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Modelling of runaway electron –induced PFC damage

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The potential of localized heat loads under disruptions to cause considerable melting of plasma-facing components (PFC) has been extensively investigated. Two distinctive regimes exist, which lead to different types of PFC damage and necessitate different modelling approaches; surface loading and volumetric loading.
Surface heating is caused by electrons and ions with energies in the keV range with depth ranges of the order of a few nm. Dedicated EUROfusion and ITPA coordinated experimental activities have provided a wealth of empirical data on PFC melting induced by transient surface loads, which have guided the development of physics models that enable high-fidelity simulations. This led to the reduction of the incompressible resistive thermoelectric MHD description under the magnetostatic shallow water approximation. Coupling with heat transfer including phase transitions supplemented with free interface boundary conditions, as implemented in the MEMENTO code, yields a very accurate description of melt dynamics and deformation. Successful validation against multiple tokamak experiments has lent confidence in the predictive power of such tools.
Volumetric heating is caused by electrons with relativistic energies far into the MeV range with depth ranges of the order of mm even inside high-Z metals like W. Runaway electrons (REs) constitute the final frontier in the context of PFC damage. RE incidence can lead to deep melting beyond the shallow water approximation, induce material explosions driven by uneven thermal expansion and cause loss-of-coolant accidents due to heat deposition close to the cooling pipe. Unique evidence of explosive RE-PFC interaction accompanied by the expulsion of fast solid debris have been obtained in FTU (accidental, TZM) and DIII-D (deliberate, graphite). Extensive RE-induced damage has also been reported in JET, WEST and COMPASS.
RE velocity distributions at the PFC surface constitute the initial conditions for Monte-Carlo (MC) modelling of electron transport inside metals to obtain volumetric heat maps. Determination of the heat map gradients comprises an essential part of the work-flow, since these control how the internal thermal stresses build-up and whether explosive detachment will occur. However, these are highly sensitive not only to the RE energies but also to their impact angles. The depth range refers to normal incidence and is thus indicative of energy loss along the path, which lies just beneath the surface at grazing incidence. The magnetic field presence, the large PFC area / wetted area and need for large particle statistics, makes the MC simulations costly. The situation is also complex regarding the PFC response, since pure thermal or even linear thermoelastic modelling does not suffice for ductile metals with stable liquid phase like W. Finally, high power densities (grazing incidence and fast ms deposition within a thin surface layer) yield temperatures in excess of 10000K at which thermophysical W properties are unknown.
A complete work-flow will be presented that has been developed to model the thermal response of ITER W first wall panels under RE impacts. The results on short (relevant for PFC damage) and long (relevant for coolant failure) temporal scales will be critically assessed.

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