Plasma/Liquid-Metal Interactions during Tokamak Operation

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One of the critical technological challenges of future tokamak fusion devices is the ability for plasma-facing components to handle both normal and abnormal plasma/surface interaction events that compromise their lifetime and operation of the machine.

During normal operation of H-mode, edge-localized modes (ELMs) are a serious concern for divertor and nearby plasma-facing components (PFCs). During ELMs part of the total plasma energy is released and deposited on the divertor surface during 0.1 to 1.0 ms with a frequency of between 1 to 20 Hz, depending on the ELM type. The power from the scrape-off-layer (SOL) to the PFC in ITER-like devices can then increase from 5 MW/m^2 to ≈ 300-3000 MW/m^2. Erosion lifetime strongly depends on ELM power deposited on PFC. Moreover, the resulting evaporated material can reach the core and disrupt the plasma. In addition, with higher ELM frequency, thermal cycling takes place and can result in thermal stresses and fatigue. At high ELM power, the resulting high surface temperature causes vapor cloud formation with similar consequences to disruptions. Vapor shielding decreases energy deposition at the surface but increases radiation flux to nearby components. Metallic PFC can melt and liquid metal flow instabilities occur with mass losses due to both MHD splashing effects and vaporization. A comprehensive two-fluid model is developed to integrate Core and SOL parameters during ELMs with PFC surface evolution using HEIGHTS package.

In addition to thermal erosion due to ELMs, physical erosion (i.e., sputtering) can also be enhanced. The significant increase in particle flux to the divertor and nearby PFCs can enhance sputtering erosion by an order of magnitude or more. Advanced designs of first wall and divertor systems propose the application of liquid-metals as an alternate PFC to contend with high-heat flux constraints of large-scale tokamak devices. Liquid-metals considered include: lithium, tin, gallium, flibe, and tin-lithium. However, replenishable liquid surfaces also have concerns. Enhanced liquid erosion with temperature and with incident particle energy has been measured for most of these candidate PFC materials. Monte Carlo and Molecular Dynamic methods along with experimental data are used to calculate the enhanced erosion rates.

Initial results indicate that high-power ELMs in ITER-like machines can cause serious damage to PFCs, may terminate plasma in disruptions, and because of large contamination may affect subsequent plasma operations. Erosion lifetime and plasma contamination for solid and liquid PFCs are studied in ITER-like devices.