# A Validated Multi-Physics Modeling Approach to Predicting Erosion, Re-deposition and Gas Retention in Fusion Tokamak Divertors

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Plasma-surface interactions (PSI) span diverse physical processes and decades of time and length scales (ps–s and Å–m). Here, we present an experimentally validated, integrated suite of models to capture the multi-physics nature of interactions between the edge plasma and the divertor surfaces in a fusion tokamak. This workflow includes the description of the edge plasma in steady-state conditions (SOLPS), the effect of the sheath at shallow magnetic angles (hPIC), the migration of impurities eroded from the divertor surface (GITR) and the response of the divertor surface to these plasma conditions (coupled F-TRIDYN and Xolotl). We benchmark this workflow against dedicated PISCES experiments, which measured mass loss, spectroscopy and gas concentration profiles for W substrates exposed to mixed (D-He) plasmas, in addition to recent helium plasma exposure in the tokamak environment of WEST. The positive initial comparison gives confidence to predicting impurity migration, changes in surface morphology and gas recycling in the ITER divertor, under conditions expected for helium and burning-plasma operations (BPO).

SOLPS predicts standard strongly radiating, partially-detached plasmas in the divertor for both ITER scenarios. Although our model indicates that much of the impact energy-angle distributions (IEAD) of light ions are below the energy threshold for W sputtering, the high-energy tails extend well above this threshold, leading to net erosion across the outboard divertor target under He operation, despite strong W re-deposition (predicted by GITR). In contrast, Xolotl predicts that the balance between erosion/re-deposition of W and swelling driven by He implantation, results in surface recession far from strike point, but growth near it (R-Rsep~0–0.15m). Under burning plasma conditions, Ne is the main radiative species and main contributor to wall erosion. Over 90% of the eroded W locally re-deposits, which produces net deposition where the plasma temperature is low (R~Rsep<0.15m) and net erosion where the plasma temperature is high (R-Rsep>0.2m). The depth profiles of gases implanted in the W divertor are not strongly impacted by dilute impurities. However, heat fluxes greatly affect the sub-surface D and T profiles, as increases in substrate temperature (of up to 175K at the peak heat flux location) during steady-state operation lead to faster gas diffusion, resulting in higher outgassing and permeation into the bulk. We also evaluated the influence of pre-exposure of the W substrate to He plasma (from the He-operation) on the tungsten divertor response to burning plasma operation. In this case, the higher concentration of He and vacancy clusters near the surface locally increase the D and T concentration (relative to an initial crystalline W) and reduce the permeation of hydrogenic species, consistent with findings in the PISCES experiments.