LETTER TO THE EDITOR

Inter-ELM power exhaust in tokamak fusion reactors

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Abstract. Recent infra-red measurements of divertor power loads on JET and AUG [1], revealed that the inter-ELM power width at the outer mid-plane in attached ELMy H-modes, λ_Q, does not exhibit any noticeable scaling with machine size [1]. Making use of these results to calculate the effective radial heat diffusivity, $\chi_\perp$, and then including this $\chi_\perp$ in parametrized expressions based on edge plasma fluid simulations, it is possible to estimate the peak inter-ELM divertor power loads, Q_t^{max}, in future fusion devices with conventional divertor designs. Two additional constraints are imposed: (i) power flow across the separatrix must exceed the $L-H$ access power, P_{L-H}, as given by an empirical scaling [2], in order to maintain H-mode operation, i.e., $P_{sol} = f_{L-H}P_{L-H}$, with $f_{L-H} > 1$, and (ii) the upstream separatrix density is given by some fraction, $f_{GW}^{sep} < 1$, of the Greenwald density, $n_{GW} \sim I_p/\pi a^2$, while line average density is set equal to n_{GW}. Affecting the calculation yields the following expression: $Q_t^{max} \propto f_{GW}^{sep-0.75} f_{LH}^{1.47} q^{-0.84} B_T^{2.57} R^{0.15} \kappa^{0.2} \varepsilon^{-0.23} Z_{eff}^{0.31}$. Hence, Q_t^{max} increases only weakly with reactor size and should be comparable in future and present devices, for comparable levels of f_{GW}, f_{LH}, q, B_T and $\theta_\perp$. Calibrating the scaling against a high density JET shot with nitrogen seeding, and allowing for an additional factor of two reduction due to divertor closure, leads to an estimate of Q_t^{max} in ITER and DEMO (R = 8.5 m, B_T = 5.7 T, q_{cyl} = 2, Z_{eff} = 3) as $8-16$ MW/m^2 and $20-50$ MW/m^2, respectively. It thus appears that H-mode operation of a tokamak fusion reactor cannot be reconciled with the thermo-mechanical properties of leading candidate materials (<5 MW/m^2 for irradiated W), and the power exhaust cabilities of conventional divertors, requiring either advanced materials and/or advanced divertor solutions. The main uncertainties in the above prediction are the upper limit on the separatrix density, distribution of divertor radiation and the impact of divertor closure.

Recent infra-red measurements of divertor power loads on JET and AUG [1], revealed that the inter-ELM power width at the outer mid-plane in attached ELMy H-modes, $\lambda_Q = |\nabla_\perp Q_\parallel / Q_\parallel|^{-1}$, can be approximated by,

$$\lambda_Q \approx 0.73 \cdot B_T^{-0.78\pm0.25} q^{1.2\pm0.27} P_{sol}^{0.1\pm0.11} R^{0.02\pm0.2}. \quad (1)$$

Here parallel power e-folding length, λ_Q, is in mm, the toroidal magnetic field, B_T, is in T, the power entering the SOL, P_{sol},

$$P_{sol} = P_{core} - P_{rad}^{core} = f_{rad}^{core} P_{core}, \quad (2)$$

is in MW and the central major radius R is in m, while the cylindrical safety factor,

$$q \equiv q_{cyl} = \frac{2\pi\varepsilon\kappa a B_T}{\mu_0 I_p}, \quad (3)$$

is dimensionless. The remarkable, and at first glance deeply worrying, feature of (1) is the fact that λ_Q is virtually independent of reactor size. In this letter, we examine the implication of this lack of size scaling on the peak divertor (target) power load, Q_t^{max}, and the peak divertor electron temperature, T_{et}^{max} in future tokamak reactors.

