Topic: OV

Raising fusion readiness by addressing plasma-material interactions and fusion nuclear science with linear plasma devices, an overview.

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As we enter the era of fusion energy production first wall and divertor plasma facing components will experience unprecedented loads. Most notably the exposure of materials by fusion neutrons and high energy ions at high fluxes and fluence will lead to expected material damage far beyond that of today's experimental conditions. In general, one can distinguish the near-surface damage and the bulk material damage. The evolving surface due to erosion/redeposition has been a research topic over many decades. Near-surface damage due to high fluxes of hydrogen and helium has gotten attention in the last 15 years. The interaction of hydrogen and helium with tungsten is now in focus as most fusion reactor designs have pivoted to this plasma facing material. It has been found that in certain operational conditions high fluxes of hydrogen and helium can alter the surface morphology. Hydrogen implantation can generate blisters in the near surface due to gas accumulation at low surface temperatures. Helium was found to lead to nano-bubble formation in tungsten plasma facing materials, which can lead to nano-tendril growth (so-called W-fuzz). This work was pioneered on NAGDIS. Accumulation of helium bubbles in the subsurface has also been found to reduce the thermal conductivity potentially impacting the temperature operation window of a plasma facing component, at least for transient load conditions. Defect production caused by these fluxes during plasma-material interactions (PMI) in the near-surface region will induce stresses and produce stress-induced vacancies, which can then migrate deeper into the material bulk and act as trap sites for gas atoms, driving material degradation and leading to large scale erosion processes. Neutrons create further defect production by energetic particle-induced displacement damage cascades, He production, and transmutation in the near surface region and in the bulk of the Plasma Facing Material (PFM). Study of the combined effects of neutron irradiation damage with PMI is an emerging scientific focus. The diffusion, trapping/de-trapping of dissolved gas atoms within the complex of defects, and migration, merging, and annihilation of vacancies, voids, and larger defects, remains unclear. These combined effects will change the tritium retention and the thermal conductivity and will lead to embrittlement and enhanced erosion that needs to be quantified. Both regions, the near surface region and the bulk of the PFM, are connected and transport of heat, particles and defects created by irradiation will determine the ultimate plasma facing component performance. Recreating experimental conditions that capture this science is challenging as simultaneous plasma exposures with high neutron flux/fluence are only possible in a burning plasma experiment. Most of todays' confinement facilities do not produce fusion neutrons in any appreciable amount nor do they operate in a duty-cycle allowing for high fluence exposures. However, linear plasma devices can expose materials at high ion fluxes in steady state. That still leaves the effect of fusion neutron damage, which is being investigated in several ways. The most common approach is to irradiate materials with high-energy ions, creating high displacement damage in the near surface region (1-5microns). The material samples are then subsequently exposed to high flux plasmas. Almost all data on the effect of irradiation damage on hydrogen retention were obtained this way. Recently, limited data on the effect of neutron irradiation on hydrogen retention were obtained in TPE where material samples were irradiated previously in a fission reactor, the High Flux Isotope Reactor at ORNL. Experimental capabilities are being increased significantly in this area. UPP at DIFFER and POSEIDON at UCSD, two linear plasma devices, which are currently being commissioned, will address the simultaneous irradiation damage by high-energy ions and plasma exposure to answer research questions related to the synergistic effects of displacement damage by neutrons (here high-energy ions as proxy) and plasma exposure. JULE-PSI at Juelich and MPEX at ORNL, two devices in construction, will address research questions related to the interaction of plasmas with neutron damaged PFMs. Both newbuilds are key elements of the EUROFusion program and the US DOE Fusion Energy Science program respectively. Dedicated experimental campaigns are planned to elucidate the effects of simultaneous vs sequential irradiation damage/plasma exposure, as well as surface versus bulk effects. Diagnostic suites on the various devices will be introduced and discussed. Linear plasma devices are increasingly being equipped with in-situ/in-operando diagnostics to capture the fast-changing PMI effects as well as in-vacuo diagnostics to avoid surface chemical modifications and allow for the characterization of surface morphology changes with electron microscopy. By addressing the PMI in conjunction with irradiation damage on the various linear plasma devices a holistic picture should emerge spanning the multi-scale physics over time and space.

This contribution provides an overview of the recent experimental results from high-flux Linear plasma devices Magnum-PSI, NAGDIS, GAMMA10, TPE and PSI-II and it will be shown how these findings address urgent ITER R&D needs. This includes the influence of plasma entrainment of W erosion and re-deposition, more detailed investigations on W-fuzz growth during W co-deposition and simultaneous exposure to Ne, Ar and N and detachment physics in general. In addition, initial results from the linear devices UPP and POSEIDON are expected to provide insights into the synergistic effects of PMI and irradiation damage by high-energy ions. At UPP, initial results comparing neutron-irradiated and ion-irradiated tungsten which were exposed to ITER-relevant D plasma flux, show significantly different D transport as determined via operando Nuclear Reaction Analysis. The status of the devices in construction, JULE-PSI and MPEX, will also be discussed. MPEX is a major component of the US DOE FES program poised to close science gaps identified by the US community. Both devices will continue the experimental work pioneered by TPE and address how bulk damage of Plasma Facing Components (PFCs) by neutrons impacts PMI and ultimately affecting the PFC performance and lifetime. MPEX aims for first plasma in 2026, and JULE-PSI is slated to be operational in the hot-cell by 2028. MPEX has entered the assembly phase. A status of the construction, including the manufacturing and testing of the superconducting magnets, the status of the various plasma production and heating systems, the vacuum system, the target handing and surface analysis station will be described.