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ELM HEAT FLUX IN THE ITER DIVERTOR*

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Edge-Localized-Modes (ELMs) have the potential to produce unacceptable levels of erosion of the ITER divertor. Ablation of the carbon divertor target will occur if the surface temperature rises above about 2,500°C. Because a large number of ELMs, ≥ 1000, are expected in each discharge it is important that the surface temperature rise due to an individual ELM remain below this threshold. Calculations that have been carried out for the ITER carbon divertor target [1] indicate ablation will occur for ELM energy $\geq 0.5 \mathrm{MJ/m^2}$ if is deposited in 0.1 ms, or 1.2 $\mathrm{MJ/m^2}$ if the deposition time is 1.0 ms. Since $\Delta T \propto Q \Delta t^{-1/2}$, an ablation threshold can be estimated at $Q\Delta t^{-1/2} \approx 45\ \mathrm{MJm^{-2}\,s^{-1/2}}$ where Q is the divertor ELM energy density in $\mathrm{J\text{-}m^{-2}}$ and Δt is the time in seconds for that deposition. If a significant fraction of ELMs exceed this threshold then an unacceptable level of erosion may take place.

The ablation parameter in ITER can be determined by scaling four factors from present experiments: the ELM energy loss from the core plasma, the fraction of ELM energy deposited on the divertor target, the area of the ELM profile onto the target, and the time for the ELM deposition. ELM data from JET, ASDEX-Upgrade, JT-60U, DIII–D and Compass-D have been assembled by the ITER Divertor Modeling and Database expert group into a database for the purpose of predicting these factors for ELMs in the ITER divertor.

The magnitude of energy lost from the main plasma, ΔW, has been reported from a number of tokamaks to be in the range of 2%–6% of the main plasma stored energy [2]. These measurements from JET, ASDEX-Upgrade, DIII–D and COMPASS-D are for TYPE I ELMs with no additional gas puffing. As the heating power was increased the ELM energy remained constant while the ELM frequency increased linearly with heating power. The product of ELM amplitude and frequency represents a nearly constant fraction of the heating power, 20%–40%, being carried across the separatrix by ELMs. For an ITER stored energy of 1200 MJ and a power of 200 MW crossing the separatrix this data would indicate an ITER ELM energy between 25 MJ and 80 MJ with an ELM frequency of approximately 1–5 Hz.

To improve projections of ELM characteristics to ITER, the ITER Divertor Modeling and Database Expert Group has sought contributions from the world's tokamaks for a multi-machine ELM database . At this time the database contains ELM ΔW data only from JET and DIII–D, while ELM frequency data has been obtained from JET, DIII–D, JT-60U and ASDEX-Upgrade. The preliminary state of the database makes it difficult to predict, with any confidence, ELM energy loss, ΔW, for ITER. Future results from analysis of the database will depend upon additional data collection and refinement of the database that is now underway .

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Initial study of the database has focused on examining the relationship between the edge pedestal characteristics and the ELM energy loss. Previous work on DIII–D has shown the energy loss of individual ELMs to be nearly a constant fraction of the edge pedestal energy, i.e., the plasma pressure at the top of the steep gradient region inside the separatrix integrated over the plasma volume. The ELM ΔW for JET and DIII–D are plotted versus the edge pedestal energy in Fig. 1. We find the ELM ΔW is ~36% of the pedestal electron energy in DIII–D and ~26% in JET. The data is too sparse with too much scatter, however, to determine if the ELM fractional pedestal energy loss decreases with machine size or is constant.

There are examples of operation with ELM ΔW that are clearly less than the 2%–6% of the plasma stored energy reported above. DIII–D has reported a factor of 4 or more reduction in ELM amplitude and a similar increase in ELM frequency with external gas puffing [3]. JET has reported ELM amplitude was reduced a factor of 5 with rf heating and little degradation of main plasma confinement [4]. When operated near the H–mode threshold, Type III ELMs have been observed with ΔW more than an order of magnitude smaller than the Type I ELMs.

If a significant fraction of the ELM energy can be radiated then the possibility exists for reducing the energy flux onto the target. ELM radiation on DIII–D has been measured to be less than 20% of the ELM ΔW [2]. JET has reported that additional radiation due to ELMs occurs after the fast ELM heat pulse, too late to be of benefit [5].

