Characteristics and scaling of energy and particle losses during Type I ELMs in JET H-modes

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Abstract
Recent experiments on the Type I ELMMy H-mode regime performed at JET with improved diagnostics have expanded the range of parameters for the study of Type I ELM energy and particle losses. Deviations from the standard behaviour of such losses in some areas of the Type I ELMMy H-mode operating space have revealed that the ELM losses are correlated with the parameters (density and temperature) of the pedestal plasma before the ELM crash, while other global ELM characteristics (such as ELM frequency) are a consequence of the ELM-driven energy and particle flux and of the in-between ELM energy and particle confinement. The relative Type I ELM plasma energy loss (to the pedestal energy) is found to correlate well with the collisionality of the pedestal plasma, showing a weak dependence on the method used to achieve those pedestal plasma parameters: plasma shaping, heating, pellet injection and impurity seeding. Effects of edge plasma collisionality and transport along the magnetic field on the Type I ELM particle and energy fluxes onto the divertor target have also been observed. Two possible physical mechanisms that may give rise to the observed collisionality dependence of ELM energy losses are proposed and their consistency with the experimental measurements investigated: collisionality dependence of the edge bootstrap current with its associated influence on the ELM MHD origin and the limitation of the ELM energy loss by the impedance of the divertor target sheath to energy flow during the ELM event.

1. Introduction
The Type I ELMMy H-mode regime is the reference regime for inductive operation of some next step devices such as ITER (ITER Physics Basis 1999). Experiments in various divertor
Tokamaks have demonstrated that the ELMy H-mode is a robust regime with acceptable energy confinement at the high densities required in next step devices and fusion reactors, particularly at higher plasma triangularities (Saibene 1999, Kamada 1999, Osborne 2000, Stober 2000). Furthermore, high density Type I ELMy H-modes show experimental performances with respect to steady-state helium exhaust (Wade 1998, Bosch 1999, Sakasai 1999, Groth 2002) and divertor power deposition (Petrie 1997, Kallenbach 1999, Riccardo 2001) which could meet the necessary requirements when extrapolated to next step devices such as ITER (Kukushkin 2001).

A major drawback of the Type I ELMy H-mode is the periodic large power loads on plasma facing components associated with the Type I ELMs (Zohm 1996, Herrmann 1997, Clement 1999, Leonard 1997). Such power loads are generally of no concern in existing devices but they can lead to unacceptable divertor target lifetime when extrapolated to next step devices (ITER Physics Basis 1999, Leonard 1999, Janeschitz 2001, Loarte 2001a, Federici 2002). ELM-driven particle losses from the core plasma have, on the contrary, a positive influence on the performance of ELMy H-modes. The particle confinement time in H-modes is significantly increased with respect to L-mode and the ELMs provide the required particle outflux to achieve stationary plasma content (Zohm 1996). The influence of the ELM-driven particle fluxes on impurities is even more dramatic and, in the absence of ELMs, H-mode discharges suffer from impurity accumulation (Zohm 1996).

Understanding of the physics mechanisms behind the ELM particle and energy loss from the main plasma onto the plasma-facing components requires well diagnosed discharges, with reproducible ELM behaviour. The ELM measurements obtained during these dedicated experiments carried out at JET to characterize steady-state Type I ELMy H-modes are described in this paper. All of the discharges studied here are dominantly heated by neutral beam injection (NBI), with steady-state gas fuelling and with and without impurity seeding (Ongena 2001, Saibene 2001, 2002, Sartori 2001, 2002). An example of the core and pedestal plasma parameters for such discharge is shown in figure 1(a).

The ELMs considered in this study are from steady phases of JET discharges with constant additional heating and plasma fuelling, which typically last for 5 s. Correspondingly, the ELM parameters (ELM frequency, ELM energy drop, ELM particle drop, ...) remain fairly reproducible for the length of this steady-state phase. This is shown in figures 1(b) and (c) for the discharges in figures 3–8. Figure 1(b) shows the probability distribution function of the ELM frequency (calculated in intervals of 0.5 s) versus the average frequency calculated for the whole steady phase of the discharge, which is used in this study (typically 4–5 s). The standard deviation of the ELM frequency around its average value is 10%. Figure 1(c) shows the probability distribution function of the ELM energy loss for the same set of discharges and steady-state periods. The standard deviation of the ELM energy loss around its average value is 15%. Similar probability distribution functions are found for the ELM particle loss and ELM pedestal temperature drop. Hence, the typical error bar for the measurements in our study, to account for ELM variability, is typically 10–15% for Type I ELMs at JET.

The measurements (and time resolutions) used in these ELM studies are:

(a) The plasma energy as determined by the diamagnetic energy (~200 µs).
(b) The electron temperature of the plasma from the ECE heterodyne radiometer diagnostic (~1 ms).
(c) The line-averaged density along a vertical line at a radius of 3.75 m, which corresponds typically to 7–15 cm inside the separatrix at the outer midplane (~1 ms).
(d) Dα emission along viewing lines that cover the inner, outer divertor and across the plasma at the midplane (~200 µs).
Figure 2 shows the arrangement of the various diagnostics described above together with two typical MHD equilibria (high and low triangularity) for the discharges analysed in this paper.

For detailed ELM studies, a series of measurements (such as electron temperature, soft x-ray emission, $D_\alpha$ emission, $dB_\theta/dt$ from Mirnov coils, and line-integrated edge density) are available at very high time resolution ($\sim 100 \mu s$ for the edge line-integrated density and $\sim 4 \mu s$ for the others) with the common timing and data acquisition system CATS (Central Acquisition and Trigger System) (Edwards 1995). This allows studies of the absolute timing
and duration of the different processes that take place during the ELM events as discussed in sections 2.2 and 3 of this paper.

This paper is organized as follows: section 2 describes the measurements of ELM energy and particle losses from the bulk plasma with emphasis on their dependence on global and pedestal plasma parameters, including the detailed analysis of the evolution of the edge plasma profiles with high time resolution. Section 3 describes the observations of energy and particle fluxes onto the divertor target during ELMs focusing on the duration of these ELM-induced pulsed fluxes as well as on the transport of energy and particles along the field lines. Section 4 discusses the validity of the ELM physics models, which have been put forward to explain the ELM energy and particle losses, in view of these new experimental measurements. Finally, section 5 summarizes the conclusions of our study.

2. Type I ELM energy and particle losses from the bulk plasma in ELMy H-modes

2.1. Global behaviour of Type I ELM energy and particle losses

The behaviour of the ELM energy and particle losses from the bulk plasma found in the experiments considered in this paper for discharges at medium triangularity ($\delta \leq 0.3$) and medium input power ($P_{\text{input}}/P_{\text{L-H}} \leq 2$, where $P_{\text{L-H}}$ is the H-mode power threshold calculated with the ITER-96 scaling (ITER Physics Basis 1999)) is similar to that reported from previous
Figure 2. Geometrical layout of the viewing lines for some of the diagnostics used in the studies of ELMs (interferometer, visible spectroscopy and ECE radiometer) together with two typical MHD equilibria (high triangularity in red (——) and medium triangularity in blue (- - - -)).

