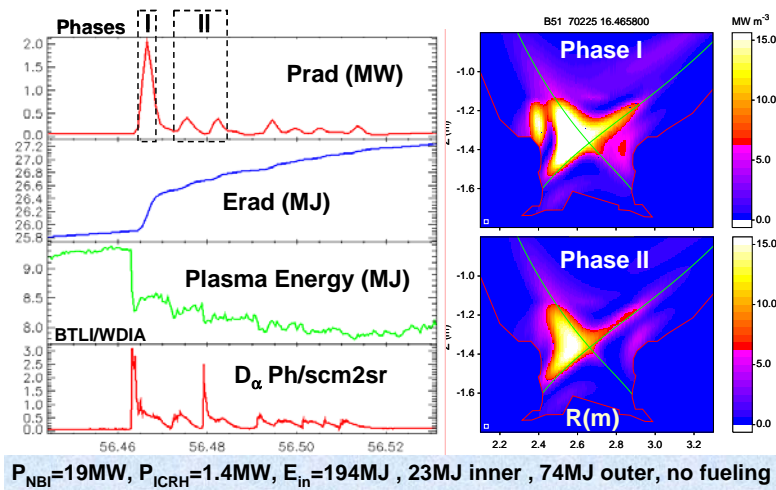


Fig.2 Typical large ELM radiation distribution

the large influence of the gas fuelling on the ELM behaviour, the global energy balance shows negligible variations with different gas levels and correspondingly with different ELM sizes.

Fig.2 shows the divertor radiation distributions integrated over two different phases during a large ELM with $\Delta W_{ELM} \sim 0.9\text{MJ}$. The first phase, of $\sim 4\text{ms}$ duration includes radiation during the ELM crash and the second ($\sim 14\text{ms}$) during the Type III ELM compound phase which follows. The left side of the figure shows the total power, stored energy, radiated energy, and inner divertor D_{α} -emission. The time intervals (phases I and II) in the shaded regions delimit the time over which the bolometry signals have been averaged.

In both phases the radiation distribution is strongly weighted to the inner divertor region (in-out asymmetries of \sim factor 3 in phase I). This is also the case during the inter-ELM period, but with a lower asymmetry factor of ~ 2 . This reflects the higher density, cooler plasma at the inboard divertor for forward toroidal field operation. The total radiated energy during the Type I ELM, evaluated by an algorithm similar to that described in [3], is 570kJ , corresponding to 72% of the ELM-energy losses ($\Delta W_{ELM} \approx 790\text{kJ}$).

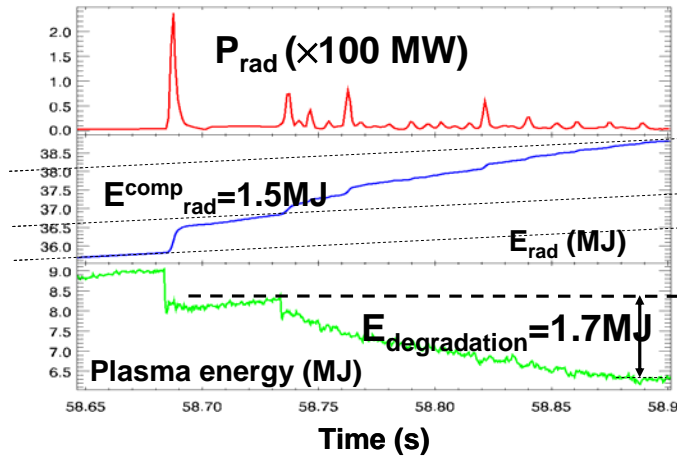


Fig.3 Calculation of the radiated energy during the „compound“ phase of the ELM.

It is important to note that that the radiated power is determined by the radiation from the particle release due to the ELM-target interaction together with the changes in the local plasma parameters provoked by the ELM.

Along with the critical question of the radiated energy during the Type I phase, the radiated energy during the compound phase is an important parameter. Fig. 3 illustrates the strong degradation of the plasma energy during the compound phase; analysis of the radiation occurring during this phase shows that it accounts for a significant fraction (up to 90%) of the plasma energy loss.

Fig. 4 presents the dependence on ΔW_{ELM} of the radiated plasma energy following the ELM crash. Here the radiated energy contains only the part of the radiated losses which occurs during the first main peak during the ELM. For an ELM energy below about 700kJ , the radiated plasma energy is proportional to the ELM energy, as expected from the observed linear correlation between impurity influxes and ELM sizes. In this range the ELMs radiates $\sim 50\%$ of the ELM energy drop.

