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ELM energy and particle losses and their extrapolation to burning plasma experiments

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Abstract

Analysis of Type I ELMs from present experiments shows that ELM energy losses decrease with increasing pedestal plasma collisionality (ν^*_{ped}) and/or increasing $\tau_{\parallel}^{\mathrm{Front}}$, where ($\tau_{\parallel}^{\mathrm{Front}} = 2\pi R q_{95}/c_{s,\mathrm{ped}}$) is the typical ion transport time from the pedestal to the divertor target. ν^*_{ped} and $\tau_{\parallel}^{\mathrm{Front}}$ are not the only parameters that affect the ELMs, also the edge magnetic shear influences the plasma volume affected by the ELMs. ELM particle losses are influenced by this ELM affected volume and are weakly dependent on other pedestal plasma parameters. 'Minimum' Type I ELMs, with energy losses acceptable for ITER, where there is no change in the plasma temperature profile during the ELM, are observed for some conditions in JET and DIII-D. The duration of the divertor ELM power pulse is well correlated with $\tau_{\parallel}^{\mathrm{Front}}$ and not with the duration of the ELM-associated MHD activity. Similarly, the time scale of ELM particle fluxes is also determined by $\tau_{\parallel}^{\mathrm{Front}}$. The extrapolation of present experimental results to ITER is summarised.

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Keywords: Edge pedestal; ELMs; ELMy; H-mode; ITER; Plasma-wall interactions; Divertor power load

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1. Introduction

The Type I ELMy H-mode regime is the reference regime for inductive operation of some next step devices such as ITER [1]. 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 [2], which might lead to unacceptable divertor

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target lifetime when extrapolated to next step devices [1,3–6].

Understanding of the physics mechanisms behind the ELM particle and energy loss and its extrapolation to ITER requires the comparison of measurements from various experiments. In this paper we present the results from such a comparison with experimental data from ASDEX Upgrade, DIII-D, JET and JT-60U. The ELMs considered in this study are from discharges with dominant NBI heating and reproducible ELMs. The typical scatter of the ELM energy drop with respect to its average for a large dataset of JET ELMs is 15% [7].

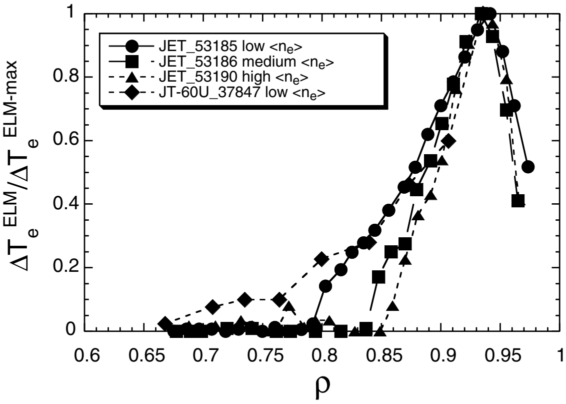

Fig. 2. Normalised ELM temperature perturbation ($\Delta T_e^{\mathrm{ELM}}/\Delta T_e^{\mathrm{ELM\text{-}max}}$) versus normalised radius ($\rho = r/a$) for a series of discharges in JET and JT-60-U showing the change of ELM affected volume with increasing plasma density.

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

For fixed discharge conditions (P_{INPUT}, I_p, B_T, plasma shape, etc.) the ELM energy losses (ΔW_{ELM}) are correlated with the density of the plasma. Higher plasma densities correspond to smaller ELM energy losses, as shown in Fig. 1. The decrease of ΔW_{ELM} (normalised to the pedestal energy $W_{\mathrm{ped}} = 3/2 n_{\mathrm{e,ped}}[T_{\mathrm{e,ped}} + T_{i,\mathrm{ped}}]V_{\mathrm{plasma}}$) is due to the decrease of the ELM-associated temperature drop and not to the density drop both for JET [7] and DIII-D [8]. The volume of the plasma, which the ELMs affect, is the outermost 20–35% in DIII-D, JET and JT-60U. In JET, the ELM affected volume depends on plasma shaping, with smaller ELM affected volumes observed for discharges with higher shaping (i.e., triangularity). With increasing density, the ELM affected volume decreases weakly (~10–30%) from the lowest to the highest density, as shown in Fig. 2. This decrease is smaller than the reduction of the ELM size in this density range, which is typically more than a factor of 2.