JET experiments (Lingertat 1995, Mohanti 1997, Fishpool 1998, Horton 1999, Saibene 1999) and consistent with observations in other devices (Kamada 1994, Herrmann 1997, Leonard 1997, Suttrop 2000, Asakura 2002). For such discharges with NBI fuelling only, the ELM frequency ($f_{\text{ELM}}$) increases linearly with input power and decreases with the square of the plasma current (for discharges with $q_{95} \sim 3-4$) as previously reported ($f_{\text{ELM}} \sim P_{\text{in}}/I_p^2$) (Kamada 1994, Mohanti 1997). Similarly, with increasing gas fuelling, which is used to increase the bulk and pedestal density, $f_{\text{ELM}}$ increases as well. While such discharges remain in the Type I ELMy H-mode regime, there is an inverse correlation between $f_{\text{ELM}}$ and the loss of bulk plasma energy due to the ELM ($\Delta W_{\text{ELM}}$) so that the power loss due to ELMs ($f_{\text{ELM}} \times \Delta W_{\text{ELM}}$) remains a constant fraction of the input power ($f_{\text{ELM}} \times \Delta W_{\text{ELM}} \sim 0.3-0.4 \, P_{\text{in}}$) as previously reported from JET and DIII-D (Leonard 1999) and ASDEX Upgrade (Herrmann 1997, Suttrop 2000). The observed inverse correlation between $f_{\text{ELM}}$ and $\Delta W_{\text{ELM}}$ and the observed confinement deterioration with increasing gas puffing lead to the interpretation that the achievement of small ELM energy losses was unavoidably linked with high-ELM frequencies and degraded H-mode confinement (Fishpool 1998).

Starting from this basic picture, experiments have been carried out in JET in order to explore new areas in the parameter space of Type I ELMy H-modes so as to improve our understanding of this regime and of the ELM energy and particle losses: at higher triangularities ($\delta \sim 0.5$) (Saibene 2001, 2002), at medium triangularities ($\delta \sim 0.3$) and large input powers ($P_{\text{in}}/P_{\text{L-H}} \geq 3$) (Sartori 2001, 2002), and (in a range from low to high $\delta$) in discharges with impurity seeding (Ar) (Ongena 2001). In these conditions, clear deviations from the standard behaviour of the ELM energy and particle losses described above have been observed. Figure 3 shows the behaviour of $f_{\text{ELM}}$ with gas puffing for discharges with similar parameters ($I_p = 2.5 \, \text{MA}$, $B_t = 2.4-2.7 \, \text{T}$, $P_{\text{NBI}} = 14-17 \, \text{MW} \sim 1.5 \, P_{\text{L-H}}$) and different plasma triangularities ($\delta = 0.3$, 0.5). At $\delta \sim 0.3$ (the typical medium triangularity for the JET experiments) $f_{\text{ELM}}$ increases with increasing gas fuelling until the transition to Type III ELMs is
observed, following the standard ELM behaviour. However, at $\delta \sim 0.5$, a decrease of $f_{\text{ELM}}$ with gas fuelling is routinely observed at the highest fuelling rates (larger than $1.5 \times 10^{22}$ atoms s$^{-1}$) in a broad range of fuelling rates before the transition to Type III ELMs (Becoulet 2001a, Loarte 2001b), which occurs typically at a fuelling rate of $\sim 5–6 \times 10^{22}$ s$^{-1}$ for these conditions. This ‘anomalous’ ELM behaviour is also seen at medium triangularities ($\delta \sim 0.3$) and large input powers ($P_{\text{input}}/P_{\text{L–H}} \geq 3$) (Sartori 2001, 2002). Inevitably, the clearance of the JET plasma from the wall is lower for high $\delta$ discharges than for low $\delta$ discharges. The typical distance from the separatrix at the outer midplane to the outer limiter is 3 cm for discharges with $\delta \sim 0.5$. Previous experiments at JET with the Mk II divertor have shown that the H-mode behaviour is unaffected by wall clearance, provided that the separation between the separatrix and the limiter at the outer midplane is larger than 2 cm (Righi 2001). Hence, we conclude that the anomaly in the ELM behaviour for the $\delta \sim 0.5$ discharges is associated with the magnetic configuration itself and not with the distance between the bulk plasma and the wall in these discharges.

This new ELM behaviour breaks the link between $f_{\text{ELM}}$ and $\Delta W_{\text{ELM}}$, seen at lower $\delta$ and lower $P_{\text{input}}$, as $f_{\text{ELM}}$ decreases without a corresponding $\Delta W_{\text{ELM}}$ increase. Figure 4 shows the relative (to the total diamagnetic plasma energy) ELM energy drop ($\Delta W_{\text{ELM}}/W_{\text{dia}}$) versus $f_{\text{ELM}}$. For $\delta \sim 0.3$, the usual inverse correlation of $f_{\text{ELM}}$ and ($\Delta W_{\text{ELM}}/W_{\text{dia}}$) is found (Mohanti 1997, Horton 1999), while for $\delta \sim 0.5$, $f_{\text{ELM}}$ decreases by a factor of 2 (highest fuelling rates) while $\Delta W_{\text{ELM}}/W_{\text{dia}}$ remains approximately at a constant value of $\sim 3–4\%$. Similarly, discharges with impurity seeding (particularly those at $\delta \sim 0.3$ and low gas fuelling) can achieve very low $f_{\text{ELM}}$ with moderately small $\Delta W_{\text{ELM}}/W_{\text{dia}}$ ($\sim 5\%$). The anomalous $f_{\text{ELM}}$ behaviour for $\delta \sim 0.5$ discharges is correlated with an increased level of the magnetic (Becoulet 2002a, Saibene 2001, 2002) and density fluctuations (Saibene 2001,
Figure 4. Normalized ELM energy loss ($\Delta W_{\text{ELM}}/W_{\text{dia}}$) versus ELM frequency ($f_{\text{ELM}}$) for discharges with $I_p = 2.5$ MA, $B_T = 2.4$–2.7 T, $P_{\text{input}} = 14$–17 MW and medium ($\sim 0.3$) and high ($\sim 0.5$) triangularity. Note the unusual decrease of $f_{\text{ELM}}$ with constant $\Delta W_{\text{ELM}}/W_{\text{ped}}$ for discharges with $\delta \sim 0.5$ (corresponding to the large fuelling rates in figure 3). Two discharges (at medium and high $\delta$) with impurity seeding (Ar) are shown for comparison. Lines are to guide the eye.

2002) also visible in the divertor $D_\alpha$ emission (see figure 5) which lead to enhanced power losses between ELMs (Saibene 2001, 2002). For impurity seeding, the reduction of $f_{\text{ELM}}$ is driven by the increase of radiated power, which decreases the edge power flux (Ongena 2001). The reduction in ELM frequency by impurity radiation seems to be larger in unfuelled low $\delta$ discharges than in fuelled high $\delta$ discharges, despite the similar level of radiation achieved in both. Presently, it is not known if this difference is due to the different radiation pattern in both discharges (more bulk radiation in low $\delta$ discharges for the same total radiation) or to the effect of the fuelling, because the best results in low $\delta$ discharges were obtained at very low fuelling rates and in the high $\delta$ ones at high fuelling rates. Further research is needed to clarify this point. The observed decrease of $f_{\text{ELM}}$ without a corresponding increase of $\Delta W_{\text{ELM}}$ causes a decrease of the ELM power losses ($f_{\text{ELM}} \times \Delta W_{\text{ELM}}$) to values $\sim 0.1 P_{\text{input}}$, i.e. about a factor of 3–4 lower than for the usual ELM behaviour, as shown in figure 6.

