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A 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 as well as many decades of time and length scales (ps–s and Å–m). Correspondingly, comprehensive modeling of PSI must accurately target each scale and mechanism. Here, we present an integrated model designed to capture the multi-physics nature of interactions between the edge plasma and the divertor surfaces in a fusion tokamak. This workflow includes SOLPS simulations of the edge plasma in steady-state conditions; the effect of the sheath at shallow magnetic angles, evaluated by hPIC; GITR calculations of migration and re-deposition of impurities eroded from the divertor surface; and the divertor response to these plasma conditions, which includes evaluating surface growth and erosion, as well as sub-surface gas dynamics, modeled by coupling 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. Given the positive comparison, we apply the model to predicting impurity migration and re-deposition, surface growth and erosion, and gas recycling in the ITER divertor, under conditions expected for helium and burning-plasma operations.

SOLPS predicts standard strongly radiating, partially-detached edge plasma in the divertor for both ITER scenarios. Our model shows that during He plasma discharge much of the impact energy-angle distributions are below the energy threshold for W sputtering. However, the high-energy tails of He+ and He2+ extend well above this threshold, leading to net erosion across the outboard divertor target, and despite the strong W re-deposition predicted by GITR. Xolotl predicts that the surface position reflects the balance between this erosion/re-deposition of W, and swelling driven by He implantation, resulting in surface recession far from strike point, but growth near it (R-Rsep~0–0.15m). He retention is largest where plasma temperature is high due to deeper gas implantation, even though the flux is ~10x less than its peak value. 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, and produces net deposition where the plasma temperature is low (R~Rsep<0.15m), and to 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, at least over 10 second operating times. However, heat fluxes greatly affect the sub-surface D and T profiles, as increases in substrate temperature (from 343K to 525K at the peak heat flux location) during steady-state operation lead to faster gas diffusion, both into the bulk and outgassing. We also demonstrate our integrated PSI modeling capability by evaluating the influence of pre-exposure of the W substrate to He plasma (e.g., 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.

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