For some discharge conditions, Type I ELMs at high densities cause no change in the plasma temperature. Hence, the ELM energy loss is solely due to the decrease of the plasma particle content due to the ELMs. These are the so-called 'Minimum' Type I ELMs [7], which have been observed both in DIII-D and JET [7,8]. For 'Minimum' Type I ELMs $\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}} < 5\%$, which is within the ITER acceptable range from divertor lifetime considerations [6].

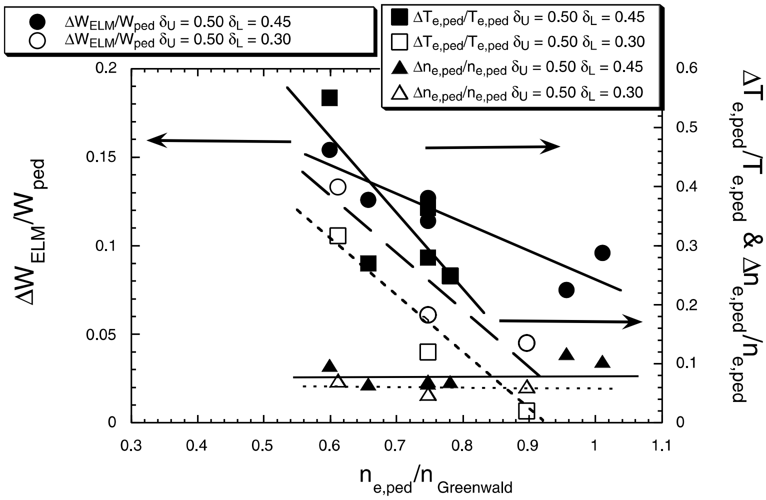

Fig. 1. Normalised ELM energy loss ($\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$) and pedestal temperature ($\Delta T_{\mathrm{e,ped}}/T_{\mathrm{e,ped}}$) and density ($\Delta n_{\mathrm{e,ped}}/n_{\mathrm{e,ped}}$) drop versus pedestal density normalised to the Greenwald limit ($n_{\mathrm{e,ped}}/n_{\mathrm{Greenwald}}$) for discharges with high upper and high/medium lower triangularities. The decrease of $\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$ with $n_{\mathrm{e,ped}}$ is associated with the decrease of $\Delta T_{\mathrm{e,ped}}/T_{\mathrm{e,ped}}$, as $\Delta n_{\mathrm{e,ped}}/n_{\mathrm{e,ped}}$ seems independent of $n_{\mathrm{e,ped}}$. At the highest $n_{\mathrm{e,ped}}$, the ELM energy loss is due almost entirely to the ELM particle loss for discharges with medium lower triangularities (discharges with $P_{\mathrm{INPUT}} = 16$ MW). Lines are to guide the eye.

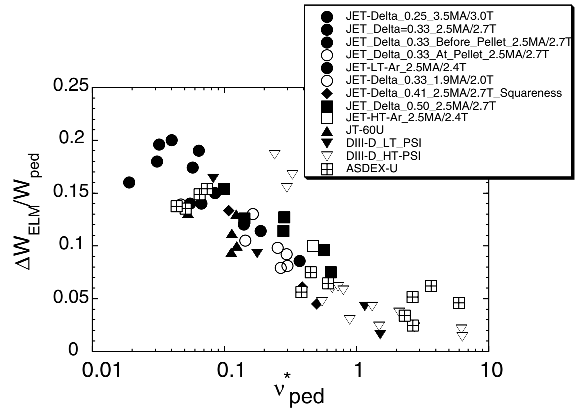

Fig. 3. Normalised ELM energy loss ($\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$) versus pedestal plasma collisionality for a large range of Type I ELMy H-mode plasmas in ASDEX Upgrade, DIII-D, JT-60U and JET including various plasma triangularities, ratios of $P_{\mathrm{INPUT}}/P_{\mathrm{L\text{-}H}}$, impurity seeding (Ar) and pellet triggered ELMs.