In JET, the decrease of the plasma particle content caused by ELMs ($\Delta N_{\text{ELM}}$) is determined from the Abel inversion of the density profile. Due to the scarcity of edge chords available for the inversion, the calculated total particle content ($N_{\text{tot}}$) is dominated by the chords along the core plasma. This procedure is known to underestimate the absolute value of $\Delta N_{\text{ELM}}$ by about a factor of 2 when compared with that deduced from the density profiles measured directly by Thomson scattering, as shown for DIII-D experiments (Porter 2001). Despite this, relative changes of $\Delta N_{\text{ELM}}/N_{\text{tot}}$ deduced from Abel inversion are in reasonable agreement with those from the Thomson scattering density measurements (Porter 2001). The density profiles in JET and DIII-D have a similar shape for ELMy H-modes (Saibene 1999, Porter 2001). Hence, we will assume that the conclusions reached in the DIII-D experiments with respect to the relative changes of $\Delta N_{\text{ELM}}/N_{\text{tot}}$ by Abel inversion and Thomson scattering are general to Type I ELMy.
Figure 5. Divertor Dα emission for a gas fuelling rate scan at high δ ~ 0.5 (discharges with $I_p = 2.5$ MA, $B_T = 2.7$ T, $P_{\text{input}} = 16$ MW). For fuelling rates larger than $1.5 \times 10^{22}$ atoms s$^{-1}$ the ELM frequency ($f_{\text{ELM}}$) decreases with increasing plasma fuelling. Together with this $f_{\text{ELM}}$ decrease the level of the inter-ELM fluctuations in the Dα emission increases.

Figure 6. Normalized ELM power loss ($f_{\text{ELM}} \times \Delta W_{\text{ELM}} / P_{\text{input}}$) versus gas fuelling rate for discharges with $I_p = 2.5$ MA, $B_T = 2.4$–2.7 T, $P_{\text{input}} = 14$–17 MW and medium (~0.3) and high (~0.5) triangularity. Note the unusual decrease of the ELM power loss for discharges with δ ~ 0.5 at large fuelling rates. Two discharges (at medium and high δ) with impurity seeding (Ar) are shown for comparison. Lines are to guide the eye.
Type I ELMs in JET H-modes

H-modes and, thus, applicable to our study. As it will be discussed in section 2.2, there is evidence that points towards the ELM density collapse not being poloidally symmetric in its initial phases (Nunes 2001, Oyama 2001). In spite of this initial asymmetry, the final plasma density profile \( \sim 1 \text{ ms} \) after the ELM is poloidally symmetric, as indicated by inner–outer midplane reflectometry measurements in ASDEX Upgrade (Nunes 2001). We assume that these results are also general to Type I ELMy H-modes and, thus, utilize the Abel inverted profiles to analyse the JET particle losses caused by ELMs. In order to avoid possible poloidal asymmetries in the density profiles close to the ELM collapse that could affect the particle loss evaluation, we have taken time-slices well separated from the ELM collapse (typically 2 ms) to evaluate the particle content after the ELM.

In contrast to the ELM-driven plasma energy losses (in which for ‘normal’ ELM behaviour \( f_{\text{ELM}} \times \Delta W_{\text{ELM}} / P_{\text{input}} \sim \text{constant} \)), the bulk plasma particle drop caused by ELMs (\( \Delta N_{\text{ELM}} \)) does not correlate with \( f_{\text{ELM}} \) in a universal way, as shown in figure 7, for the same discharges considered above. As a consequence of this, the ELM-driven particle outflux depends mostly on the behaviour of \( f_{\text{ELM}} \) for low \( \delta \) discharges. For discharges in which \( f_{\text{ELM}} \) remains low even at large fuelling rates (such as those with Ar seeding and those at high \( \delta \) with decreasing \( f_{\text{ELM}} \)), the ELM particle outflux (\( f_{\text{ELM}} \times \Delta N_{\text{ELM}} \)) is low. These are also the discharges where the density in Type I ELMy H-modes reaches levels close or beyond the Greenwald limit (Ongena 2001, Saibene 2002, Sartori 2002). Figure 8 shows the measurements of \( f_{\text{ELM}} \times \Delta N_{\text{ELM}} \) versus fuelling rate for the same set of discharges as in figure 7 illustrating this point. Further research is needed to clarify the role of ELM particle losses and in-between ELM particle losses in the achievement of densities close to Greenwald limit in Type I ELMy H-modes.

![Figure 7](image_url)

**Figure 7.** Normalized ELM particle loss (\( \Delta N_{\text{ELM}} / N_{\text{tot}} \)) versus ELM frequency (\( f_{\text{ELM}} \)) for discharges with \( I_p = 2.5 \text{ MA}, B_T = 2.4-2.7 \text{ T}, P_{\text{input}} = 14-17 \text{ MW} \) and medium (\( \sim 0.3 \)) and high (\( \sim 0.5 \)) triangularity. Contrary to the behaviour of \( \Delta W_{\text{ELM}} / W_{\text{ped}} \) (figure 4) the ELM particle loss does not show ‘anomalies’ either at medium or high \( \delta \). Two discharges (at medium and high \( \delta \)) with impurity seeding (Ar) are shown for comparison. Lines are to guide the eye.
2. Detailed observations of Type I ELM energy and particle losses

Detailed measurements of the ELM energy and particle losses have been obtained for numerous Type I ELMy H-mode discharges in a wide range of conditions with very fast time resolution (\(\sim 4 \mu s\) for the electron temperature profile and \(100 \mu s\) for the edge line-averaged density). Type I ELMs in JET cause a fast change of the edge temperature profile in a time interval of \(\sim 200–300 \mu s\), which is the JET typical timescale for the duration of the ELM-associated MHD activity (Becoulet 2002a). This perturbation of the temperature then propagates inwards in a much longer timescale (Erba 1997).

Figure 9 shows a few time-slices of the temperature profile at various instants of the ELM cycle (during the duration of the large ELM-associated MHD, the ECE-measured temperature profiles are frequently very distorted due to the presence of supra-thermal electrons at the edge (Gill 1998)). This figure shows that the fast change in electron temperature caused by the ELMs in JET remains confined to the outer 20% of the plasma minor radius, i.e. 2–4 times the temperature pedestal width in between ELMs. Because of this, it is customary in ELM studies to compare the drop of plasma energy caused by the ELM to the pedestal plasma energy. The pedestal energy is defined as 

\[
W_{\text{ped}} = \frac{3}{2}n_{e,\text{ped}}(T_{e,\text{ped}} + T_{i,\text{ped}})V_p,
\]

where the values of plasma density and electron and ion temperature are taken at the top of the H-mode pedestal before the ELM and \(V_p\) is the total plasma volume. \(W_{\text{ped}}\) is usually calculated assuming \(T_{e,\text{ped}} = T_{i,\text{ped}}\), because of the reduced availability of edge \(T_i\) measurements. This is a reasonable assumption for most of the JET medium- or high-density discharges analysed in this paper (Saibene 1998, 1999). In JET, there are no measurements of \(n_{e,\text{ped}}\) with enough time resolution to discriminate the ELMs. Hence, the value used to estimate \(n_{e,\text{ped}}\) in our study comes from the edge interferometer channel shown in figure 2. The value for the pedestal density obtained
Figure 9. Typical electron temperature measurements in JET ELMy H-modes showing the collapse of the edge temperature in the outermost 10–20% of the plasma radius caused by the ELM (discharge with \(I_p = 2.5\,\text{MA}, B_T = 2.7\,\text{T}, P_{\text{inj}} = 16\,\text{MW}, \delta \sim 0.5\) and gas fuelling rate \(\sim 1.5 \times 10^{22}\,\text{atoms s}^{-1}\)). The magnetic axis is at \(R = 3.1\,\text{m}\) for this discharge.

in this way is always within 15% of the space resolved (but not time resolved) one (Saibene 2002). Comparing energy \(\Delta W_{\text{ELM}}\) with \(W_{\text{ped}}\) and not \(W_{\text{dia}}\) eliminates a source of scatter in the analysis due to changes in the relation between \(W_{\text{ped}}\) and \(W_{\text{dia}}\) that can originate from the additional heating power deposition profile (Rimini 2002) or density peaking, which is observed at JET in some experiments (Ongena 2001, Valovic 2001).