In order to make this prediction, we resort to results of 2-D plasma fluid simulations in which the plasma density, power entering the SOL, reactor size and heat diffusivity in the SOL were all varied independently [4]. In the high density (high recycling) regime of SOL operation, the results were found to agree reasonably well with the following expressions:

$$Q_{\parallel t}^{max}[MW/m^2] \approx 1120 \times n_{eu}^{-1.82} (P_{sol}/S_\perp)^{2.37} \chi_\perp^{-1.07} q^{0.52} R^{0.33} \quad (4)$$

$$T_{et}^{max}[eV] \approx n_{eu}^{-5.52} (P_{sol}/S_\perp)^{4.06} \chi_\perp^{-1.51} q^{0.18} R^{-0.66} \quad (5)$$

$$n_{et}^{max}[10^{20} m^{-3}] \approx n_{eu}^{3.36} (P_{sol}/S_\perp)^{-2.01} \chi_\perp^{0.8} q^{0.37} R^{1.15} \quad (6)$$

where the peak parallel divertor (target) power density, $Q_{\parallel t}^{max}$ is in MW/m^2, upstream separatrix density, n_{eu} is in $10^{20} m^{-3}$, power into the SOL, P_{sol} is in MW, the plasma surface area $S_\perp$ is in m^2, radial heat diffusivity, $\chi_\perp$, is in m^2/s, the cylindrical safety factor q is dimensionless, and R is in m. It is worth noting that ELMs were absent from the simulations, such that comparison with experiment requires replacing P_{sol} by the power entering the SOL in between ELMs, P_{sol}^{i-E}, which is defined as some fraction of P_{sol},

$$P_{sol}^{i-E} = f_P^{i-E} P_{sol}. \quad (7)$$

Since the effects of radial transport enter (4)-(6) via the SOL radial heat diffusivity, $\chi_\perp$, it is necessary to estimate this quantity based on the experimental power e-folding length, λ_Q, (1). For this purpose we employ a well known expression [3],

$$\lambda_Q / L_\parallel \sim \sqrt{\kappa_\perp / \kappa_{\parallel e}} = \sqrt{\chi_\perp / \chi_{\parallel e}}, \quad (8)$$

which is obtained by assuming energy conservation in the absence of source/sinks, $\nabla \cdot \boldsymbol{Q} = 0$, and purely conductive transport in both parallel and perpendicular directions,

$$Q_\parallel \approx Q_{\parallel e} \approx \kappa_{\parallel e} \nabla_\parallel T_e, \qquad Q_\perp \approx \kappa_\perp \nabla_\perp T_e. \quad (9)$$

One then finds

$$\nabla_{\parallel}\kappa_{\parallel e}\nabla_{\parallel}T_e \approx \nabla_{\perp}\kappa_{\perp}\nabla_{\perp}T_e. \quad (10)$$

Assuming that $\kappa_{\parallel e} \propto T_e^{5/2}$ and $\kappa_{\perp} \propto T_e^{\zeta}$, and estimating the gradients by characteristic lengths, we find

$$(\frac{5}{2}+1)\kappa_{\parallel e}/L_{\parallel}^2 \approx (\zeta+1)\kappa_{\perp}/\lambda_T^2, \quad L_{\parallel} \approx \pi q R, \quad (11)$$

where $\lambda_T = T_e/\nabla_{\perp}T_e$. Since $\kappa_{\parallel e} \propto T_e^{5/2}$ implies that $\lambda_Q \approx \frac{2}{7}\lambda_T$, the above can also be rewritten as

$$\lambda_Q/L_{\parallel} \approx \left(\frac{2}{7}\right)^{3/2}\sqrt{\zeta+1}\sqrt{\kappa_{\perp}/\kappa_{\parallel e}}. \quad (12)$$

Isolating for $\chi_{\perp} = n\kappa_{\perp}$, we obtain the required expression,

$$\chi_{\perp} \approx \left(\frac{7}{2}\right)^{3}(\zeta+1)^{-1}\chi_{\parallel e}(\lambda_Q/L_{\parallel})^2. \quad (13)$$

In the presence of an edge transport barrier extending into the near-SOL, one typically finds $\zeta \approx 3.5$ so that

$$\chi_{\perp} \approx 10\chi_{\parallel e}(\lambda_Q/L_{\parallel})^2. \quad (14)$$

