Predicted ELM Energy Loss and Power loading in ITER-FEAT

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Abstract. Scaling of Type I ELM energy losses from existing experiments to the ITER-FEAT reference inductive scenario shows that the ELM energy loss is ~ 12 MJ, marginal from divertor lifetime considerations. B2-Eirene modelling of the transient radiative losses induced by the ELMs shows a factor of 2 reduction of the divertor load for small ELMs but not for the expected ~ 12 MJ ELMs. Regimes with reduced ELM sizes (Type II) compatible with the ITER-FEAT reference performance would be required to achieve a long lifetime of the divertor target.

1. Introduction

The reference inductive scenario for ITER-FEAT (Q_{DT} = 10) is an ELMy H-mode with I_P = 15 MA, B_T = 5.3 T and a density of 1.0 10^{20} m^{-3}, which is ~ 85% of the Greenwald limit value. The need to maintain good H-mode confinement at these high densities has moved the ITER-FEAT design towards higher triangularities than in the FDR design, with a nominal separatrix triangularity of 0.5. This choice of triangularity is consistent with the experimental observations of good H-mode confinement with densities close to the Greenwald limit at triangularities similar to that of ITER [1, 2, 3, 4]. In these ELMy H-mode experiments larger pedestal pressures are obtained, while maintaining high values of the pedestal temperatures, with increasing triangularities. Such behaviour is consistent with the existence of a minimum temperature required to achieve good H-mode confinement, given by the transition between stiff and non-stiff temperature profiles [5]. Operating at pedestal temperatures lower than this transition point leads to deteriorated energy confinement. Applying the simple model in [5] to ITER leads to a minimum pedestal temperature for good confinement of 3.5 keV. In the absence of significant density peaking, the density at the pedestal of ITER will be similar to the line average density and close to values of 8.0 10^{19} m^{-3} (~ 65% of the Greenwald limit) for the reference scenario. Such pedestal densities, as fraction of the Greenwald value, can be routinely achieved in most experiments [1, 2, 3, 4]. The resulting ITER pedestal pressure is in reasonable agreement with that expected from scalings of the pedestal multimachine database [6,7].

The main drawback of operation at these high triangularities and associated large pedestal pressures is that the energy content in the pedestal is large. This can lead to larger Type I ELM energy losses compared to those at lower triangularities, as has been seen in some experiments [8]. Although ELMs, by themselves, do not pose a fundamental problem to achieve the ITER reference performance, the energy losses associated with them are of serious concern for the lifetime of the divertor target. If the energy loss and the ELM duration are such that the sublimation temperature of the divertor material is exceeded, the erosion rates become unacceptable and the divertor target would have to be replaced every few hundred discharges. This paper describes our present understanding of the Type I ELM power load that can be expected in the ITER reference regime on the basis of experimental data and modelling.

2. ELM energy loss in the ITER reference scenario

Understanding the relation between the ELM energy loss and plasma parameters such as input power, triangularity etc., has become a major area of research in existing experiments in view of its importance for ITER. The data obtained in most experiments so far seems to indicate the same common basic trends for the energy losses. A comparison of low density ELMy H-modes in JET and DIII-D has shown that the proportion of pedestal energy expelled in every ELM is similar in both experiments, and of the order of 0.13 - 0.18 [9]. The pedestal energy is defined as $W_{ped} = 3/2\ (n_{e,\ ped}\ T_{e,\ ped} + n_{i,\ ped}\ T_{i,\ ped})\ {}^*V$, where $n_{e,\ ped}$, $T_{e,\ ped}$, $n_{i,\ ped}$, $T_{i,\ ped}$ are the plasma parameters at the pedestal top before the ELM crash and V is the total plasma volume (normally $T_{i,\ ped}$ is not measured so $T_{e,\ ped} = T_{i,\ ped}$ is assumed). Measurements from ASDEX-U [10], as well as new experiments with gentle gas puffing in DIII-D [11], show a much lower normalised ELM energy loss (typically a factor of 4) than the results in [9]. Comparing results from various experiments indicates that an ordering parameter for the ELM energy loss is the plasma collisionality at the pedestal (ν^*) (see Fig. 1), with decreasing ELM size the higher the collisionality. If that were the only parameter that determines the ELM energy loss, the extrapolated ELM size to ITER would be ~ 0.15 - 0.2 W_{ped} = 15 - 20 MJ (i.e. 4 - 6% of W_{dia}). Such loads would lead to very large erosion rates of the divertor target in ITER.