Analysis of the decrease of \(\Delta W_{\text{ELM}}/W_{\text{ped}}\) with increasing gas fuelling (or increasing pedestal density) shows that such decrease is mainly due to the reduction of the relative temperature drop caused by the ELM in the pedestal region \((\Delta T_e/\bar{T}_e)_{\text{ped}}\) and not of the density \((\Delta n_e/\bar{n}_e)_{\text{ped}}\), as shown in figures 10(a) and (b) for two high triangularity configurations. This is consistent with the observations of the differences between the behaviour of \(\Delta W_{\text{ELM}}\) and \(\Delta N_{\text{ELM}}\) with increasing gas fuelling described in section 2.1 and in agreement with observations in similar experiments in DIII-D (Leonard 2001). The region of the temperature profile that is affected by the ELM crash (ELM affected area) is mostly dependent on the plasma shape. The largest ELM affected areas are seen at the lowest triangularities (see figure 11). This is probably because of the different edge magnetic shear associated with the various magnetic configurations. The ELM affected area decreases only slightly with increasing gas fuelling for every plasma configuration, as shown in figure 11. This, together with the observations in figures 10(a) and (b), indicates that the reduction of \(\Delta W_{\text{ELM}}/W_{\text{ped}}\) with increasing fuelling (or density) is mostly due to a reduction of the magnitude of \(\Delta T_e/\bar{T}_e\) caused by the ELM, rather than to a reduction of the region of the plasma affected by the ELM. The decrease of \(\Delta W_{\text{ELM}}/W_{\text{ped}}\) with increasing pedestal densities is associated with a decrease of the intensity of the ELM-associated MHD activity (i.e. \(dB_\theta/dt\) from Mirnov coils) but no cause–effect relation between these observations has been established so far (Becoulet 2002b).

The natural consequence of the above arguments is that, at high enough \(n_{e,\text{ped}}\) and low enough \(T_{e,\text{ped}}\), it should be possible to obtain ELMs in which the entire ELM energy drop
Figure 10. Normalized ELM energy loss ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) and pedestal temperature ($\Delta T_{e,\text{ped}}/T_{e,\text{ped}}$) and density ($\Delta n_{e,\text{ped}}/n_{\text{Greenwald}}$) drop versus pedestal density normalized to the Greenwald limit ($n_{e,\text{ped}}/n_{\text{Greenwald}}$) for discharges with (a) high both upper and lower triangularities and (b) high upper and medium lower triangularities. At the highest $n_{e,\text{ped}}$, the ELM energy loss is due almost entirely to the ELM particle loss (discharges with $P_{\text{input}} = 16$ MW). Lines are to guide the eye.

$\Delta W_{\text{ELM}}$ is due to the loss of particles associated with the ELM ($\Delta N_{\text{ELM}}$), while the plasma temperature remains unaffected by ELMs. Indeed, such ELMs have been achieved in JET, as shown in figure 10(b), but only for a restricted set of plasma configurations (Saibene 2001, 2002). These ELMs have produced the smallest energy drop $\Delta W_{\text{ELM}}/W_{\text{ped}}$ observed in JET Type I ELMs ($\sim 5\%$) so far. This value is close to the value required in ITER ($\sim 4\%$) for the ELMs not to impose a severe limitation to the lifetime of the divertor target due to
enhanced ELM-caused erosion (Janeschitz 2001, Loarte 2001a, Federici 2002). An example of the two high triangularity ($\delta = 0.41$ and $\delta = 0.47$) configurations for the discharges in figures 10(a) and (b) is shown in figure 12(a); the difference between these configurations being the X-point radial position and lower triangularity ($\delta_L$) of the plasma. Figure 12(b) and (c) show the typical Type I ELM temperature drop for two similar discharges in both plasma configurations ($I_p = 2.5 \text{ MA}, B_T = 2.7 \text{ T}$) with $\langle n_e \rangle \approx n_{\text{Greenwald}}$ ($\langle n_e \rangle$ is the line-averaged electron density) and $P_{\text{input}} \approx 15 \text{ MW}$. Type I ELMs in the discharge with smaller $\delta_L$ ($\delta_L \sim 0.30$) do not cause a change of the temperature profile, in contrast to those for the discharge with higher $\delta_L$ ($\delta_L \sim 0.45$). Thus, these Type I ELMs at $\delta_L \sim 0.30$ cause no additional energy loss from the bulk plasma beyond that associated with the ELM particle expulsion.

Such $\Delta T_{\text{ped}}/T_{\text{ped}} \sim 0$ ELMs have been named ‘minimum’ Type I ELMs (Loarte 2001c) because a decrease of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ below the value observed in these experiments would require a significant decrease of $\Delta N_{\text{ELM}}/N_{\text{tot}}$ while remaining in the Type I ELM H-mode. This has not been observed so far either in the JET experiments (as already shown in figures 7, 10(a) and (b)) or in other tokamak experiments (Leonard 2002).

From the available experiments, it is not clear whether the plasma configuration and the lower triangularity $\delta_L$, as such, is essential for the achievement of these ‘minimum’ Type I ELMs. $\Delta T_{\text{ped}}/T_{\text{ped}}$ decreases with increasing $n_{\text{e,ped}}$ and decreasing $T_{\text{e,ped}}$ for all plasma configurations. For most plasma configurations, a transition from Type I to Type III ELMs takes places before the ‘minimum’ Type I ELMs can be reached, i.e. $\Delta T_{\text{ped}}/T_{\text{ped}} \neq 0$ for the highest $n_{\text{e,ped}}$ and lowest $T_{\text{e,ped}}$ that are achieved in the Type I ELMy H-mode. It is possible that the plasma edge stability for the low $\delta_L$ configuration is such that the parameter space between the Type I (determined by the edge stability) and Type III boundaries allows the ‘minimum’ Type I ELMs to occur, but further research is needed to draw definitive conclusions on this point. The analysis of this issue is further complicated by the fact that at very high densities,
the edge temperature cannot be determined from ECE emission due cut-off effects, so that the amount of available data in these conditions is very scarce.

The ELM particle and temperature drop contribution to the total ELM energy drop ($\Delta W_{ELM}$) behave not only in a different way with increasing density but also seem to have different time behaviour from the available diagnostics at JET. Figure 13(a) shows $T_{e,ped}$ for a typical type I ELM in JET, together with measurements of the $D_\alpha$ emission along various viewing lines and $dB_\theta/dt$ measured with Mirnov coils. The pedestal temperature collapses in a typical time interval of $\sim 200$–300 $\mu$s, while the line-averaged pedestal density (figure 13(b))

![Figure 12. (Continued)](image-url)
shows a perturbation coincident in time with the one seen in $T_{e, \text{ped}}$ but then decays with a much longer timescale (2–3 ms), in agreement with previous JET results with lower time resolution (Lingertat 1995, 1997). The measurements of the pedestal density in JET are obtained with an interferometer diagnostic and are, thus, integrated along a chord (see figure 2). Therefore, it is not possible to deduce whether locally the pedestal density collapses in a longer time interval than that of the pedestal temperature or if the longer timescale for pedestal density decay is due to the effect of line averaging by the interferometer, which includes the SOL plasma. From these measurements, we cannot rule out that the local pedestal density in JET collapses in similar time interval as the temperature, as results from JT-60U (Oyama 2001) and ASDEX Upgrade (Nunes 2001) seem to indicate.