The upstream separatrix temperature, T_{eu}, may be evaluated using a modified two point model of SOL transport [3, 11],

$$T_{eu}^{7/2} \approx T_{et}^{7/2} + \tfrac{7}{4}P_{sol}L_{\parallel}/(S_{\parallel}\kappa_{0e}), \quad (15)$$

where T_{eu} and T_{et} are the upstream and target values of the temperature and $\kappa_{0e} \propto 1/Z_{eff}$ is a constant in the Spitzer-Harm expression for parallel heat conduction, $\kappa_{\parallel e} = \kappa_{0e}T_e^{5/2}$ [9, 10]. This relation follows directly from a quadrature of the parallel electron heat conduction equation,

$$P_{sol}/S_{\parallel} = Q_{\parallel e} \approx \kappa_{\parallel e}\nabla_{\parallel}T_e = \kappa_{0e}T_e^{5/2}\nabla_{\parallel}T_e, \quad (16)$$

between the upstream and target regions. The parallel energy flow (cross-sectional surface) area, $S_{\parallel}$, may be derived from a divergence form of energy conservation, $\nabla_{\parallel}Q_{\parallel} \approx \nabla_{\perp}Q_{\perp}$,

$$S_{\parallel} = S_{\perp}(L_{\perp}/L_{\parallel}) \approx 4\pi R\sqrt{\kappa}\lambda_Q\varepsilon/q. \quad (17)$$

The target temperature in (15) may be obtained by invoking two additional assumptions of the 2 point model: (i) pressure conservation, $n_uT_u \approx 2n_tT_t$, and (ii) the target energy flux boundary condition,

$$P_{sol}/S_{\parallel} = Q_{\parallel t} = \gamma T_{et}n_{et}C_{St}, \quad \Rightarrow \quad T_{et} \propto \left(P_{sol}/S_{\parallel}n_{et}\right)^{2/3} \quad (18)$$

where $\gamma = \gamma_e + \gamma_i \approx 8$ is the total sheath energy transmission coefficient. However, in high recycling (high density) conditions, the second term in (15) dominates, and the expression for T_{eu} becomes

$$T_{eu} \approx [\tfrac{7}{4}P_{sol}L_{\parallel}/(S_{\parallel}\kappa_{0e})]^{2/7}, \quad (19)$$

Inserting (11) and (19), into (13) we obtain

$$\chi_\perp \propto \lambda_Q^{9/7} P_{sol}^{5/7} n_{eu}^{-1} q^{-4/7} R^{-2} (\varepsilon\sqrt{\kappa})^{-5/7} Z_{eff}^{-2/7} \tag{20}$$

i.e., $\chi_\perp$ increases with λ_Q and P_{sol}, and decreases with n_{eu}, q and R, and decreases linearly with both size and density. Finally, inserting (1) for λ_Q, we find

$$\chi_\perp \propto P_{sol}^{0.84} n_{eu}^{-1} B_T^{-1} q^{0.97} R^{-1.98} (\varepsilon\sqrt{\kappa})^{-5/7} Z_{eff}^{-2/7} \tag{21}$$

which introduces an inverse dependence with B_T and yields a linear scaling with q.

Finally, we impose two additional constraints. First, in order to maintain H-mode operation, we require that the power flow across the separatrix exceed the $L-H$ access power, P_{L-H}, as given by an empirical scaling [2],

$$P_{L-H} \propto B_T^{0.803\pm0.03} \langle n_e \rangle^{0.717\pm0.04} S_\perp^{0.94\pm0.02} \tag{22}$$

where $S_\perp \approx 4\pi^2 R^2 \varepsilon \sqrt{\kappa}$ is the plasma (separatrix) surface area. This can be written as

$$P_{sol} = f_{L-H} P_{L-H}, \qquad f_{L-H} > 1. \tag{23}$$

This expression replaces (7) and effectively specifies the core radiative fraction,

