Implications of Small SOL widths on Tolerable ELM Size and ELM Tungsten Sputtering

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To avoid unacceptable melting/erosion of the tungsten divertor plate, the ELM energy reaching the plate on ITER must be reduced by a considerable factor. The reduction factor, presently estimated to be ~ 20, was obtained from several inputs, including: 1) Experiments indicate that the effective SOL width for small ELMs is ~1-1.5 times the *inter-ELM* SOL, and 2) the inter-ELM width for ITER is ~ 5mm.

Recent projections of upstream inter-ELM SOL width for ITER, however, bring it down to the range ~ 1mm. *This vastly reduced SOL width brings down the maximum tolerable ELM size proportionately*- to a value of ~ 1/100 of the unmitigated ELM size.

ELMs of such magnitude should surely be classified as small ELMs, and so the use of the inter-ELM width (from empirical considerations) appears justifiable; it is also theoretically plausible: for such small ELMs, the instantaneous power into the SOL for ITER is only ~ 5 times the inter-ELM value-arguably, in a range so that the dynamics determining inter-ELM SOL width could still pertain. The inter-ELM SOL width is found to be *highly insensitive* to SOL power- so it is reasonable that the SOL width during very small ELMs will be about the same size as the inter-ELM value. Hence we argue that a width of ~ 1mm is consistent for ELMs of order 1/100 the unmitigated value, leading to the conclusion that the maximum tolerable ELM size for ITER is also of that order, based on the consideration of plate melting.

The SOL width of ~ 1 mm is really the upstream width. Downstream physics can increase the SOL width on the target. Such downstream spreading is, however, small in the sheath limited regime which we argue below is precisely the regime that ELMs, even when mitigated to 1/100 (or even significantly less) of the original value, will drive the system to. The onset of this regime implies, in addition to its impact on the SOL width, very serious implications for sputtering of tungsten (or for any material). An investigation of the relevant divertor plasma behavior, is, therefore, strongly indicated.

To keep the heat flux below 10MW/m^2 on ITER for 1mm upstream SOL width, the divertor must operate with a high~90% fraction of radiative dissipation in the *inter- ELM* phase: the corresponding inter-ELM plate temperature will be low ~ 5-10eV, and the density very near the target will be high (a consequence of approximate pressure balance along the field lines). *Such an initial state is quite sensitive to perturbations in the upstream power along a field line:* an increase in upstream power initiates a set of feedback physical mechanisms that will, rather quickly, drive the divertor into the sheath limited regime. Consider what happens on ITER when a very small ELM- say 1/3-1/5 the limit for plate melting- occurs for the duration estimated for an ITER ELM: ~ 500 μs. If this energy is deposited in the SOL as heat rather than particles, *upstream parallel heat flux goes by a factor of at least ~2-3* relative to the inter-ELM value. The following sequence of events is predicted by a recently performed simple 1D divertor simulation: Electrons conduct this power to the target rather quickly; *radiative dissipation does not commensurately increase, so the heat flux <u>reaching the plate</u> increases by over an order of magnitude relative to the inter-ELM value, causing the plasma temperature at the target to increase strongly* (because of the sheath boundary condition); on a ~ 100-200μs timescale the electron plate temperature T_e exceeds 100-200eV. The higher T_e reduces radiation, and also, leads to a parallel pressure imbalance *if* the density at the plate stays the same- the pressure (nT) near the target would be much higher than the pressure even slightly upstream from there. Hence, parallel sonic dynamics expels the plasma density upstream, strongly reduce it at the target (~ 50μs timescale for relevant short spatial scales somewhat near the target). This reduction in target density causes the plate temperature to increase further (again, due to the sheath boundary condition). Feeding on itself, this sequence drives the divertor towards the sheath limited regime over a time of only ~ 200 μs- a time shorter than the ELM duration, and also short compared to the time needed for relatively slow sound waves to transport high density expelled upstream by the ELM the long distance to the target-which will cool the target.

If most of the ELM energy is expelled into the SOL as heat, target temperatures can easily reach or exceed~ ½ keV. At such target temperatures (and commensurately low sheath densities) self-sputtering of W (or any material) can exceed unity, and "avalanche" self-sputtering can ensue. If the ELM primarily expels particles, plate temperatures are far lower. Avalanche sputtering of a high Z material is probably unacceptable for a fusion device- it will ultimately "stabilize" by modifying the sheath, but sputtering will nonetheless increase enormously. Even "ordinary" sputtering by plasma species at several hundred eV might well be unacceptable. Sputtering (or other mechanisms such as unipolar arcs, which are strongly favored by high sheath temperatures) may well set the actual tolerable size of an ELM, rather than plate melting, especially for high Z materials. This likely aspect of ELMs is inadequately investigated. For 1 mm SOL widths, the actual limit on ELMS could be in the range of 1/500 of the unmitigated value, rather the presently used estimate of 1/20.

Acceptability of proposed operating modes and materials for burning plasmas should be reexamined in light of the above. One must also note that the dominant determinants of the peak target temperature in ELMs are not quantitatively well accounted for at present:

1) The amount of ELM energy introduced into the SOL as heat rather than particles for small ELMs, especially very small ELMs
2) The degree to which ELM energy transport to the plate (from electrons *and* ions) exceeds density convection; kinetic effects (especially for ions) are very important
3) Extraordinarily strong sputtering, it's effect on the sheath and impurity re-deposition, and other possible determinants of impurities such as unipolar arcs, etc.

This regime, with strong implications for determining the tolerable ELM level for ITER operation, and also for all tokamak burning plasmas in H-mode, needs urgent examination.

Even in the inter-ELM period, the heat flux into the SOL can vary significantly, since "normal" turbulent transport often has significant variations around the mean value on the time scale of ~ 100μs- particularly for bursty transport found recently. These variations can cause atomic dissipation and sputtering to differ greatly from the values found for constant SOL power- implications for satisfactory divertor operation in this phase are obvious. In particular, it may be necessary to operate with a much higher level of detachment than is presently anticipated, and/or, a low Z divertor material surface may be turn out to be the only viable solution.

High Z impurity issues during transients highlight the urgency of research on advanced divertors, liquid PFCs, and other ways of achieving a low Z PFC surface (e.g. continuous re-coating). It is likely that *any* surface will produce extremely high impurity deposition into the plasma during an ELM – even a mitigated one- in a burning plasma scale of device. However, the core plasma sensitivity to Li is ~10^3 lower than for W. Analysis also indicates that advanced divertors (e.g., it appears the X-divertor can be implemented on ITER without hardware changes) can ameliorate the issues above for low Z targets more effectively than for high Z targets.