2.3. Type I ELM energy losses and their relation to pedestal parameters

Analysis of the ELM energy losses in Type I ELMy H-modes from several divertor tokamaks (ASDEX Upgrade, DIII-D, JET, JT-60U) have indicated a correlation between the relative ELM size ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) and pedestal plasma collisionality (Loarte 2001a). Such correlation has been corroborated in the experiments described in this paper over a large range of the Type I ELMy H-mode operation space, with the possible exception of the ‘minimum’ Type I ELMs. Figure 14 shows the relative ELM energy drop ($\Delta W_{\text{ELM}}/W_{\text{ped}}$) versus the electron–electron collisionality ($\nu_{\text{ped}} = \pi R q_{95}/\lambda_{ee}$) of the pedestal plasma before the ELM for a large variety of
Figure 13. Measurements with high time resolution (a) (∼4 µs) of the pedestal temperature collapse ($T_{e,\text{ped}}$) and (b) (∼100 µs) of pedestal density collapse ($n_{e,\text{ped}}$) during a Type I ELM in JET. The collapse of $T_{e,\text{ped}}$ occurs over a time interval of 200–300 µs similar to the period of large MHD activity (measured with Mirnov coils). $n_{e,\text{ped}}$ shows usually a spike at a time coincident with the $T_{e,\text{ped}}$ collapse (within 100 µs) but, after this, $n_{e,\text{ped}}$ continues decreasing over a much longer period than $T_{e,\text{ped}}$ (∼ few ms).

JET Type I ELMy H-modes including: plasma triangularity variations (Saibene 2001, 2002), various ratios of $P_{\text{input}}$ to $P_{L-H}$ (Sartori 2001, 2002), impurity seeding (Ongena 2001) and Type I ELMs triggered by the injection of pellets. The experimental data included in this figure are from discharges for which the ELM behaves according to the standard picture
Type I ELMs in JET H-modes

Figure 14. Normalized ELM energy loss (\(\Delta W_{\text{ELM}} / W_{\text{ped}}\)) versus pedestal plasma collisionality for a large range of Type I ELMy H-mode plasmas in JET including various plasma triangularities, ratios of \(P_{\text{input}} / P_{\text{L-H}}\), impurity seeding (Ar) and pellet triggered ELMs.

(for instance, \(f_{\text{ELM}}\) increasing with gas fuelling and \(f_{\text{ELM}} \times \Delta W_{\text{ELM}} \sim 0.4 P_{\text{input}}\) but also those with ‘anomalous’ ELM behaviour as described in section 2.1. This fact demonstrates that the size of the ELM energy drop is controlled by the pedestal plasma parameters, while the frequency is a consequence of the various timescales involved in the recovery of the pedestal plasma to its pre-ELM state (pedestal temperature and density recovery) following the ELM collapse. For the cases in which the pedestal recovery is modified by enhanced losses in the inter-ELM period, either by an increased level of fluctuations (Saibene 2001, 2002, Sartori 2001, 2002) or by an increased bulk radiation (Ongena 2001), the recovery of the pedestal is slowed down and consequently the ELM frequency decreases. Under these circumstances, the ‘standard’ link between \(f_{\text{ELM}}\) and \(\Delta W_{\text{ELM}}\) can be broken. The ELM size is determined chiefly by the pedestal plasma parameters before the ELM and, hence, unaffected by the inter-ELM processes that are the cause of the low \(f_{\text{ELM}}\).

When pellets are used to fuel the plasma, the plasma density increases transiently at the pedestal as the pellet is ablated and this transient pedestal overpressure usually triggers an ELM, as shown in figures 15(a) and (b) for two consecutive ELMs (one ‘naturally triggered’ and one ‘pellet triggered’). Despite the very different trigger mechanisms of these two ELMs, the ELM energy losses observed for both (included in figure 13) are as expected from the respective pre-ELM pedestal plasma density and temperature (and corresponding pedestal collisionality). This provides further evidence for the above statement on the ELM energy loss being determined by the pedestal plasma parameters. Although pellets are efficient in reducing the ELM size, they also cause a phase of enhanced energy loss in the post-pellet phase (Lang 2001). Experiments are planned in JET in the autumn of 2002 to investigate the trade-off between ELM amelioration with pellet injection velocity and size, pellet refuelling and energy confinement deterioration.

In Type I ELMy H-modes the density and temperature at the pedestal before the ELM are linked through the stability boundary, which limits the maximum pedestal pressure in
Figure 15. Collapse of the pedestal parameters and ELM energy loss during a Type I ELMy H-mode discharge (a) before pellet injection and (b) at the time of the pellet injection. Despite the very different mechanisms behind the triggering of this ELM and that of (a), the normalized ELM energy loss for both ELMs is as expected from the collisionality of the pedestal plasma before the ELM, as shown in figure 14.

this regime (Suttrop 1997, Osborne 1998, Lingertat 1999). Therefore, any correlation between ELM losses and pedestal temperature and density (such as collisionality) can be expressed in terms of only one of them ($n_{e,\text{ped}}$ or $T_{e,\text{ped}}$). A natural choice is to consider the dependence of $\Delta W_{\text{ELM}}$ with respect to the pedestal density normalized to the Greenwald limit ($n_{e,\text{ped}}/n_{\text{Greenwald}}$) (Leonard 2002), as shown in figure 16 for the same discharges in
Type I ELMs in JET H-modes

0.25
0.20
0.15
0.10
0.05
0
0.25
0.20
0.15
0.10
0.05
0

\[ \Delta W_{\text{ELM}} / W_{\text{Ped}} \]
\[ n_{\text{e, ped}} / n_{\text{Greenwald}} \]

\[ 2.5\text{MA}/2.7T \delta = 0.33 \]
\[ 2.5\text{MA}/2.7T \delta = 0.33 \text{ Before Pellet} \]
\[ 2.5\text{MA}/2.7T \delta = 0.33 \text{ After Pellet} \]
\[ 2.5\text{MA}/2.7T \delta = 0.50 \]
\[ 1.9\text{MA}/2.0T \delta = 0.33 \]
\[ 2.5\text{MA}/2.7T \delta = 0.45 \text{ - Low } \delta_i \]
\[ 2.5\text{MA}/2.7T \delta = 0.30 \text{ Ar Puffing} \]
\[ 2.5\text{MA}/2.7T \delta = 0.40 \text{ Ar Puffing} \]

\textbf{Figure 16.} Normalized ELM energy loss ($\Delta W_{\text{ELM}}/W_{\text{Ped}}$) versus pedestal density normalized to the Greenwald limit ($n_{\text{e, ped}}/n_{\text{Greenwald}}$) for the same JET discharges as in figure 14. Although for every set of global plasma parameters $\Delta W_{\text{ELM}}/W_{\text{Ped}}$ decreases with $n_{\text{e, ped}}/n_{\text{Greenwald}}$, this parameter does not describe the trends of $\Delta W_{\text{ELM}}/W_{\text{Ped}}$ across different plasma Type I ELMy H-mode scenarios, in contrast to the pedestal collisionality.