$$f_{rad}^{core} = f_{L-H} P_{L-H} / P_{core}. \tag{24}$$

Second, we set the line average density $\bar{n}_e$ in (22) equal to the Greenwald density,

$$n_{GW} \approx I_p / \pi a^2, \tag{25}$$

where n_{GW} is in units of $10^{20} m^{-3}$, the plasma current, I_p, in MA, and the minor radius a in m, and set the the upstream separatrix density at some fraction of n_{GW},

$$\langle n_e \rangle = f_{GW} n_{GW}, \qquad n_{eu} = f_{GW}^{sep} n_{GW}, \tag{26}$$

where $f_{GW} \approx 1.0$ and $f_{GW}^{sep} < f_{GW}$. Since the Greenwald density is a fair proxy for the appearance of the H-mode density limit, i.e., degradation of energy confinement, we will assume that $f_{GW} = 1$ henceforth.

Inserting (22) to (26) into (21), we find

$$\chi_\perp \propto f_{LH}^{0.84} f_{GW}^{sep-1} n_{GW}^{-0.4} q^{0.97} B_T^{-0.33} R^{-0.4} (\varepsilon\sqrt{\kappa})^{0.08} Z_{eff}^{-2/7}. \tag{27}$$

Substituting for n_{GW} using (25) and (3),

$$n_{GW} \propto \frac{I_p}{a^2} \propto \frac{\kappa B_T}{qR}, \tag{28}$$

the above expression reduces to

$$\chi_\perp \propto f_{LH}^{0.84} f_{GW}^{sep-1} q^{1.37} B_T^{-0.73} R^{0.01} \varepsilon^{0.08} \kappa^{-0.36} Z_{eff}^{-2/7}. \tag{29}$$

Finally, inserting (27), (23), (22), (28), (26) into (4) yields the following scaling for the parallel power load,

$$Q_{\|t}^{max} \propto f_{GW}^{sep-0.75} f_{LH}^{1.47} q^{-0.82} B_T^{2.55} R^{0.15} \kappa^{0.19} \varepsilon^{-0.23} Z_{eff}^{0.31}. \tag{30}$$

Note that $Q_{\|t}^{max}$ increases only weakly with reactor size, and would hence be comparable in future and present devices provided the other quantities in (30) do not change markedly. Unfortunately, the magnetic field is expected to roughly double in future devices compared

Table 1. Major radius, toroidal field, plasma current, cylindrical safety factor and effective charge for JET, ITER and DEMO.

Quantity:	R (m)	B_T (T)	I_p (MA)	q	Z_{eff}
JET	2.9	2.5	2.5	2.7	1.7
ITER	6.3	5.3	15	2	1.7
DEMO	8.5	5.7	23	2	3

to the largest present device, e.g., in going from JET to ITER, see Table 1, which would introduce a significant (factor of 6), increase in the parallel heat load.

Needless to say, the above prediction is only as accurate as the results of the plasma-fluid simulations, specifically (4). There are two criticisms that may be raised against these simulations. First, the various shortcomings in the simulations themselves, e.g., the relative simplicity of the neutral particle transport (analytic prescription), the rather rudimentary treatment of atomic and molecular collisions, the absence of impurities, etc. These were largely remedied by subsequent studies with more advanced treatment of neutrals and impurities [5–8], although machine size scans with the improved treatment of neutrals and impurities are not reported. Second, the fact that the scalings implied by the simulations have not been validated against experimental data from tokamaks.

