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Implications of net erosion and redeposition of solid-surface plasma facing material in long-pulse fusion devices

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It is estimated that long-pulse fusion devices may experience rates of net erosion and deposition of solid PFC (Plasma Facing Component) material of 10ˆ3 –10ˆ5 kg/year, whatever the material used [1]. Even if the net erosion (wear) problem can be solved, the redeposition of so much material has the potential for major interference with operation, including disruptions due to so-called 'UFOs'and unsafe dust levels. The potential implications appear to be no less serious than for plasma contact with the divertor target, i.e., a dust explosion or major UFO-disruption could be as damaging for an actively-cooled DT tokamak as target failure. Therefore, it is necessary to manage material deposits to reduce operational risk. This situation appears to require a fundamental paradigm shift regarding meeting the challenge of taming the plasma-material interface; in that any acceptable solid PFC material will in effect be flow-through, like liquid-metal PFCs, although at far lower mass flow rates. Solid PFC material will have to be treated as a consumable like car brake pads. The implications for such a paradigm shift and near-term research needs will be discussed.
The management of eroded material migrating within fusion devices is a well-known issue. A critical open issue is the formation of large/thick redeposited material in the divertor region, colloquially called slag. The stability of the slag layers can lead to the aforementioned 'UFOs'and/or dust. In JET-ILW and ITER, the use of a high-Z (tungsten) armor on the divertor targets and low-Z (beryllium) on the main walls presents unique challenges with regards to both slag formation and its stability. Furthermore, future reactors like the US ARIES-AT reactor design calls for a similar arrangement, but with SiC cladding of the main walls. Non-metallic low-Z refractory materials such as ceramics (graphite, SiC, etc.) used as in situ replenishable, relatively thin (of order mm's) claddings on a substrate which is resistant to neutron damage could provide a potential solution for the main walls, while reducing risk of degrading the confined plasma. In situ removal of these layers, both metallic and non-metallic, e.g., using strike-point sweeping and/or chemical 'scavenger'methods, requires increased research since understanding and predictive capability for the formation and stability of these thick layers is almost completely lacking.
Separately, wall conditioning has proven essential for achieving high performance. For long-pulse fusion devices, standard methods appear unworkable, but recently powder droppers injecting low-Z material ˜continuously into discharges have been quite effective and may be usable in long-pulse devices as well. The resulting massive generation of low-Z debris, however, has the same potential to seriously disrupt operation as noted above. Powder droppers also provide a unique opportunity to carry out controlled studies on the management of low-Z slag in all current magnetic confinement devices, independent of whether their protection tiles use low-Z or high-Z material.
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[1] P.C. Stangeby, E.A. Unterberg, et al. (2022) Plasma Phys. Control. Fusion, Part A: 64 055018 & Part B: 64 055003.

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