Although the ELM losses are well correlated with $n_{\text{e, ped}}/n_{\text{Greenwald}}$ for every set of global discharge parameters ($I_p$, $B_T$, $\delta$), the scatter of $\Delta W_{\text{ELM}}/W_{\text{Ped}}$ for similar values of $n_{\text{e, ped}}/n_{\text{Greenwald}}$ is larger than that in figure 13, in which the pedestal collisionality is used.

The comparison of $\Delta W_{\text{ELM}}/W_{\text{Ped}}$ ($P_{\text{inut}} = 15\text{ MW}, I_p = 2.5\text{ MA}, B_T = 2.7\text{ T}$) for medium ($\delta \sim 0.3$) and high ($\delta \sim 0.5$) triangularity demonstrates that at least for JET, the proximity of the pedestal density to the Greenwald limit is not the parameter that controls $\Delta W_{\text{ELM}}/W_{\text{Ped}}$. In order to achieve $n_{\text{e, ped}}/n_{\text{Greenwald}} \sim 0.6$ in the $\delta \sim 0.3$ discharges it is necessary to use very strong gas fuelling, while no gas fuelling is necessary for discharges with $\delta \sim 0.5$ (Saibene 2001, 2002). Correspondingly, the value of $\Delta W_{\text{ELM}}/W_{\text{Ped}}$ is about a factor of 2 lower for discharges with $n_{\text{e, ped}}/n_{\text{Greenwald}} \sim 0.6$ and $\delta \sim 0.3$ than for discharges with the same $n_{\text{e, ped}}/n_{\text{Greenwald}} \sim 0.6$ and $\delta \sim 0.5$ shown in figure 16. However, discharges at $\delta \sim 0.5$ and $n_{\text{e, ped}}/n_{\text{Greenwald}} \sim 0.6$ have a higher pedestal temperature than those at $\delta \sim 0.3$, due to the increased pedestal pressure at higher triangularities (Saibene 1999, 2001, 2002), and the pedestal plasma is less collisional in these conditions for $\delta \sim 0.5$. Following the correlation shown in figure 14, the ELM energy losses for these $\delta \sim 0.5$ discharges is larger than those for $\delta \sim 0.3$ at the same $n_{\text{e, ped}}/n_{\text{Greenwald}} \sim 0.6$.

Summarizing the arguments above, the data from JET experiments are consistent with the plasma collisionality (or a combination of dimensionless plasma parameters combined to produce a $\sim (q_0 T_{\text{e, ped}}) / T_{\text{e, ped}}^2$ dependence) being the parameter with which the ELM energy loss are best correlated and not the pedestal density and temperature separately. The implications of these findings on the processes that lead to the ELM energy drop and the extrapolation of the existing data to next step devices is discussed in section 4.
3. Divertor ELM power and particle fluxes in JET Type I ELMy H-modes and their dependence on pedestal plasma parameters

The study of ELM power and ELM particle fluxes onto first wall components is the topic of separate studies (Eich 2001, 2002, Jachmich 2001, Laux 2001) and will not be discussed in detail here. In this paper, we will only consider the dependence of the temporal evolution of these fluxes on the values of the pedestal parameters before the ELM crash. The details of this temporal evolution give valuable information on the physical processes by which the ELM energy and particle losses from the bulk plasma are transferred to the first wall components and on the spatial localization of such losses in the bulk plasma.

For low collisionality conditions, such as shown in figure 17, the collapse of the pedestal temperature is approximately coincident (within $\sim 50$ $\mu$s) with the arrival of the particle pulse at both the inner and outer divertors, as measured by the D$_\alpha$ emission. During the collapse of the temperature at the pedestal, a strong increase of the soft x-ray emission is detected for viewing lines that observe the divertor targets. This increase in the soft x-ray emission is typical of ELMy H-mode discharges with high pedestal temperatures in JET and has been attributed to Bremsstrahlung emissions of multi-keV energy electrons slowing down in the divertor target (Gill 1998). With increasing pedestal collisionality, the characteristic time over which the temperature collapses remains approximately unchanged, in agreement with measurements of the duration of the ELM MHD activity (Becoulet 2002b), and it lasts the same as the phase with strong soft x-ray divertor emission (the intensity is much smaller in these cases because of the lower $T_{e,\text{ped}}$ (Gill 1998)), as shown in figure 18. However, in these conditions of higher

![Figure 17. Measurements of the ELM pedestal temperature collapse ($T_{e,\text{ped}}$), inner divertor soft x-ray emission and D$_\alpha$ emission at various locations (midplane, inner and outer divertor). For this low density discharge, the increase of the D$_\alpha$ emission at all spatial locations occurs simultaneously with the pedestal temperature collapse, the increase of the soft x-ray emission and the phase of enhanced MHD activity as measured by Mirnov coils.](image-url)
pedestal collisionality, the increase of the divertor D_{α} emission associated with the ELM is not simultaneous at both divertors. While for the outer divertor the D_{α} emission starts increasing almost simultaneously with the temperature collapse, the inner divertor emission increases with a delay of \( \sim 200 \mu s \) after the pedestal electron temperature collapse. This indicates that the dynamics of the flow of (at least) particles to the divertor during the ELM has two phases: one in which hot electrons with typical pedestal plasma energies arrive at the divertor target (phase of strong soft x-ray emission, which coincides with the phase of enhanced MHD activity associated with the ELM) and a second phase during which a large flux of plasma ions is deposited onto the divertor target (Janeschitz 2001, Loarte 2001a). This second phase has a characteristic timescale determined by the flow of ions from the pedestal to the divertor target and may be delayed with respect to the first one. If the pedestal plasma is sufficiently cold (and collisional) before the ELM crash, the phase of increased divertor particle flux can even start when the first phase (high-energy electron flux) is over. Figure 18 shows such an example, in which the inner divertor D_{α} emission starts to increase when the phase of large MHD activity and soft x-ray emission from the inner divertor (high-energy electron flux phase) is practically finished.

The delay between the arrival of the ELM particle flux to the inner and outer divertors with increasing pedestal collisionality (increasing pedestal density and decreasing pedestal temperature) is not only reflected on the D_{α} emission (which could change with the temperature of the plasma at constant ion flux) but it is also measured with Langmuir probes located near the separatrix strike point at both divertors, as shown in figures 19(a) and (b). The typical time delays between the ion flux peak at the two divertors is \( \sim 200–300 \mu s \) in JET. This is
Figure 19. Measurements with high time resolution (∼4 µs) of the ELM particle fluxes to first wall components at various locations (inner and outer divertor) as measured by the D$_{α}$ emission and Langmuir probe measurements near both separatrix strike points. (a) This ELM occurs at low pedestal densities ($n_{e,\text{ped}} = 5.2 \times 10^{19} \text{ m}^{-3}, T_{e,\text{ped}} = 1650 \text{ eV}$) and the increase of particle fluxes at both divertors is approximately simultaneous. (b) This ELM occurs at medium pedestal density ($n_{e,\text{ped}} = 6.4 \times 10^{19} \text{ m}^{-3}, T_{e,\text{ped}} = 850 \text{ eV}$) and the increase of the particle flux at the inner divertor is delayed with respect to that at the midplane and outer divertor by ∼200–300 µs.
consistent with ELM particles being lost at the outer midplane region and travelling towards
the divertors at velocities \( \sim c_{s,\text{ped}} \) (sound speed calculated with pedestal plasma parameters,
\( c_{s,\text{ped}} = \sqrt{(T_{e,\text{ped}} + T_{i,\text{ped}})/m_i} \), because the connection length along the field line from
the midplane to the inner divertor is 3 times longer than that to the outer divertor. The delays
between the D\(_e\) emission at the midplane and the outer divertor remain small \((\lesssim 50 \mu s)\) in all
experiments analysed so far. Most likely, this is due to the fact that the midplane D\(_e\) emission
originates from the ionization of neutrals recycled at the main chamber walls during the ELM
and, hence, it is not trivially linked to the ELM collapse. The absence of significant delays
between the D\(_e\) emission at the outer divertor and midplane indicates that the timescale for the
ions being lost from the plasma to travel across the SOL to the main chamber wall, to recycle
there and to come back to the edge plasma (where they are ionized and emit D\(_e\) radiation) is
similar to that for the flow of ions along the field from the outer midplane to the outer divertor

target.

