*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-5.204 (2009)*

Hydrogenic retention of high-Z refractory metals exposed to ITER divertor relevant plasma conditions

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1. Introduction

Numerous laboratory studies have confirmed low hydrogenic retention in tungsten (W) [1-3] and molybdenum (Mo) [4,5]. From this it has been assumed that W and Mo have an advantage over carbon-based materials (i.e. graphite, CFCs) with respect to trapped fuel inventory in fusion applications. However, it should be noted that these laboratory studies are performed at ion flux densities orders of magnitude lower than what is measured in current tokamaks and what is expected in ITER.

Recent studies have identified a mechanism for trap production in refractory metals that may be linked to high plasma flux densities. It has been postulated that exposure of refractory metals (W and Mo) to a high flux of low energy (≤200 eV) ions leads to a build-up of stresses in the material lattice due to the low hydrogenic solubility of these metals [3]. These stresses are relieved through deformation of the lattice and the creation of vacancies, dislocations or voids, which then represent hydrogen trapping sites. There are indications that this trap production mechanism is dependent on the incident ion flux density [3], but the relationship and how it extrapolates to ITER-relevant flux densities is not clear. The purpose of this study is to expose W and Mo targets to high plasma flux densities ($\sim 10^{24}$ $m^{-2}s^{-1}$) to determine the impact on hydrogenic retention.

2. Experiment

W and Mo targets were exposed to ITER divertor-relevant deuterium plasmas in the linear plasma device Pilot-PSI. The cascaded arc plasma source used in Pilot-PSI produces high plasma densities ($\leq 10^{21}$ m^{-3}) at low electron temperatures ($T_e \leq 5$ eV) [6]. The plasma is magnetically confined with an axial B-field to a narrow column (~15 mm diameter) with the highest densities and temperatures located at the center of the column. The plasma electron density and temperatures are measured with Thomson scattering [7] (see Fig. 1a-b).

The W and Mo targets are mechanically clamped to an actively-cooled copper heat sink. The surface temperature was measured with a near-IR (900-1700 nm) multi-wavelength spectropyrometer. 1-D surface temperature profiles can be seen for W and Mo in figure 1c. The lower temperatures for the Mo exposures are due to improved thermal contact between the Mo target and the heat sink with the use of grafoil as an interface layer.

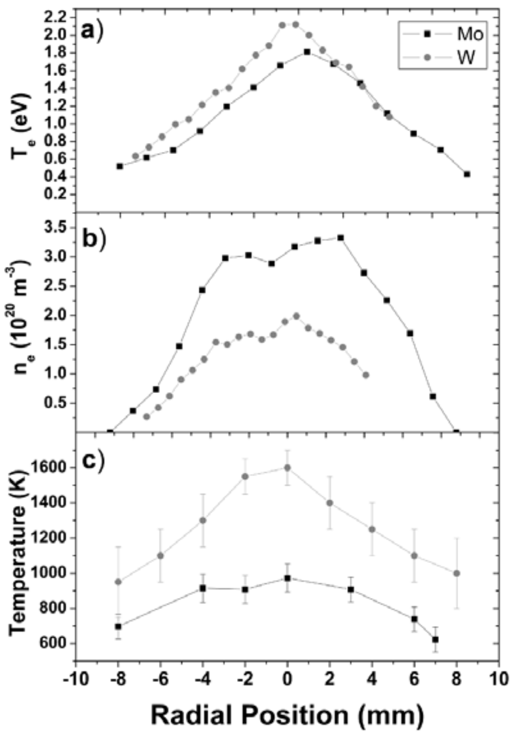

Fig. 1: a) Electron temperature and b) electron density from a typical Thomson scattering for the Pilot-PSI plasma column. c) The surface temperature of the W and Mo targets as a function of radial position.

All targets are disks of 20 mm diameter (16 mm diameter exposed area) and 1 mm thickness. All targets are exposed in the "as received" condition (i.e. rough surface, unannealed) and were electrically grounded during plasma exposure. The hydrogenic retention at various radial locations on the exposed surface was determined with ex-situ ion beam analysis using the d(^{3}He,p)α nuclear reaction. The global hydrogenic retention is determined by thermal desorption spectroscopy (TDS).

3. Results and Discussion

The nuclear reaction analysis (NRA) technique has the advantage of measuring the local concentration of D within the beam spot (~1 mm diameter) but only to the depth of the ^{3}He ion range. The NRA results were taken from various points on the target surface and each point corresponds to a different set of plasma parameters and surface temperature (see Fig. 1).

In Fig. 2a, a 2-D NRA scan of a W target with 80 s plasma exposure shows that the D retention increases with radial distance from the center in all directions. Target surface temperature appears to be causing the difference in retention at these locations. At the center point the surface temperature is ~1600 K and at 8 mm off-center the temperature is ~1000 K (see Fig. 1). At 8 mm off-center the molybdenum clamping ring overlaps with the target, so shadowing effects could be playing a role in the low retention seen at some 8 mm points. It is well known that surface temperature plays a role in the hydrogenic retention properties [1,2], thus it is likely that the lower surface temperatures in the off-center regions are responsible for the higher D retention measured there despite this being a region of lower plasma flux and fluence.

In Fig. 2b, a 2-D NRA scan of the Mo target with 80 s of plasma exposure shows a much more even distribution of D across the Mo surface as compared to W. This is likely due to the flatter, and generally lower, surface temperature profile of the Mo targets during plasma exposure (see Fig. 1c). Data from literature [5,8] also indicate that the dependence of hydrogenic retention rates on surface temperature is weaker at temperatures in the range of 700-1000 K. The lower surface temperatures for the Mo plasma exposures also leads to overall larger D retention in the Mo targets. The retention in the Mo targets is typically a factor of 4-5 higher than measured with the W targets.