One would expect these deficiencies to have the biggest impact on the scaling of $Q_{\|t}^{max}$ with n_{eu}, since the presence of neutrals and impurities would enhance divertor radiation and other power losses (charge exchange) roughly as the square of the electron density,

$$P_{rad}^{div} \sim c_Z n_e^2 L_Z(T_e) V_{rad}, \tag{31}$$

where c_Z is the impurity concentration, L_Z is the power loss function and V_{rad} is the radiation volume. Since P_{rad}^{div} would reduce the power flowing to the divertor, and hence should subtract fron P_{sol} in (4), we would expect it to augment the inverse density dependence. Indeed, just such a dependence has been observed experimentally on JET, where $Q_{\|t}^{max}$ was observed to decrease by a factor of 4 for a roughly 30 % change in n_{eu}, yielding a scaling of $Q_{\|t}^{max} \propto n_{eu}^{-\alpha}$ with $\alpha \sim 5$ [13]. This scaling exponent was further refined by detailed modeling of the JET discharges using a multi-fluid plasma transport code EDGE2D, coupled to a Monte-Carlo neutral transport code EIRENE [12]. These results confirm the interpretation proposed above and indicate a mean value of α as ≈ 4.5. Moreover, they provide refined values of the power and heat diffusivity exponents appearing in (4), as follows,

$$Q_{\|t}^{max} \propto n_{eu}^{-\alpha} (P_{sol}/S_{\perp})^{\beta} \chi_{\perp}^{-\gamma}, \tag{32}$$

where the exponents are found in the range,

$$\alpha \approx 4.5, \qquad \beta \approx 3.0 - 3.3, \qquad \gamma \approx 1.5 - 2.0. \tag{33}$$

It is worth noting that the variation in the exponents reflects stronger scalings at higher density. Comparing with (4), we find that the density, power and diffusivity scalings are all more pronounced than in the PHP result: $\alpha \sim 4.5$ vs. 1.82, $\beta \sim 3$ - 3.3 vs 2.37 and $\gamma \sim 1.5$ - 2 vs 1.07. In the β and γ expressions in (33), the first value corresponds to the lower limit and the second to the upper limit. We will use these limits to define the range of predictions for extrapolating to future devices.

Rewriting (4) with α, β and γ as free parameters, we obtain

$$Q_{\|t}^{max} \approx const \times n_{eu}^{-\alpha} (P_{sol}/S_{\perp})^{\beta} \chi_{\perp}^{-\gamma} q^{0.52} R^{0.33}. \tag{34}$$

Repeating the above analysis, (30) is then replaced by

$$\begin{aligned} Q_{\|t}^{max} &\propto (f_{GW}^{sep})^{\gamma-\alpha} f_{LH}^{\beta-0.84\gamma} R^{0.33+\alpha-0.84\beta-0.006\gamma} \\ &\times q^{0.52+\alpha-0.72\beta-1.37\gamma} B_T^{-\alpha+1.52\beta+0.72\gamma} \\ &\times \kappa^{-\alpha+0.69\beta+0.36\gamma} \varepsilon^{-0.06\beta-0.078\gamma} Z_{eff}^{0.28\gamma}. \end{aligned} \tag{35}$$

It is worth noting that the density dependence, measured by α, propagates into all but one term in the above. This can be traced to (25), which introduces the Greenwald density, and with it dependencies on size, field and safety factor. Finally, we write (30) as the peak power load onto the divertor tile, $Q_t^{max} = Q_{\|t}^{max} \sin\theta_{\perp}$, where $\theta_{\perp}$ is the inclination angle between the field line and the tile,

$$\begin{aligned} Q_t^{max} &\approx 2 \left(\frac{\sin\theta_{\perp}}{\sin 3^{\circ}}\right) \left(\frac{f_{GW}^{sep}}{0.5}\right)^{\gamma-\alpha} \left(\frac{f_{LH}}{1.3}\right)^{\beta-0.84\gamma} \left(\frac{R}{2.9}\right)^{0.33+\alpha-0.84\beta-0.006\gamma} \\ &\times \left(\frac{q}{2.7}\right)^{0.52+\alpha-0.72\beta-1.37\gamma} \left(\frac{B_T}{2.5}\right)^{-\alpha+1.52\beta+0.72\gamma} \left(\frac{\kappa}{1.7}\right)^{-\alpha+0.69\beta+0.36\gamma} \\ &\times \left(\frac{\varepsilon}{0.33}\right)^{-0.06\beta-0.078\gamma} \left(\frac{Z_{eff}}{1.7}\right)^{0.28\gamma}, \end{aligned} \tag{36}$$