Comparison of (ΔW_{ELM}), for a large range of experiments/devices, reveals that the ELM energy losses are well correlated with the collisionality of the pedestal plasma ν^*_{ped}, as shown in Fig. 3, where $\nu^*_{\mathrm{ped}} = \pi R q_{95}/\lambda_{\mathrm{e,e}}$ and $\lambda_{\mathrm{e,e}}$ is the electron–electron collision mean-free path calculated with the values of the pedestal plasma parameters before the ELM. The correlation of (ΔW_{ELM}) with the value of the pedestal density (n_{ped}) (normalised to the Greenwald limit) for this dataset is poor, contrary to similar studies that only include DIII-D measurements [9]. The ELM particle losses (ΔN_{ELM}) normalised to the pedestal particle content ($N_{\mathrm{ped}} = n_{\mathrm{e,ped}} V_{\mathrm{plasma}}$) seem to be linked to the size of the ELM affected volume and nearly independent of pedestal plasma parameters (either ν^*_{ped} or n_{ped}).

3. Type I ELM power and particle fluxes on plasma facing components

The detailed study of ELM power and ELM particle fluxes onto first wall components is the topic of separate papers [10–12]. We only discuss here the outcome of comparing results from our multi-machine database. Measurements of the energy flux to the divertor during ELMs have shown that the duration of the ELM power pulse is linked with the transport of energy from the pedestal to the divertor target and not with the duration of the ELM-associated MHD event [7,10,13]. An illustration of this is shown in Fig. 4 for a medium density ELMy H-mode discharge in JET. For these conditions, the duration of the ELM-caused divertor target temperature rise is $\tau_{\mathrm{IR}}^{\mathrm{ELM}} \sim 650$ µs, while the ELM enhanced MHD activity phase duration is only ~250 µs [13]. It is important to note that, although we use $\tau_{\mathrm{IR}}^{\mathrm{ELM}}$ for inter-machine characterisation of the ELM energy pulse duration, a significant amount of the ELM energy (25–50%) reaches the target after the temperature has started to decrease (for typically [0.5–1.0] $\tau_{\mathrm{IR}}^{\mathrm{ELM}}$). This has a significant influence on the extrapolation of present results to ITER [6]. Measurements from ASDEX Upgrade, JET and JT-60U show that the duration of the ELM power deposition (characterised by $\tau_{\mathrm{IR}}^{\mathrm{ELM}}$) is well correlated with the ion transport time from the pedestal to the divertor target $\tau_{\parallel}^{\mathrm{Front}}$ ($\tau_{\parallel}^{\mathrm{Front}} = 2\pi R q_{95}/c_{s,\mathrm{ped}}$), with $\tau_{\mathrm{IR}}^{\mathrm{ELM}}(\mu\mathrm{s}) = 0.29[\tau_{\parallel}^{\mathrm{Front}}(\mu\mathrm{s})]^{1.38}$ over a large range of plasma conditions, as shown in Fig. 5. $\tau_{\parallel}^{\mathrm{Front}}$ is calculated with the values of plasma parameters at the pedestal and, hence, with a temperature which is larger than the average of the ELM expelled particles. This explains why the duration of the divertor ELM power deposition is longer than $\tau_{\parallel}^{\mathrm{Front}}$, in contrast to the estimate from steady-state SOL energy balance and sheath-limited transport, for which $\tau_{\parallel}^{\mathrm{Energy}} = 3/\gamma\tau_{\parallel}^{\mathrm{Front}}$, where γ is the sheath transmission coefficient ($\gamma \geqslant 8$ for the plasma conditions during the ELM).

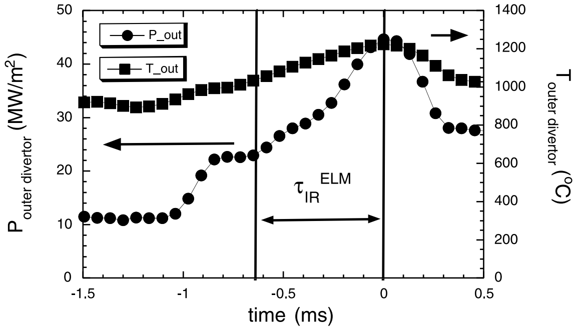

Fig. 4. Time evolution of the surface temperature of the outer divertor target and the deduced power flux, for typical medium density ELMy H-modes conditions in JET.