A critical parameter that also determines the acceptability of ELMs for the divertor target is the duration of the ELM power load pulse. Larger experiments such as JET and JT-60U measure a power deposition time in the divertor of 100 - 200 μs [12, 13, 14] while the typical deposition time for DIII-D [9] is 200 - 300 μs and for ASDEX-U [15] is 400 μs or more. All these values are typically much longer than the characteristic time for electron collisionless transport in the SOL, assuming that ELMs increase the values of the plasma parameters at the separatrix to typical pedestal values. This observation and the correlation of the ELM size with pedestal collisionality has lead to a model for the ELM energy loss which links the ELM size with the parallel ion losses along the field to the divertor target [16]. When an ELM occurs, the pedestal plasma loses energy towards the divertor plate (through the electron and ion channels) during a time τ_{ELM}. Because of the short duration of the ELM process (few 100 μs) the expelled ions and electrons have no time to equilibrate (the typical equilibration time is few 10 ms). Due to the larger electron thermal parallel conductivity, the electron temperature at the divertor will increase in few μs and a new sheath, consistent with the pedestal electron plasma, will be established. As a consequence, the energy will be delivered to the divertor in time scales typical of the ion parallel flow. Such picture is consistent with the observation of large and short-lived currents which have been measured at JET during Type I ELMs [17]. Following this hypothesis, the ELM energy drop is determined by the ratio of the ion parallel loss time and the ELM time. A simple ansatz for this is given by :

$$\frac{\Delta W_{ELM}}{W_{ped}} = \left|\frac{\Delta W_{ELM}}{W_{ped}}\right|_0 \frac{1}{\left(1 + \tau_{||}/\tau_{ELM}\right)}$$

where $\tau_{||} = 2L/c_s \left(1 + \sqrt{3/2}\ \nu^*\right)$ is the parallel ion loss time (collisionless or collisional) and $\left|\Delta W_{ELM}/W_{ped}\right|_0$ would be the ELM energy loss, if parallel transport would be much faster than τ_{ELM}. This ansatz has been calibrated with DIII-D data [11], which show a large span in edge collisionality, and applied to other experiments. Results in Fig.2, for discharges with $\delta = 0.2 - 0.3$, show the reasonable agreement found, when comparing this prediction with ASDEX-U [2] and JET experiments [1]. In these JET experiments the pedestal temperature is decreased by moderate gas puffing [1] while maintaining Type I ELMs.

Using such ansatz for the ITER reference point leads to $\Delta W_{ELM} = 12$ MJ (12 % of W_{ped}) deposited onto the target with a typical time of 200 μs. This prediction is about a factor of 2 smaller than the one arising from the straight comparison of JET and DIII-D low density discharges. However, even in this case the predicted ELM energy loss leads to erosion rates such that the lifetime of the divertor target is marginal (somewhat better if W is used for the divertor target), as shown in Table 1 [18].

	C (0.2 ms)	**W (0.2 ms)**
Allowable energy deposition $E\ (MJ/m^2)$ for 10^6 ELMs, deposition time = 0.2 ms	**0.33**	0.76 **(0.52)**
Allowable $\Delta W_{ELM}\ (MJ)$ for 10^6 ELMs with deposition area $S = S_{SS} = 8\ m^2$	**2.61**	6.07 **(4.16)**
Allowable $\Delta W_{ELM}\ (MJ)$ for 10^6 ELMs with deposition area $S = 2 \times S_{SS} = 16\ m^2$	**5.22**	12.16 **(8.33)**

S_{SS} -. Strike zone Surface **( ) considering melting**

Table 1: Allowable Energy deposition on the divertor targets during ELMs

Analysis of JET [1] and DIII-D data [11] shows that the ELM energy loss normalised to the pedestal energy increases with δ at low values ($\delta < 0.15$) but saturates at moderate to high triangularities ($\delta > 0.2 - 0.4$) to values of $\Delta W_{ELM}/W_{ped} \sim 0.2 - 0.25$. Therefore, the extrapolation of experimental data with $\delta = 0.2 - 0.3$ to ITER ($\delta = 0.5$) done here is justified.

As expected, the simple ansatz above does not describe correctly experimental results in which the plasma collisionality is changed by other means than gas fuelling without adjustments of the two parameters contained in the model. In particular, to describe the decrease of the normalised ELM size with increasing input power (no gas puff) seen in JET [1] would imply that either τ_{ELM} or $\left|\Delta W_{ELM}/W_{ped}\right|_0$ decrease with input power. Work is in progress to test parametric dependences of the model with data from several divertor experiments.