where Q_t^{max} is in MW/m^2, R in m, B_T in T and the remaining factors are dimensionless. The pre-factor in (36) has been obtained empirically from JET data, and corresponds to a deuterium fuelled discharge [12, 13]; by introducing impurity (nitrogen or neon) seeding, it was possible to reduce the target heat load further by an additional factor of 2, while maintaining Type-I ELMy H-mode level of confinement [12, 13]. However, since a quantitative scaling of the heat load with divertor radiation, supported by multi-fluid modelling, is not available at present, we prefer to benchmark the above results to the deuterium only (unseeded) discharges, and discuss the effect of impurity seeding separately below.

The exponents in (36) can now be evaluated based on the estimated values of α, β and γ, see (33). In the lower limit (as relevant to (33)) this yields

$$\begin{aligned} &a_{GW} = -3, \quad a_{LH} = 1.74, \quad a_R = 2.3, \quad a_q = 0.81, \\ &a_B = 1.14, \quad a_{\kappa} = -1.89, \quad a_{\varepsilon} = -0.3, \quad a_Z = 0.42, \end{aligned}$$

while in the upper limit one finds

$$\begin{aligned} &a_{GW} = -2.5, \quad a_{LH} = 1.62, \quad a_R = 2.05, \quad a_q = -0.1, \\ &a_B = 1.96, \quad a_{\kappa} = -1.5, \quad a_{\varepsilon} = -0.35, \quad a_Z = 0.56, \end{aligned}$$

where a_X denotes the exponent for quantity X.

Armed with these expressions we can now predict the divertor power loads in ITER and DEMO. Assuming that the relative power, as measured by f_{LH}, the elongation, κ, inverse aspect ratio, ε, and the inclination angle $\theta_\perp$, remain constant, while the size, field and safety factor are given by the values in Table 1, then (36) yields,

$$ITER: Q_t^{max} \approx 2\left(\frac{f_{GW}^{sep}}{0.5}\right)^{a_{GW}}\left(\frac{6.3}{2.9}\right)^{a_R}\left(\frac{2}{2.7}\right)^{a_q}\left(\frac{5.3}{2.5}\right)^{a_B}, \quad (37)$$

$$DEMO: Q_t^{max} \approx 2\left(\frac{f_{GW}^{sep}}{0.5}\right)^{a_{GW}}\left(\frac{8.5}{2.9}\right)^{a_R}\left(\frac{2}{2.7}\right)^{a_q}\left(\frac{5.7}{2.5}\right)^{a_B}\left(\frac{3}{1.7}\right)^{a_Z}, \quad (38)$$

In the low and high density limits, i.e., using the exponents from (37) and (37), these two expressions become

$$ITER: Q_t^{max} \approx \left[22\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-3}, 44\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-2.5}\right], \quad (39)$$

$$DEMO: Q_t^{max} \approx \left[60\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-3}, 130\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-2.5}\right], \quad (40)$$

where $[\cdot,\cdot]$ denotes the predicted range of values, and the f_{GW}^{sep} dependence has been retained to allow for additional density increase. It is worth noting that the original expression, (4), yields

$$ITER: Q_t^{max} \approx 20\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-0.73}, \quad DEMO: Q_t^{max} \approx 29\times\left(\frac{f_{GW}^{sep}}{0.5}\right)^{-0.73}, \quad (41)$$

which is generally below the above estimates, especially for DEMO. Since material limits require that Q_t^{max} remain below ~ 10 MW/m^2 for ITER, and likely below $\sim 3-5$ MW/m^2 for DEMO (due to increased neutron load, and hence much larger number of displacements per atom in the target material), we may broadly conclude that the power load would be roughly a factor of $2-4$ above the material limits in ITER, and roughly a factor of $20-40$ above the material limits in DEMO.