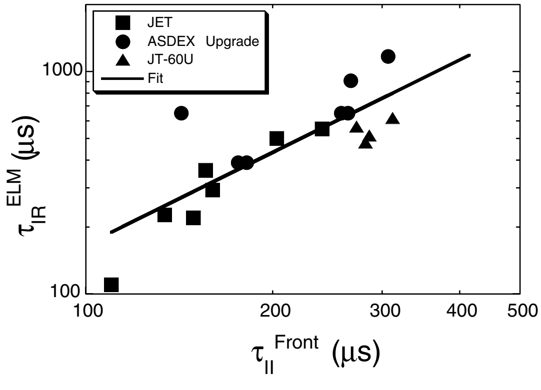

Fig. 5. Duration of the ELM power pulse measured with infrared cameras for Type I ELMs ($\tau_{\mathrm{IR}}^{\mathrm{ELM}}$) in ASDEX Upgrade, JET and JT-60U versus the SOL ion flow parallel time calculated for the pedestal plasma parameters ($\tau_{\parallel}^{\mathrm{Front}}$). $\tau_{\parallel}^{\mathrm{Front}}$ increases with decreasing pedestal plasma temperature.

4. Extrapolation of ELM energy losses to ITER

Although a consistent picture for the ELM energy and particle losses and the associated fluxes on plasma facing components from all divertor tokamaks is emerging, the extrapolation of present results to ITER remains uncertain. The experimental evidence for the duration of the ELM energy flux provides a reliable and physics based means of extrapolating present experimental results to ITER. For the expected pedestal parameters in ITER ($n_{\mathrm{ped}} = 8 \times 10^{19}$ m^{-3}, $T_{\mathrm{ped}} = 3.5$ keV), the duration of the ELM power pulse in ITER is $\tau_{\mathrm{IR}}^{\mathrm{ELM}} = 498$ μs. This, together with more realistic assumptions on the ELM power pulse temporal shape, ELM energy loss to the main chamber walls, ELM power profile broadening and the possibility of modifying the ITER divertor towards more glancing poloidal angles, have increased the estimates of the ELM energy loss for acceptable divertor lifetime in ITER to 5–10 MJ [6]. This is a factor of 2–3 larger than previous simpler estimates [4,5].

Extrapolation of the ELM energy loss from the main plasma based on present experiments to ITER is being carried out along two lines. The first takes into account the experimental correlation of ELM energy loss with ν^*_{ped} and assumes that it is a valid empirical law on which to extrapolate to ITER. In ITER, $\nu^*_{\mathrm{ped}} = 0.033$ and, hence, the expected ΔW_{ELM} would be 22 MJ (for $W_{\mathrm{ped}}^{\mathrm{ITER}} = 112$ MJ). The physics basis behind this approach comes from the ballooning-peeling model for the ELM and the influence of ν^*_{ped} on the bootstrap current and the associated MHD unstable mode structure [14]. The second line takes into account the transport of energy during the ELM and its time scale with respect to the MHD duration of the ELM event. The basis for this is that the duration of the ELM power pulse seems to be independent of the ELM MHD duration and, thus, the transport of energy along the field plays an important role on the ELM energy losses. The most uncertain parameter in this line is the duration of the ELM MHD event [13], which is poorly determined in most experiments. Previous studies of this hypothesis [4,5] characterised the energy transport along the field during the ELM by the time for the arrival of the maximum particle flux to the divertor $\tau_{\parallel}^{\max} = 2\pi R q_{95}/c_{s,\mathrm{ped}}(1 + \sqrt{3/2}\nu^*_{\mathrm{ped}})$. Fitting to the present ELM energy loss multi-machine database according to this hypothesis produces $\Delta W_{\mathrm{ELM}}^{\mathrm{ITER}} = 13$ MJ. However, the analysis presented in this paper shows that the characteristic time for energy flux to the divertor target is determined by $\tau_{\parallel}^{\mathrm{Front}} = 2\pi R q_{95}/c_{s,\mathrm{ped}}$ and, hence, independent of ν^*_{ped}, as shown in Fig. 5. The normalised energy losses are reasonably well correlated with $\tau_{\parallel}^{\mathrm{Front}}$, although some experiments deviate clearly from this correlation, as shown in Fig. 6. The reasons behind these deviations are being investigated. This new re-examination of the ELM energy losses by considering $\tau_{\parallel}^{\mathrm{Front}}$ to be the relevant time for ELM energy transport has clear implications for the extrapolation of present results to ITER. $\tau_{\parallel}^{\mathrm{Front}}$ in present experiments is usually shorter than the ITER value (due to the shorter connection length). If $\tau_{\parallel}^{\mathrm{Front}}$ is the relevant parameter on which to extrapolate present results to ITER this would mean that the ELM energy losses in ITER would be in the range typical of high density conditions in existing experiments ($\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}} \sim$ 5–10%), i.e., $\Delta W_{\mathrm{ELM}}^{\mathrm{ITER}} = 5$–11 MJ. Further analysis of the existing experimental measurements and new experiments should be carried out to investigate whether ν^*_{ped} or $\tau_{\parallel}^{\mathrm{Front}}$ are the proper parameters on which to scale to ITER.