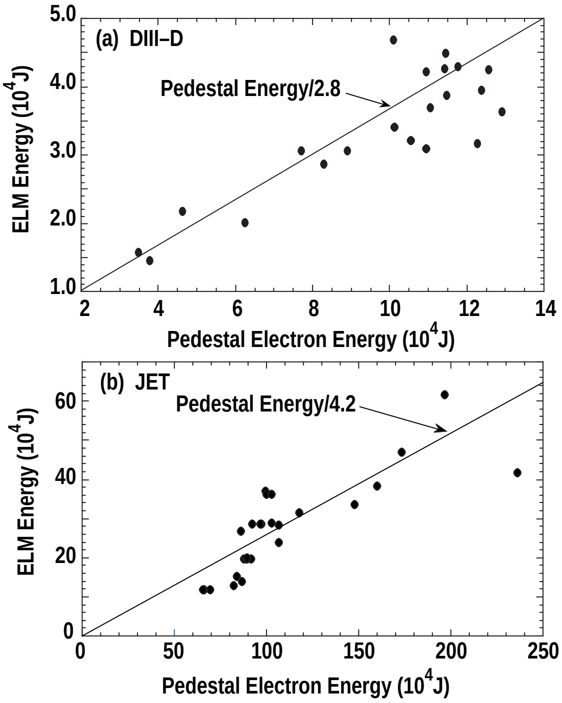

Fig. 1. The ELM energy loss, ΔW, versus the pedestal electron pressure integrated over the plasma volume for (a) JET and (b) DIII–D.

Measurements of the ELM divertor heat flux on ASDEX-Upgrade and DIII–D have accounted for between 50% and 80% of the ELM ΔW [2], though with large uncertainty due to the difficulty with interpretation of divertor surface temperature measurements. However, to accurately project if radiation may dissipate a significant fraction of the ELM energy in ITER, time-dependent modeling with the proper atomic physics is necessary. Simulations of ELMs have been carried out using the B2/EIRENE code. This study found that for ITER conditions much less than ~1 MJ of the ELM energy could be dissipated by radiation[6].

The energy density on the target due to the ELM will depend on the area, or profile, of the energy deposition. Though accuracy of instantaneous measurements of heat flux from surface temperature measurements during the ELM pulse are susceptible to uncertainties in the surface thermal properties of the carbon target, the total energy deposited by an ELM, and the profile of that energy is less susceptible to such errors. An example of an ELM divertor energy profile from ASDEX-Upgrade is shown in Fig. 2. This profile is similar to profiles that are observed on JET, DIII–D, JT-60U and COMPASS-D. A common feature of the ELM profiles is that the width of the ELM heat flux ranges from the same order to twice the width of the heat flux between ELMs. With the fast parallel transport governed by the same processes as the steady-state heat flux, the expected ELM heat flux width should be wider than the steady-state width, depending on the level of additional transport the ELM instability introduces. Future work should correlate the ELM energy profile with measured magnetic fluctuations during the ELM instability. Asymmetries in the ELM energy deposition position will reduce the effective area of the deposition. The ELM energy profile is often observed to be 2–4 times greater in the inboard divertor compared to the outboard as is clearly seen in Fig. 2. This asymmetry could reduce the effective deposition area by up to a factor of 2. One possible source for the observed in/out asymmetries is a variation in surface properties between the inboard and outboard divertors. The extent to which such variations in the surface may affect interpretation of the heat flux measurements remains for future work.

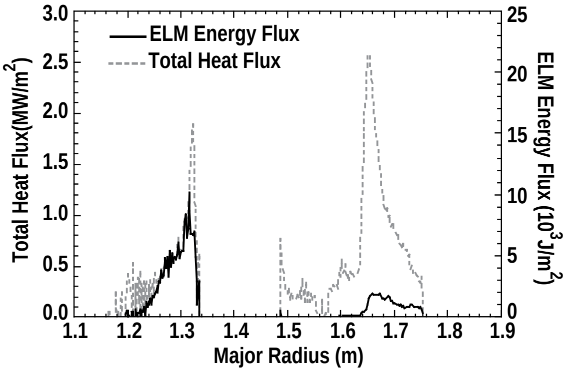

Fig. 2. ELM divertor energy deposition profile for ASDEX-Upgrade.

If the ELM energy falls far from the separatrix then it may land on in-vessel components that are not designed for high heat flux. A shift in the ELM profile of several SOL widths has often been observed in JET [7], while other tokamaks report shifts of less than one SOL width. Currents of sufficient magnitude to produce such a shift have been measured at the JET divertor target. This phenomena is not well understood, but does appear to decrease in magnitude with smaller amplitude ELMs on JET.