There are three principle methods to further reduce the peak target heat load, within the context a conventional divertor design. These can be roughly described as (i) additional gas fuelling, (ii) impurity seeding and (iii) increased divertor closure. We will discuss each of these separately below.

As is evident from the strong dependence of Q_t^{max} on f_{GW}^{sep}, the most direct method of reducing the peak heat load is to further increase the separatrix Greenwald fraction. Based on JET observations under H-mode conditions [14], f_{GW}^{sep} can be increased to values as high as ~ 0.7, which would reduce Q_t^{max} by a factor of $2.4-2.7$. However, it remains to be demonstrated that such an increase of separatrix plasma density is possible without triggering an X-point MARFE, which would degrade the pedestal pressure and energy confinement. Therefore, it is safer to adopt $f_{GW}^{sep} \approx 0.5$ as the upper limit.

As already mentioned, in the JET experiments it was possible to reduce the target heat load further by an additional factor of 2, while maintaining Type-I ELMy H-mode level of confinement, by introducing impurity (nitrogen or neon) seeding. Although multi-fluid simulations involving seeded impurity species are available, their agreement with experiment is not satisfactory to confidently predict the degree of divertor radiation in a future device [12]. A simple estimate may be obtained based on (31) assuming that divertor radiation is concentrated in the vicinity of the X-point, as is observed experimentally, hence $n_e \approx n_{GW}$, $c_Z \approx 0.01, L_Z(T_e) \approx \max(L_Z) \approx 10^{-31} W m^3$, and $V_{rad} = 2 \times 2\pi R(a/10)\lambda_Q FX$, with $FX \approx 10$. Normalizing the result to the JET value one thus finds,

$$P_{rad}^{div} \approx 4(R/2.9)^2 MW \tag{42}$$

compared to $P_{L-H} \sim 8$ MW on JET. Since both powers increase as R^2, and the Greenwald density is roughly constant between JET and DEMO, the divertor radiative fraction is found to scale mainly with the magnetic field,

$$f_{rad}^{div} \equiv P_{rad}^{div}/P_{L-H} \approx 0.5(B_T/2.5)^{-0.8} \tag{43}$$

Thus for ITER and DEMO, one would expect a lower radiative fraction than in JET, provided the divertor closure were kept constant. In that case, one could adopt a downward correction of only $\sim 25\%$ as a proxy for the effect of seeded impurities.

Finally, the JET results have been obtained with a relatively open divertor design, in which the outer strike point was situated on the horizontal (downward sloping) divertor tile. Based on past experiments, including those on JET it was observed that peak heat load can be reduced in more closed divertor configurations (with outer target on vertical targets). As a proxy for this effect we may thus assume a reduction of Q_t^{max} by an additional factor of 2.

Assuming that the above effects do not interfere with each other, e.g., that core and edge radiation can be controlled independently, etc., their impact may be combined by multiplying the reduction factors to yield a net multiplication by a factor of $(1-0.25) \times (1-0.5) = 0.375$. This yields a modified estimate on the range of peak heat loads in ITER and DEMO as

$$ITER : Q_t^{max} \approx [8,16]\, MW/m^2, \quad DEMO : Q_t^{max} \approx [19,49]\, MW/m^2. \tag{44}$$

Based on these predictions we may tentatively conclude that a conventional divertor should be sufficient to handle the inter-ELM power loads in ITER (although the predicted range of values may exceed the material limit of ~ 10 MW/m^2 if the mitigating factors prove less pronounced than assumed above), but is most likely to be inadequate in DEMO, where even the most optimistic predictions are an order of magnitude above the material limit of $\sim 3-5$ MW/m^2.

This finding motivates two urgent actions. First, additional research, both experimental and numerical, into the effects of gas fuelling, impurity seeding and divertor closure. Secondly, further investigation of alternative divertor designs, specifically those involving the expansion of magnetic flux in the divertor volume, again both via theoretical and experimental studies. That such expanded divertors, which increase both $L_{\|}$ and FX, should prove effective at mitigating the peak target heat loads is apparent from the inverse scaling of Q_t^{max} on $q \propto L_{\|}$, e.g., see (30)‡, and in the linear dependance of P_{rad}^{div}, (31) and (42), on the flux expansion, FX.