The appearance of delays between the inner and outer divertor ELM particle fluxes with
increasing pedestal collisionality, first reported in JET experiments (Loarte 2001b), has been
corroborated in other tokamaks such as JT-60U (Chankin 2002) and ASDEX Upgrade (Horton
2001). This experimental evidence suggests that the region over which the ELM particle and
energy loss occurs in the bulk plasma is the outer side of the torus, where the curvature is
most unfavourable for ballooning modes. Further evidence that this is indeed the case comes
from double-null experiments in which the ELM energy and particle flux is only measured at
the outer divertors, which for this configuration are magnetically disconnected from the inner
ones (Counsell 2002).

The above experimental measurements of the electron and ion flows to the divertor during
an ELM can be understood with the following physical picture for the phenomena that lead
to the observed particle and energy fluxes at the divertor target during and ELM (Janeschitz
2001, Loarte 2001a):

(a) A plasma with typical pre-ELM pedestal parameters is connected along the field lines with
the divertor target due to ergodization of the field lines or magnetic reconnection during
the ELM.

(b) In a first phase, that lasts few \( \mu s \), a new sheath is established at the divertor target in
equilibrium with the large increase of the upstream electron plasma temperature (now
\( T_{e,\text{ped}} \)). During this phase, the ion flux to the divertor remains unchanged because the
characteristic time for ions (with typical energies \( \sim T_{i,\text{ped}} \)) to flow along the field from the
pedestal to the divertor target is more than 100 \( \mu s \).

(c) After the electron temperature at the divertor target has increased to values \( \sim T_{e,\text{ped}} \), a
second phase starts. In this second phase, the ion flux to the divertor increases as the ions
from the pedestal start arriving at the divertor target (typical timescales \( \sim 100 \mu s \)).

A natural consequence of this physics model is that the temporal behaviour of the energy
flow during the ELM is not controlled by the duration of the MHD activity and the loss of hot
electrons to the divertor target (Lingertat 1997, Gill 1998, Clement 1999) but by the dynamics
of the ion flow during the ELM. A sheath is always formed when a plasma enters in contact
with a material surface, after a very short phase (\( \sim \mu s \)) during which mostly electrons are lost.
The characteristic time for a plasma to lose its energy through a sheath is similar to the time for
ion flow along the field line (typically \( \sim 40\% \) of the ion flow time (Stangeby 2000)). Therefore,
the duration of the ELM power flux onto the divertor should be similar to the typical timescale
for ion flow from the bulk plasma to the divertor for ions with \( T_i \sim T_{i,\text{ped}} \). The above physics
model for the flow of energy onto the divertor during an ELM, initially developed using a
fluid model for the plasma (Janeschitz 2001, Loarte 2001a), has been recently confirmed by
kinetic modelling and found valid for cases in which the secondary electron emission from the divertor during the ELM is moderate (Bergmann 2002).

Analysis of the ELM power deposition pulse determined from infrared camera measurements shows that indeed the duration of this pulse is well correlated with the typical timescale for ions to flow from the bulk plasma to the divertor along the field line, $\tau_{||}$, defined as $\tau_{||} = 2\pi R_0 q_0 / c_s \left( 1 + \sqrt{3/2} \nu^*_{\text{ped}} \right)$, and not with the duration of the ELM-enhanced MHD activity phase (which remains constant in these scans), as shown in figure 20 both for JET and ASDEX Upgrade experiments. Increasing $\tau_{||}$ in this figure corresponds to increasing pedestal plasma collisionality as well.

4. Discussion

The results obtained in the JET experiments have demonstrated that the bulk plasma energy losses caused by the ELMs are determined by the values of the pedestal plasma parameters before the ELM, in particular of the pedestal plasma collisionality. Such idea was put forward in (Janeschitz 2001, Loarte 2001a) as a basis to explain the observations of ELM energy losses in several experiments. The observation of the ‘anomalous’ ELM behaviour in which $f_{\text{ELM}}$ decreases without a corresponding increase in $\Delta W_{\text{ELM}}$ has provided the first experimental proof of the above hypothesis.

At present, two possible explanations have been put forward to explain the observed dependence of $\Delta W_{\text{ELM}} / W_{\text{ped}}$ on pedestal collisionality ($\nu^*_{\text{ped}}$); one involving the MHD nature of the modes that trigger the ELM (Igitkhanov 2001, Wilson 2001) and the other, the limitation imposed on the ELM energy losses by the existence of a sheath at the divertor target during
Type I ELMs in JET H-modes

(a) Increasing $v^*_{\text{ped}}$ leads to a decrease of the bootstrap current at the edge. In the peeling-ballooning model of the ELM, the decrease of the edge bootstrap current changes the mode numbers of the most unstable modes in linear stability analysis which, in turn, determine the mode spatial structure (Wilson 2001). With increasing collisionality the mode structure has a narrower radial extent, which is interpreted as leading to a smaller region of the plasma becoming unstable during the nonlinear growth of the mode that causes the ELMs and, hence, to a decrease of the $\Delta W_{\text{ELM}}$. No quantitative comparison of these hypotheses has been performed so far for the JET experiments. First analysis of the available experimental data seems to indicate that the reduction of ELM size is not driven by a reduction of the volume of the plasma which is affected by the ELM (as it is proposed in this model) but by a decrease of the ELM-caused temperature drop, while the ELM-affected volume remains constant, as shown in figures 10(a), (b) and 11. On the other hand, increasing pedestal collisionality tends to decrease the amplitude of the ELM-associated MHD activity (Becoulet 2002b). This can be interpreted as a decrease of the amplitude of the nonlinear mode or as a change of its radial structure, becoming narrower at higher collisionalities as proposed in this model, because the measurements are obtained with Mirnov coils relatively far from the plasma boundary (Becoulet 2002b).