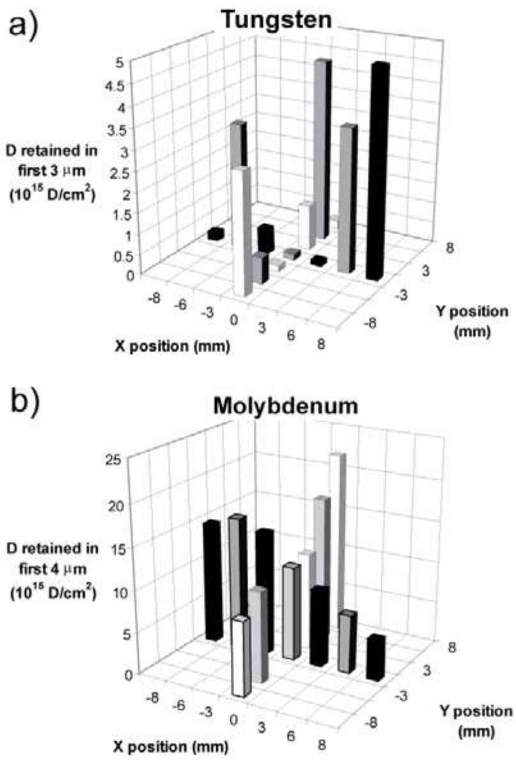

Fig. 2: 2-D NRA scan of D retention in a) W, and b) Mo exposed to 80 s of plasma.

All indications are that surface temperature is the dominating factor in determining retention rates for these conditions. Despite varying plasma flux densities and fluences, the retention rates seem to most closely follow surface temperature. This is seen clearly in Fig. 3 where the retained fraction ($D_{retained}/D^{+}_{incident}$) is plotted as a function of temperature for the data points from Fig. 2. Despite a wide range of plasma flux densities and fluences being plotted, the retention exponentially decays as a function of temperature for both W and Mo. There is also overlap between the two data sets suggesting the retention properties for these two materials are very similar under these exposure conditions.

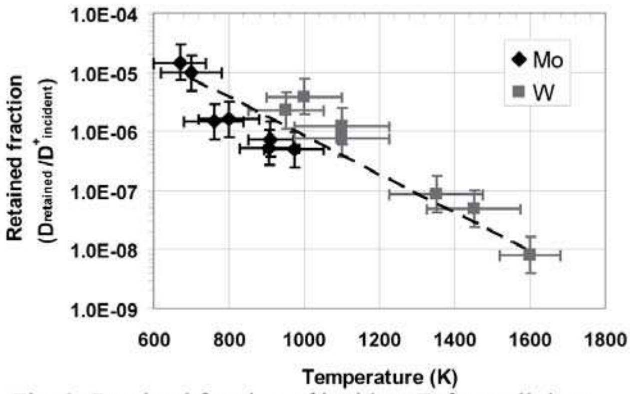

Fig. 3: Retained fraction of incident D from all data points in Fig. 2. Dashed line is exponential fit.

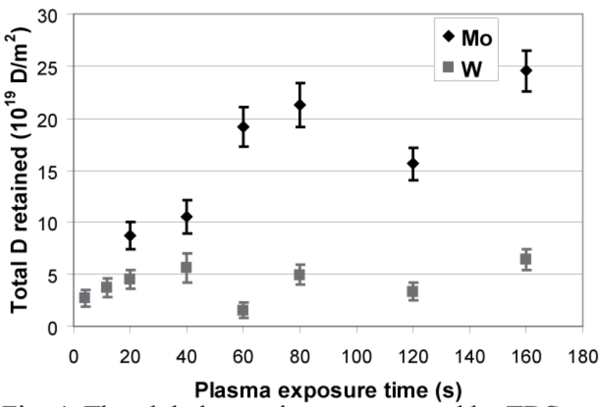

Fig. 4: The global retention as measured by TDS as a function of plasma exposure time for W and Mo.

Thermal desorption spectroscopy has the advantage of detecting all trapped D from the bulk and surface of the target. Unfortunately, it desorbs from all locations on the surface simultaneously meaning the spatial origin of the desorbed D atoms are not known. Fig. 4 shows the total retained D in the W and Mo targets as a function of plasma exposure time. The incident fluence can calculated based on an integration of the local flux density as determined by the Thomson scattering profiles (Figure 1a-b).

The TDS results show the D retention in W has no apparent dependence on the incident plasma fluence as seen by the scatter in measured retention values in figure 4. The total D content in the Mo targets are a factor of ~2-5 greater than the W targets, which is in agreement with the NRA data. D retention in Mo increases with fluence but shows indications of saturation at higher plasma fluences. At the high surface temperatures in this study, the D retention in both W and Mo quickly comes to a saturation or equilibrium level at low levels ($<2.5 \times 10^{20}$ D/m^2).

4. Conclusions

W and Mo targets have been exposed in the Pilot-PSI experiment to the plasma conditions expected at the strike point of a detached ITER divertor. The main indication from these results is that W and Mo targets retain very little D when compared to the amount of D incident to the surface ($D_{retained}/D_{incident} \sim 10^{-8}$-$10^{-5}$). The amount of D retained depends most strongly on surface temperature during plasma exposure. There is no clear dependence of D retention on plasma flux density or plasma fluence. It is likely the high surface temperatures have mitigated any build-up of lateral stresses in the material due to super-saturation of the lattice. It is concluded that at these temperatures, D retention in W and Mo comes to equilibrium at acceptably low levels. It is important to note there are many other factors to consider for extrapolation of hydrogenic retention to ITER or a reactor environment (e.g. neutron irradiation, mixed-materials, He impurities, etc.).

6. References

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