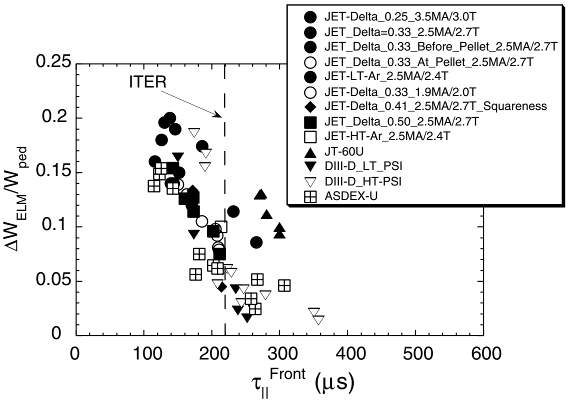

Fig. 6. Normalised ELM energy loss ($\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$) versus SOL ion flow parallel time calculated for the pedestal plasma parameters ($\tau_{\parallel}^{\mathrm{Front}}$), for a large range of Type I ELMy H-mode plasmas in ASDEX Upgrade, DIII-D, JT-60U and JET including various plasma triangularities, ratios of $P_{\mathrm{INPUT}}/P_{\mathrm{L\text{-}H}}$, impurity seeding (Ar) and pellet triggered ELMs.

5. Conclusions

Measurements of the ELM energy losses in ASDEX-U, DIII-D, JET and JT-60U have demonstrated that such losses are determined by the pedestal plasma parameters before the ELM, in particular by ν^*_{ped} or $\tau_{\parallel}^{\mathrm{Front}}$. The decrease of ΔW_{ELM} drop with increasing ν^*_{ped} and/or $\tau_{\parallel}^{\mathrm{Front}}$ comes mostly from a reduction of the plasma temperature drop caused by the ELM. Type I ELMs for which ΔW_{ELM} comes entirely from the loss of particles (with no temperature change) have been observed (Minimum Type I ELM) in DIII-D and JET.

The influence of the pedestal plasma parameters on the particle and power fluxes onto the divertor target has been demonstrated. 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 extrapolation of present experimental results to ITER has been carried out with two physical models describing the loss of energy during the ELM event. Present estimates with these two models of ΔW_{ELM} for ITER cover a wide range of values from acceptable for divertor lifetime considerations 5–11 MJ (if $\tau_{\parallel}^{\mathrm{Front}}$ determines the ELM energy loss) to unacceptable (22 MJ, if ν_{ped}^{*} controls the ELM energy size). Further experimental measurements from existing devices and experiments must be carried out to discriminate between these two hypotheses.

References

[1] ITER Physics BasisNucl. Fusion 39 (1999) 2137.
[2] H. Zohm, Plasma Phys. Control. Fusion 38 (1996) 1213.
[3] A. Leonard et al., J. Nucl. Mater. 266–269 (1999) 109.
[4] G. Janeschitz et al., J. Nucl. Mater. 290–293 (2001) 1.
[5] A. Loarte et al., Fusion Energy 2000, ITERP/11(R), Proc. 18th IAEA Fusion Energy Conference, Sorrento, Italy, 2000, IAEA, Vienna 2001, ISSN 1562-4153.
[6] G. Federici et al., these Proceedings. PII: S0022-3115-(02)01327-2.
[7] A. Loarte et al., Plasma Phys. Control. Fusion 44 (2002) 1815.
[8] A. Leonard et al., J. Nucl. Mater. 266–269 (2001) 1097.
[9] A. Leonard et al., Plasma Phys. Control. Fusion 44 (2002) 945.
[10] T. Eich et al., these Proceedings. PII: S0022-3115(02)01477-0.
[11] A. Herrmann et al., these Proceedings. PII: S0022-3115-(02)01422-8.
[12] P. Ghendrih et al., these Proceedings. PII: S0022-3115-(02)01476-9.
[13] M. Becoulet et al., Plasma Phys. Control. Fusion 44 (2002) A103.
[14] H. Wilson et al., Proc. 28th EPS Conf. Controlled Fusion and Plasma Physics, Madeira, Portugal, 2001, P3.039.