Combined high fluence and high cycle number transient loading of ITER-like monoblocks in Magnum-PSI

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Peak ELM energy fluence during the half-field half-current and full-field full-current phases of ITER is extrapolated to be in the range $\varepsilon_{\parallel} \sim 2.5\text{-}7.5$ MJ m^{-2} and 10-30 MJ m^{-2}, respectively [1]. Mitigation of ELM-loading to lower values ($\varepsilon_{\parallel} < 5$ MJ m^{-2}) is therefore essential to avoid full surface melting of the tungsten plasma-facing material (PFM) [1]. However, e-beam measurements have found that cyclical ELM-like loading at much lower energies can lead to cracking via plastic deformation leading to fatigue-like behaviour [2]. It should be noted that plasma loading typically modifies most strongly only the very near surface region consisting of the top few microns of material. However, this is the same region which is most strongly affected by short transient loading as the heat penetration depth is typically in the 10's of μm range. Therefore synergy between plasma and ELM-like loading has been previously observed (e.g. [3]). However, until now high plasma fluence and high cycle numbers have not been combined during ITER-monoblock loading, while a definition of the tolerable power level for ELM-loading under these conditions is of critical importance for predictions of safe ITER service conditions and PFM lifetime.

A mockup consisting of five ITER-grade and dimensioned monoblocks mounted on a CuCrZr pipe was exposed in Magnum-PSI [4] to combined hydrogen plasma with superimposed transient loading using a high power welding laser. The blocks received a hydrogen fluence of between $1.1\text{-}2.9\times10^{29}$ m^{-2} ($T_e \approx 1.3$ eV, $n_e \approx 5\times10^{20}$ m^{-3}) at a base temperature of 750-790 °C, while 1 ms laser pulses with heat flux factor (HFF) of 2.3-11.2 MW m^{-2} s$^{0.5}$ were superimposed during the plasma exposure. Up to 10^6 pulses were applied. The surfaces were examined using SEM and CLSM. For the lowest applied HFF no surface modifications were observed, but for higher loading conditions a crack network extending across the laser spot region was created. The crack edges were smoothed by the plasma exposure, preventing small melt regions from forming, unlike for e-beam loading [2]. For the exposure at 5.5 MW m^{-2} s$^{0.5}$ a large crack extending beyond the laser loaded region also appeared. Given that ITER may experience millions of ELMs, the results suggest that fast transients need to be mitigated to at least below $\varepsilon_{\parallel} \sim 1.7$ MJ m^{-2} in ITER ($f_{ELM}^{uncontrolled}/f_{ELM}^{controlled} \sim 18$) to avoid comprehensive surface crack networks forming, similar to the limits determined for e-beam loading [2, 5], which should be achievable with pellet pacing or RMPs. Whether this is an operational limit that would ultimately lead to component failure is not yet clear however, while effects of laser spot size, impurities and ELM particle flux and energies should be included in future investigations.

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