3. Modelling of the ELM divertor power load in the ITER reference scenario

A further important point, in order to extrapolate the ELM effects to ITER, is to model and understand how much of the energy lost by the plasma (derived from the above experimental scalings) reaches the divertor target. Besides losses by direct interaction with main chamber walls, it is expected that some of the ELM energy loss in ITER will be spent in enhanced ionisation and divertor radiation. These enhanced losses are due to the transient increase of the divertor temperature that the ELM will induce, and will dissipate some of the ELM energy before it reaches the target. Modelling of such losses for ASDEX-U [19, 20] indicates that the radiated level in the SOL and divertor can increase transiently by about a factor of 2 due to ELM effects. ELMs are simulated with B2-Eirene by increasing the anomalous transport coefficients in the plasma edge region (including pedestal and SOL) by one to three orders of magnitude during a brief period (100 - 300 μs in the results presented here). The transport increase is consistent with the experimental data that shows no narrowing of the power deposition profile at the ELM (ergodisation of the edge region). The modelling of ELMs as a pure power pulse into the SOL (without changing anomalous transport) leads to extremely narrow ELM power deposition profiles (shown in Fig. 3 for a modelled ITER ELM) which are inconsistent with experiment.

Calculations have been performed for the reference non-seeded ITER scenarios [21] with a variety of ELM sizes. For very small ELM sizes (< 1 MJ), the transient radiative losses can be similar to the power to the divertor plate, therefore reducing the ELM divertor power load by about a factor of 2. Fig. 4.a shows the calculated radiated power and target load for a 100 μs ELM with a total energy of ~ 0.5 MJ. The ELM energy pulse increases the carbon radiated losses from a steady state value of ~ 60 MW to a transient peak value of ~ 750 MW. For the ELM duration, the divertor remains in an attached-low divertor temperature (< 10 eV) state, as seen in Fig 4. b. Unfortunately, for larger ELMs this phase of enhanced radiation becomes shorter and the ELM heat pulse is able to increase the divertor temperature to several 100 eV, where carbon radiation is negligible. Fig. 5 shows the maximum radiated power and the maximum power flux to the divertor as a function of the ELM energy pulse, summarising the results of the modelling. B2-Eirene modelling of the ELMs is carried out in a fluid approximation with flux limits to correct for kinetic effects. With this plasma model, the ELM energy pulse is carried to the divertor target mainly via the electron parallel transport limited by the divertor sheath. Therefore, the total ELM energy drop is determined by the duration of the phase of enhanced transport, consistent with the model in Section 2. This and results from earlier simulations [19, 20, .22] are, however, no proof of the hypothesis in Section 2, as B2-Eirene describes the plasma with a fluid model. To prove the hypothesis in Section 2 requires a full kinetic description of the SOL beyond the scope of B2-Eirene. Calculations are in progress to check if using a higher Z impurity radiator, such as Ar, which can radiate at higher temperatures could increase the transient radiated power dissipation for larger ELMs.

4. Conclusions

Analysis of ELM energy losses in divertor tokamaks indicates that the collisionality is an important parameter is controlling the ELM size. This observation together with the larger ELM power deposition times in more collisional experiments suggest a link between the two. A model for the ELM energy losses which relates both observations reproduces the trends seen in experiments in which the edge collisionality is varied by puffing. The extrapolated ELM energy loss is ~ 12 MJ for the ITER reference scenario. This value puts severe restrictions on the divertor target lifetime, in particular for the reference carbon divertor target. B2-Eirene modelling of ELMs for ITER shows that enhanced radiation losses which would decrease the ELM divertor power load are only significant for very small ELMs (< 1 MJ). Regimes with reduced ELM sizes (Type II) compatible with the ITER-FEAT reference performance would be required to achieve a long lifetime of the divertor target [23, 24].

5. References

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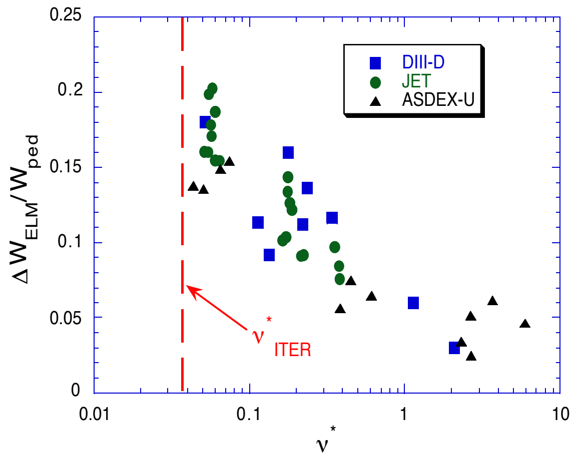

Figure.1 Fractional ELM energy loss versus pedestal collisionality.