In addition to Q_t^{max} and λ_Q in the inter-ELM phase, the energy loads on the target and the main chamber wall due to Type-I ELMs are a cause for concern. A simple model based on

‡ Although part of the q dependence relates to Greenwald fraction rather than the parallel connection length

Quantity:	a (m)	n_{GW} (10^{19} m^{-3})	$T_{\rm ped}$ (keV)	ε_t (MJ/m^2)	Q_t^{max} (GW/m^2)
JET	1	8	1.5	0.08	0.4
ITER	2	11.9	4	0.55	2.7
DEMO	3	8.1	6	0.69	3.4

Table 2. Estimated energy load during ELMs for JET, ITER and DEMO, see text.

Quantity:	$L_\parallel$ (m)	$\tau_\parallel$ (μs)	ε_t (MJ/m^2)
JET	40	106	0.04
ITER	87	140	0.39
DEMO	117	155	0.54

Table 3. An alternative estimate of ELM energy loads for JET, ITER and DEMO, see text.

relating the energy losses during an ELM crash to parallel transport from the pedestal plasma to the divertor targets [11, 15, 16] predicts the peak heat load, Q_t^{max}, and peak energy load, ε_t, where $\varepsilon_t = \int_{ELM} Q_t \mathrm{d}t$, in terms of the pedestal pressure, p_{ped}, the sound speed, $c_{s,ped}$ and the ELM crash duration in the pedestal, τ_{ELM}, as

$$\varepsilon_t \approx 0.56 p_{ped} c_{s,ped} \tau_{ELM} \sin\theta_\perp \tag{45}$$

$$Q_t^{max} \approx 0.55 p_{ped} c_{s,ped} \min\{1, \tau_{ELM}/\tau_\parallel\} \sin\theta_\perp \tag{46}$$

which agree between 1-D fluid and kinetic SOL transport codes, and are consistent with observed magnitude of Type-I ELM energy loads on the outer divertor target in JET ($0.02 - 0.08$ MJ/m^2), [17]. Adopting n_{GW} as the pedestal density, (45) and (46) yield the following scalings,

$$\varepsilon_t \propto I_p/a^2 \times T_{ped}^{3/2} \tau_{ELM} sin\theta_\perp, \quad Q_t^{max} \propto I_p/a^2 \times T_{ped}^{3/2} sin\theta_\perp, \tag{47}$$

which are valid for $\tau_{ELM} > \tau_\parallel, \tau_\parallel = L_\parallel / c_{s,ped}$. Based on the observed values on JET, these scaling may be used to estimate ε_t and Q_t^{max} in ITER and DEMO, assuming that $\tau_{ELM} \approx 200$ μs and $\theta_\perp \approx 3^o$ in all three machines. The results are shown in Table 2. Alternatively, because τ_{ELM} is not known, ε_t may be expressed as $\varepsilon_t \propto p_{ped} L_\parallel \sin\theta_\perp$, which implies that $\tau_{ELM} \approx \tau_\parallel$. Assuming $L_\parallel \propto qR$ and hence $L_\parallel \approx 40 \times (R/2.9)$, one finds $\varepsilon_t \propto I_p/a^2 \times T_{ped} qR$ and the estimates for ITER and DEMO shown in Table 3. Both methods predict values of the peak energy loads in ITER and DEMO as ~ 0.5 MJ/m^2, which would result in significant target material damage over tens of thousands of cycles [18]§. This finding motivates further investigation of both passive and active ELM mitigation techniques, as well as continued research into novel plasma facing material science and technology.

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§ Recent electron beam tests on ITER divertor tile prototypes suggest a maximum tolerable energy loads on the Type-I ELM time scales, ~ 1 ms, of only $\sim 0.1 - 0.2$ MJ/m^2 [18].

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