Beyond a ΔW_{ELM} of ~ 700 kJ, a non-linear increase of the divertor radiation occurs which is interpreted as an indication of additional carbon evolution from the target tiles, possibly due to material ablation. The target surface temperature during the transient loads as measured with infra-red thermography reaches peak values of $\sim 2000^\circ\text{C}$ at the inner divertor and only $\sim 800^\circ\text{C}$ at the outer. Even the maximum value is too low for bulk carbon ablation which would correspond to a carbon sublimation of about 10^{19} C/m² s at this temperature, yielding a total release of 2×10^{19} C/ s for a 0.5m² loaded surface during the ELM. This quantity of carbon is much smaller than the known intrinsic carbon sources ($\sim 10^{21}$ C/ s from the main wall and $\sim 7 \times 10^{21}$ C/ s from the divertor [4]). The enhanced radiation losses over $\Delta W_{ELM} \sim 700$ kJ can almost certainly be explained by the ablation of the re-deposited carbon layer which is known to exist on the inner divertor target. The inner divertor is always a region of net deposition on JET and the outer of net erosion for standard forward field operation [5]. These layers with poor thermal contact and low thermal capacity respond much more strongly to the power flux than the bulk target tiles. The re-deposited layers in the inner divertor contain a large amount of Be ($\approx 50\%$). Interestingly, the fast signals in BeII- and CIII-emission react at the same time ($\sim 300\mu\text{s}$ after fall in plasma energy) during the transient events, confirming the assumption of ablation of deposited layers in the inner divertor. As mentioned above, the inter-ELM radiation distribution is always strongly weighted to the inner divertor volume (in-out asymmetries of \sim factor 2). The ELM exacerbates this radiation asymmetry, with the magnitude of the increase linearly dependent on the ELM energy in the range $\Delta W_{ELM} \sim 100 - 600$ kJ (see Fig.5). This is consistent with fast infrared thermography of the divertor targets which finds that Type I ELMs deposit twice as much energy at the inner target than at the outer across the

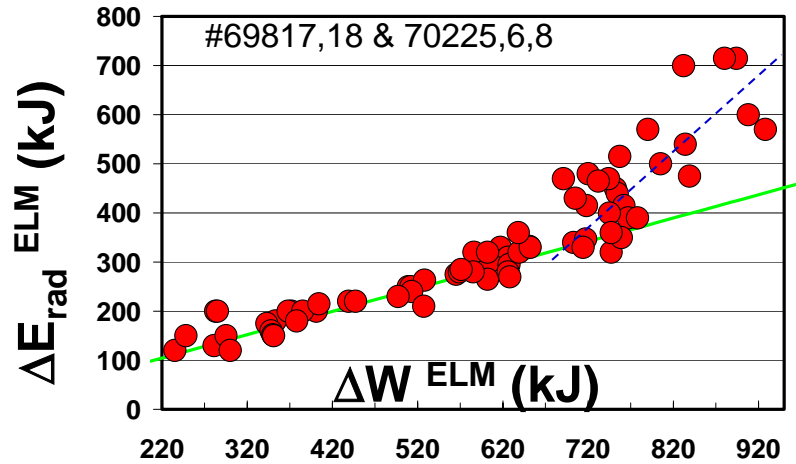


Fig.4 Radiated Plasma energy following Type I ELMs versus ELM energy loss

whole range of Type I ELM energies currently accessible ($\Delta W_{ELM} = 0.1 - 1.0$ MJ) [6]. For $\Delta W_{ELM} > 620$ kJ the in-out asymmetry shows a “break” in the linear dependence. One explanation for this observation is the assumption that ablated material can reach the outer divertor via the private flux region and thus contribute to the radiation in the outer divertor volume. Secondary peaks on fast CIII divertor spectroscopy with ~ 0.5 ms delay compared with the first peak at the outer divertor confirm this assumption. This time delay is approximately equal to the divertor transit time for thermal carbon atoms and C₂ molecules. Additionally, Fig. 5 (right) shows the radiation distribution for ELMs with medium and large sizes. For large ELMs the radiation “spills over” into the outboard X-point region.