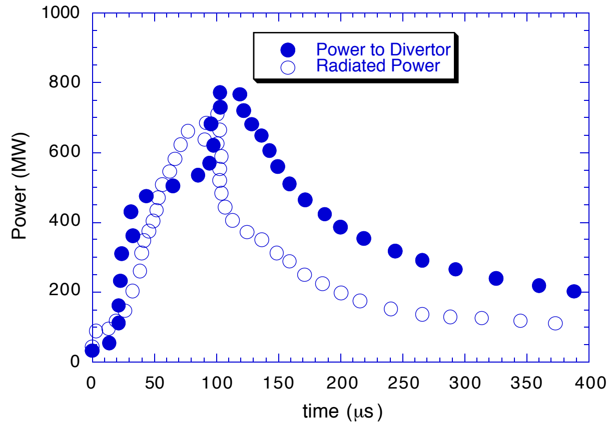

Figure.4.a B2-Eirene modelled divertor power load and radiated power during an ELM in ITER.

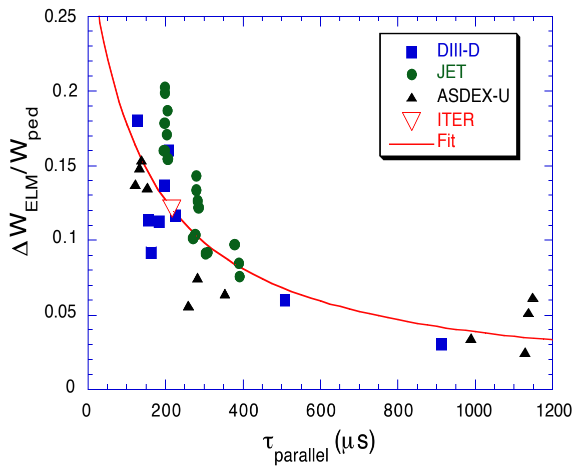

Figure.2 Fractional ELM energy loss versus parallel energy loss time.

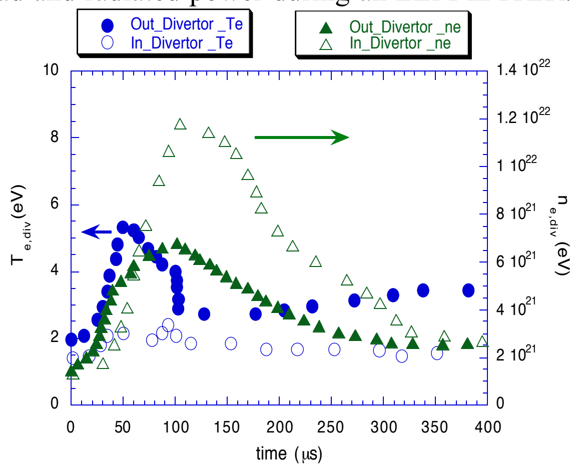

Figure.4.b. B2-Eirene modelled inner and outer Divertor electron temperature and density during an ELM in ITER.

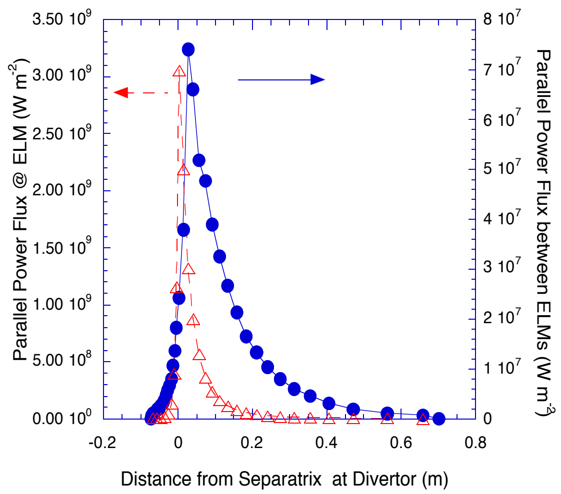

Figure.3 B2-Eirene modelled divertor power load between and at ELM without SOL anomalous transport increase in ITER.

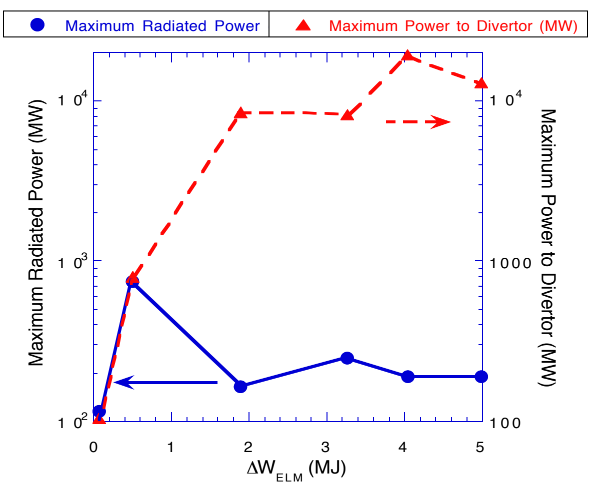

Figure.5. B2-Eirene maximum radiated power and divertor power load versus ELM energy in ITER.