High speed measurements of the JET divertor target show that most of the ELM energy can be deposited on the target in as little as about 100 μs [5]. However, similar measurements on ASDEX-Upgrade and DIII–D have measured longer deposition times at up to 1.0 ms. If only energy is released by the ELM instability the SOL will be heated with little change in density. This energy can be conducted to the divertor with some fraction of the thermal speed of the electrons. If part of the ELM energy is released as density into the SOL then the timescale for convective transport would be the slower ion sound speed.

Consistent with conduction, ELMs on JET usually reduce the temperature inside the separatrix with little change in density [5]. However, ELMs on ASDEX-Upgrade and DIII–D usually transport a greater fraction of particles across the separatrix [3]. If conduction dominates the ELM energy transport in ITER then 100 μs is the likely timescale. The fraction of ELM energy transported as particles would likely arrive at the target with a time duration of ~ 1 ms.

With these ELM characteristics we can project the ELM amplitudes that are likely to cause divertor target ablation on ITER. For the area of the ELM deposition we assume approximately 1–2 times the steady-state heat flux width between ELMs. Peaking of the ELM energy flux due to in/out asymmetries should be less than a factor of two, while radiation should dissipate only a small pfraction of the ELM energy. With an effective ELM area of 1 to 2 times the ITER target plate heat flux width, or 10–20 m^2 and an ELM duration of 0.1 ms to 1.0 ms, an ablation threshold of 45 MJm^{-2} s$^{-1/2}$ leads to a threshold ELM energy of 5–30 MJ. Though this allowed ELM energy is less than the projected ITER ELM energy of 25–80 MJ, operation with gas puffing, rf heating, pellets or perhaps even achieving Type III ELMs all have the potential to produce much smaller ELMs.

A maximum tolerable ELM for ITER may also define a maximum allowable edge pedestal. If we assume a maximum ELM of 10 MJ and the ELM is 30% of the pedestal electron energy, as shown in Fig. 1, then the maximum allowable pedestal electron energy is about 30 MJ. Using the proposed ITER operating density of ~$1.0\times10^{20}\mathrm{m}^{-3}$ and a volume of 2000 m^3 leads to an allowable pedestal electron temperature of a little less than 1 keV. This is significantly below the 3–4 keV pedestal temperature thought necessary to achieve ITER's optimal performance [8]. What is needed is operation with high pedestal parameters and small ELMs. An example of this operation is shown in Fig. 3. This data from DIII–D shows an increase in the ELM frequency with gas puffing and a reduction in the ELM amplitude by a factor of 5. However, the average height of the edge pedestal, and the confinement, does not decrease nearly as much. For some reason in this case the edge pedestal remains high with smaller ELMs and gas puffing. Hopefully future work can exploit this type of behavior.

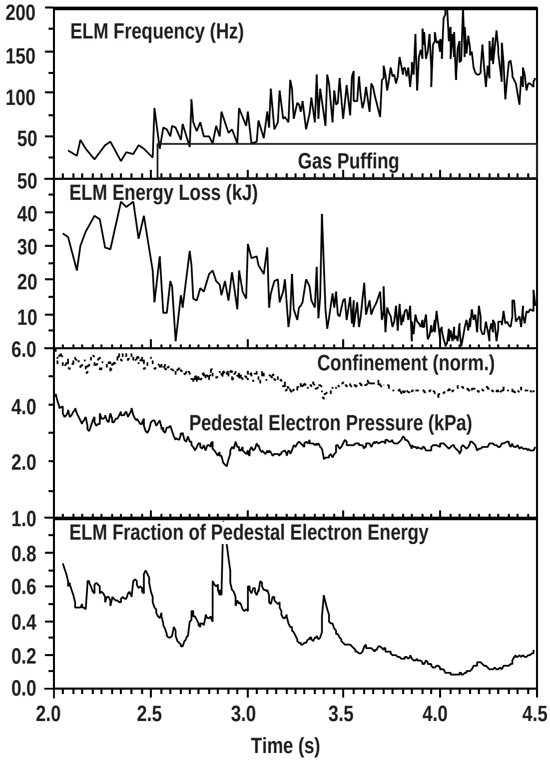

Fig. 3. The ELM and edge pedestal characteristics on DIII–D with gas puffing. Shown are the ELM frequency, the energy loss of individual ELMs, the pedestal electron pressure, the normalized confinement time and the fraction of pedestal energy lost at each ELM.

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