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The U.S. approach to address plasma-material interactions and fusion nuclear science with linear plasma devices

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A fusion power plant will produce heat, particle, and neutron fluxes that significantly exceed those in present confinement facilities. These loads will alter the plasma facing materials and components significantly impacting reactor lifetime, performance and safety. Most of these challenges can be addressed with cost effective linear plasma device experiments. The existing devices PISCES and TPE have already addressed many PMI issues in support of ITER with their capabilities to investigate tritium retention issues due to co-deposition with beryllium or tritium permeation through radiation damaged solids. Entering the era of fusion nuclear science, investigations on PISCES and TPE address the effects of irradiation damage (by fission neutrons or high energy ions) of solids on hydrogenic retention. Experiments on PISCES have shown that apriori irradiation damaged ITER-grade W can increase the hydrogen retention significantly for low irradiation temperatures (~300 K). For more fusion relevant temperatures (~1300 K) the hydrogenic retention drops to negligible levels. Neutron irradiations of tungsten samples have been carried out on HFIR at ORNL as part of the PHENIX and FRONTIER U.S./Japan bilateral collaboration programs. Several irradiation campaigns were carried out to distinguish the effects of the neutron irradiation spectrum on the hydrogenic retention in W, since the enhanced transmutation rate with thermal neutrons leads to a significant increase of Re and Os concentrations in W. For this purpose, neutron irradiations of W in Gd-shielded irradiation capsules, are compared to neutron irradiations of W in unshielded irradiation capsules. Irradiations up to 0.5 dpa were carried out at three different temperatures between 600 K and 1100 K. Subsequently, the irradiated W samples were exposed to deuterium plasmas in TPE up to a fluence of 5.0 × 1e25 m^−2 at three different exposure temperatures, closely matching the irradiation temperatures [3]. Hydrogenic retention of up to 1.9 × 1e21 m^−2 and near-surface D concentrations up to 1.7 × 1e−3 D/W were measured for the 0.1 dpa unshielded irradiated W samples. For the thermal neutron shielded irradiation campaign, W samples were irradiated at three slightly higher irradiation temperatures (773, 1073, and 1373K) to radiation damage level of approximately 0.5 dpa. Tritium permeation and retention in thermal neutron–shielded tungsten is currently being investigated with TPE and will be reported.

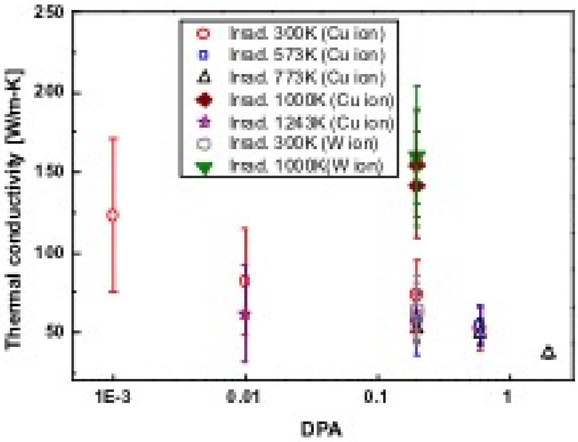

Figure 1: Thermal conductivity vs damage level (dpa) for various substrate temperatures

Interestingly, experiments on PISCES with ion-beam damaged samples show a marked reduction in thermal conductivity for 0.1-1 dpa damage levels, at low irradiation temperatures (fig.1). However, for higher irradiation temperature the thermal conductivity is unchanged, suggesting that in the absence of any synergistic plasma/ion-beam effects, annealing could overcome damage. However, it is known that the presence of a sufficiently high gas atom (H, D or He) population within materials undergoing displacement damage can have a profound effect on defect evolution and annihilation. Thus, it is essential to carry out simultaneous plasma

& energetic ion-beam irradiation to understand synergistic effects. A proposed PISCES-RF device upgrade would address that need by incorporating emerging in-situ, real-time PMI diagnostics with a high-power helicon plasma source that is coupled to a high energy ion beam.

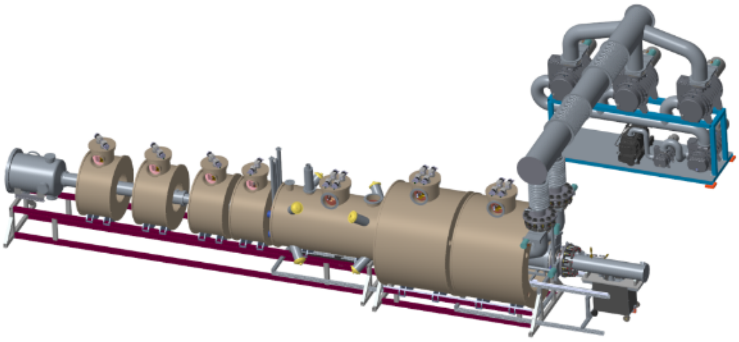

Figure 2: Conceptual design of MPEX

In addition, the U.S. is building a new linear plasma device, the Material Plasma Exposure eXperiment (MPEX) with significantly increased capabilities (fig.2). Its concept does foresee the capability to expose apriori-neutron irradiated material samples to fusion reactor grade divertor plasmas in steady-state to high fluence. The novel plasma source and heating concept of MPEX combines a high-power helicon plasma source with microwave electron heating and ion cyclotron resonance heating, which should allow to produce plasmas in front of the target with plasma densities of up to 1e20 m-3, electron and ion temperatures of up to 15 eV independently controlled and parallel heat fluxes of up to 40 MW/m2. This source and heating concept has been tested on the Prototype-Material Plasma Exposure eXperiment (Proto-MPEX). With 170 kW helicon power a plasma density of 1.8 x 1e20 m-3 was achieved. Electron heating was pursued with a 28 GHz gyrotron. Maximum electron temperatures of 21 eV have been achieved under those overdense plasma conditions with 50 kW Electron Bernstein Wave (EBW) heating. This is almost the electron temperature required for MPEX (25-30 eV). Ion heating of up to 16 eV was performed with 30 kW ion cyclotron heating (ICH) in the frequency range of 6 –7.5 MHz. The ion fluxes to the target were in excess of 1 x 1e24 m-2s-1. The experiments on Proto-MPEX provided the physics basis for MPEX by defining the requirements for the helicon, EC and IC heating powers, the requirements for the EC and ICH frequencies, the requirements of the magnetic field profile and the requirements of the vacuum and pumping systems. Based on the derived physics basis from Proto-MPEX the conceptual design of MPEX was completed and will be presented. This includes the conceptual design of the source and heating concept, the super-conducting magnet system, the vacuum system, the diagnostic system as well I&C needs.

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