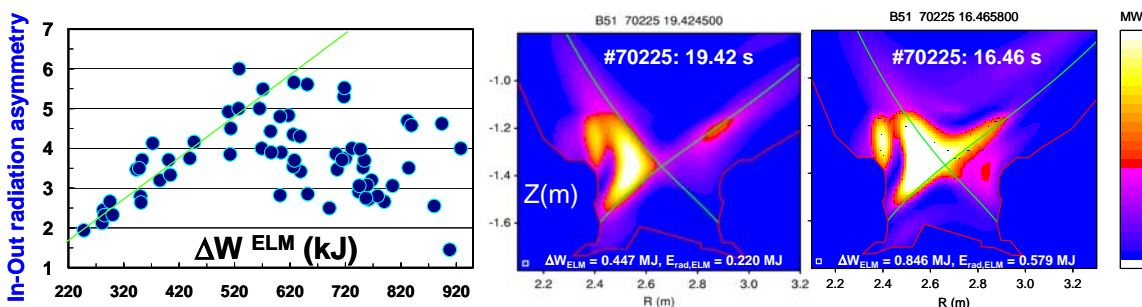


Fig.5. In-Out radiation asymmetry versus ELM energy loss and radiation reconstructions for medium and high ΔW_{ELM} .

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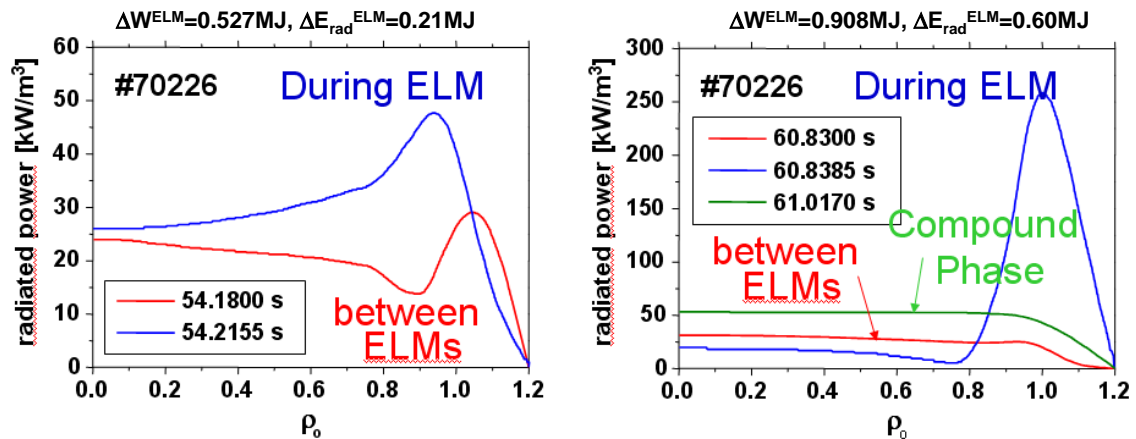


Fig. 6 Radiative profiles for ELMs with medium and large sizes

The impurity influxes associated with transient events can have a significant influence on the discharge since they can lead to an increased plasma contamination and even to a radiative collapse. Fig. 6 shows the radiation profiles for ELMs with medium (left figure) and large (on the right) sizes. This analysis shows a strong increase of the radiation in the edge (normalised minor radius $\rho > 0.8$) during the largest events in the database. The profile during the “compound” phase clearly shows increased radiation in the plasma core and correspondingly points to an increased plasma contamination. An increase of Z_{eff} by about $\Delta Z_{\text{eff}} \approx 0.4-0.5$ has been observed in the compound phase.

Summary and conclusion

- Large ELMs are often compound (Type I ELM followed by Type III ELMs).
- A significant fraction (up to 90% of radiated energy integrated over the compound phase) of the plasma energy degradation during the compound phase is exhausted by radiation.
- About $\sim 50\%$ of ΔW_{ELM} is radiated in the ELM energy range between 0.1MJ and 0.9MJ.
- Large type I ELMs with energy losses above 0.7MJ show enhanced radiation losses, almost certainly associated with ablation of a re-deposited carbon layer in the inner divertor.
- ELM-induced radiation is always higher at the inner than at the outer divertor: this asymmetry increases approximately linearly to $\Delta W_{\text{ELM}} \sim 0.6$ MJ, then decreases for higher ΔW_{ELM} .
- The higher inner divertor radiation is consistent with (but not only due to) a higher ELM energy deposition at the inboard side observed with IR thermography.
- Surface (layer) temperatures do not exceed $\sim 2000^\circ\text{C}$ at the inner target. The maximum outer target temperature amounts to $\sim 800^\circ\text{C}$ (no layers). In neither case is the surface temperature sufficient for bulk carbon ablation to occur.
- During the “compound” phase plasma contamination can increase but does not usually lead to radiative collapse of the plasma.

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