(b) The second interpretation takes into account the limitation imposed by the existence of a sheath at the divertor target during the ELM to the energy flux from the bulk plasma to the divertor target itself, as explained in section 3. In this physics model, during the ELM the magnetic field structure is modified by the associated MHD activity and the pedestal plasma connects with the divertor target (see figure 21(a)) during the time of the ELM MHD duration $\tau_{\text{MHD}}$. A new sheath is created at the target in equilibrium with the new upstream pedestal plasma parameters. As a consequence, the typical timescale for the loss of energy from the pedestal plasma during the ELM is $\sim \tau_{||}$. From the available experimental data, increasing pedestal collisionality does not change the ELM MHD duration $\tau_{\text{MHD}}$ (Becoulet 2002b) (see figures 17 and 18) but increases the time for ion flow (both because of the increase of $v^*_{\text{ped}}$ and because of the decrease of $T_{\text{ped}}$). Therefore, with increasing pedestal collisionality, the amount of energy that the pedestal plasma can loose during $\tau_{\text{MHD}}$ decreases with increasing $\tau_{||}/\tau_{\text{ELM}}$ as

$$\frac{\Delta W_{\text{ELM}}}{W_{\text{ped}}} = \left| \frac{\Delta W_{\text{ELM}}}{W_{\text{ped}}} \right|_0 \left(1 - \exp \left( \frac{\tau_{\text{ELM}}}{\tau_{||}} \right) \right),$$

where $\Delta W_{\text{ELM}}/W_{\text{ped}}$ is the normalized (to the pedestal) ELM energy loss and $\left| \Delta W_{\text{ELM}}/W_{\text{ped}} \right|_0$ is the maximum energy in the pedestal region available to be lost during the ELM. This is basically determined by the ratio of the total plasma volume to the volume of the plasma affected by the ELM. For typical Type I ELMs in JET, the ELM-affected volume is in the range 20–40% of the total plasma volume, consistent with the data in figure 11. Figure 21(b) shows the result of applying such a model to the JET experiments under the assumption that $\left| \Delta W_{\text{ELM}}/W_{\text{ped}} \right|_0$ and $\tau_{\text{MHD}}$ are similar for all the discharges considered. The model reproduces reasonably well the behaviour of $\Delta W_{\text{ELM}}/W_{\text{ped}}$ with increasing $\tau_{||}$, in particular when we consider the simplicity of the assumptions that it contains.

From the analysis of the JET data, it is not possible to determine conclusively which of the two physics models for the ELM energy loss discussed above contains the correct physical processes that determine this loss nor if both set of processes (ELM MHD pedestal activity and parallel energy transport) are equally important in determining the ELM energy loss, as suggested in Igitkhanov 2001. We have demonstrated experimentally that, indeed,
the pedestal collisionality is a parameter that plays a major role in determining the size of the ELM energy loss. In addition, experiments show that the timing and duration of the ELM power and particle flux to the divertor is linked to the ion parallel transport and not to the duration of the ELM MHD event, as previously thought. We have also shown that the experimental measurements are consistent with parallel energy transport during the ELM ($\tau_{||}$) being a determining factor for the observed ELM energy loss. However, we cannot prove that there is a cause and effect relation between parallel transport and ELM energy loss. This is
because the parameters that control the increase of $\sim \tau_{\parallel}$ ($n_{\text{ped}}$ and $T_{\text{ped}}$) are the same that control pedestal collisionality, which, in turn, affects the MHD nature of the ELM instability through the bootstrap current. Therefore, the interpretation of the $\Delta W_{\text{ELM}}/W_{\text{ped}} \sim \nu_{\text{ped}}^*$ dependence in terms of parallel transport effects (figure 21(b)) could be a result of $\nu_{\text{ped}}^*$ controlling both the ELM MHD processes (which produce the energy drop $\Delta W_{\text{ELM}}$) and the transport of $\Delta W_{\text{ELM}}$ from the bulk plasma to the divertor target and not a cause–effect relation.

Analysis of Type I ELMy H-mode experiments with different hydrogenic species (H, D, T) (Saibene 1999) and helium plasmas (Philipps 2001) can be used to determine which of the two ELM physics models describes best the experimental observations. Varying hydrogen species changes $\tau_{\parallel}$ without affecting pedestal collisionality. In helium plasmas, the ratio between electron–electron collisionality (which affects the bootstrap current) and ion–ion collisionality (which affects ion parallel transport) is changed with respect to hydrogenic plasmas. This study is presently in progress and the results obtained, if conclusive, will be the subject of a separate paper (Loarte 2002).

Determining which of these two physical pictures describes the real processes that determine the energy loss in Type I ELMs is of paramount importance for the extrapolation of the present experimental results to next step devices such as ITER (Janeschitz 2001, Loarte 2001a). With increasing device size, and due to the maximum plasma density in Type I ELMy H-modes following the Greenwald scaling, the pedestal collisionality decreases as $R/T_{\text{ped}}^2$, with $T_{\text{ped}} \sim R^2$ for $n_{\text{ped}} \sim n_{\text{Greenwald}}$ (Janeschitz 2001, Loarte 2001a). If pedestal collisionality is the only parameter that determines the ELM size, this would mean that the relative ELM energy losses would be larger in ITER than in present experiments (Loarte 2001a). If parallel energy transport along the field line determines the ELM energy loss, the extrapolation of the present results to ITER is radically different (Janeschitz 2001, Loarte 2001a). $\tau_{\parallel}$ does not depend strongly on device size, as $\tau_{\parallel} \sim R/T_{\text{ped}}^{1/2}$ and, if $\tau_{\text{ELM}}^{\text{MHD}}$ does not increase with $R$, this means that it should be possible to obtain a similar range of ELM energy losses in ITER than in present experiments. Initial comparisons of the $\tau_{\text{ELM}}^{\text{MHD}}$ measurements seem to indicate a decrease of the duration of the ELM MHD activity phase with increasing device size (Loarte 2001c). Depending on the exact relation between $\tau_{\text{ELM}}^{\text{MHD}}$ and machine size, toroidal field, plasma current, etc. the predictions of the ELM energy loss in ITER vary substantially. The present predictions include the possibility of a strong reduction of the relative ELM energy loss in ITER with respect to present experiments due to the restrictions imposed by the impedance of the sheath to the parallel energy flux during the ELM (Shimada 2001).

5. Conclusions

Measurements of the ELM energy losses in JET have demonstrated that such losses are determined by the pedestal plasma parameters before the ELM, in particular by the pedestal plasma collisionality. The ELM frequency is thus a consequence of the ELM energy losses and the inter-ELM edge plasma confinement. Bulk plasma ELM particle losses depend on plasma configuration (triangularity or edge magnetic shear), which determines the volume of the edge plasma affected by the ELM, and only weakly on pedestal plasma parameters. The decrease of the ELM energy drop with increasing pedestal collisionality comes mostly from a reduction of the plasma temperature drop caused by the ELM. Type I ELMs for which the plasma energy loss comes entirely from the loss of particles (with no temperature change) have been observed (‘minimum’ Type I ELM).
The influence of the pedestal plasma parameters on the particle and power fluxes onto the divertor target has been demonstrated in the JET experiments. Time delays between the arrival time of the ELM particle fluxes at the inner and outer divertor are consistent with ion parallel transport timescales and the ELM bulk plasma losses occurring in the region of the outer midplane of the plasma. Experimental measurements of the ELM power flux pulse on the divertor target have shown that the duration of this pulse is correlated with the transport of particles during the ELM event and not with the duration of the MHD activity and the loss of high-energy electrons from the pedestal plasma, as previously thought.

The experimental results have been compared with two physical models describing the loss of energy during the ELM event: changes in ELM energy loss being driven by changes in the ELM-associated MHD activity and being driven by the competition of parallel transport along the field lines during the ELM with the ELM MHD activity duration. It has been found that the trends present in the experimental data can be correctly described by the parallel transport hypothesis but no cause–effect relation has been experimentally demonstrated. New experiments with improved diagnostics will be carried out at JET in the near future in order to clarify which of the present physics pictures describing the ELM energy and particle losses are behind the experimental phenomena. This will provide a better physics basis on which the extrapolation of the existing results to next step devices will be possible.

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