Investigation of He-W interactions using DiMES on DIII-D

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Abstract

Tungsten button samples were exposed to He ELMing H-mode plasma in DIII-D using 2.3 MW of Electron Cyclotron heating power. Prior to the exposures, the W buttons were exposed to either He, or D, plasma in PISCES-A for 2000 seconds at surface temperatures of 225–850 °C to create a variety of surfaces (surface blisters, subsurface nano-bubbles, fuzz). Erosion was spectroscopically measured from each DiMES sample, with the exception of the fuzzy W samples which showed almost undetectable WI emission. Post-exposure grazing incidence small angle x-ray scattering (GISAXS) surface analysis showed the formation of 1.5 nm diameter He bubbles in the surface of W buttons after only a single DIII-D (3 sec., ~150 ELMs) discharge, similar to the bubble layer resulting from the 2000 sec. exposure in PISCES-A. No surface roughening, or damage, was detected on the samples after approximately 600 ELMs with energy density between 0.04 – 0.1 MJm^{-2}.

1. Introduction

In a D-T burning plasma environment, helium will be produced as a byproduct of the nuclear fusion event. This helium 'ash' will be transported into the divertor plasma where it will need to be pumped away in order to limit its accumulation in, and dilution of, the core plasma. By definition, this implies He interactions with the divertor target plate material. In both ITER and most DEMO designs, the divertor plate material is tungsten.

The interaction of helium and tungsten has been the subject of extensive investigation, both experimental and theoretical [1 and references therein]. Even though tungsten is used as the divertor material in several confinement devices [2, 3], most of the experimental He-W material investigations have been conducted in non-confinement devices (i.e. linear plasma devices, ion

beam irradiation facilities, etc.), where it is simpler to remove and examine samples after plasma exposure. Although the DIII-D confinement device [4] employs primarily graphite as its plasma facing material, it is also equipped with a divertor sample manipulator, DiMES [5], to facilitate the examination of plasma exposed samples. In this study, DiMES was used during ELMing He H-mode plasma to expose various W samples to the He ion flux in the lower divertor. The samples exposed using DiMES were pretreated, to obtain different types of surface morphologies, in the PISCES-A linear plasma device [6]. This plasma pretreatment was done in order to most effectively use the DIII-D run time and to expose a series of different types of surfaces to identical DIII-D plasma discharges.

When W is exposed to an energetic (>~30 eV) He particle flux the resulting surface morphology is strongly dependent on surface temperature. At temperatures below ~ 1000K, the implanted He coalesces into small nano-sized subsurface bubbles [7]. Above 1000K, nano-scale tendrils of W peel away from the surface resulting in a fuzzy-like W surface structure [8,9]. Eventually, over 2000K, He interacting with the surface results in large micron-scale pits and bubbles in the surface [10, 11]. W also tends to exhibit blisters in the near-surface region when exposed to D plasma in the temperature range of 400-600K. Sets of each of these types of samples, with the exception of the 2000K surface, were exposed on the DiMES manipulator along with several untreated, virgin W control samples.

The primary goals of the experiment were to determine the interaction of each surface with the incident plasma, as well as to subject the samples to extensive post-exposure surface analysis to determine the impact of the ELMing divertor plasma on the samples. During the plasma exposure the temperature rise of the samples resulting from the added energy burst due to each ELM was measured, because previous measurements have indicated a change in thermal conductivity of W surfaces containing He nano-bubbles [12]. In addition, spatially resolved W I emission from each button was recorded as an indicator of the erosion rate of each sample. The post-exposure surface analysis included; Secondary Electron Microscopy (SEM) imaging to monitor any damage or cracking that may have resulted from the repetitive ELM energy deposition, Grazing Incidence Small-Angle X-Ray Scattering (GISAXS) to measure the size and depth of subsurface He nano-bubbles, confocal microscopy surface imaging to measure changes in surface roughness of the buttons, Focused Ion Beam/Transmission Electron Microscopy (FIB/TEM) to directly image the subsurface nano-bubble layer and Nuclear Reaction Analysis (NRA) to determine the changes in the D depth profiles of the buttons that were exposed to deuterium plasma before the DiMES He plasma exposure.

2. In-situ plasma exposure results

The PISCES-A linear plasma device was used to 'pretreat' three W buttons at a time to either pure He or D plasma. The sample exposure temperature was controlled by varying the cooling

rate to the sample manipulator. A total of 18 W buttons were exposed to He fluence of 1 x 10^{26} m^{-2}, 9 at 773K, 6 at 973K and 3 at 1123K. Three additional buttons were exposed to a D plasma fluence of 1 x10^{25} m^{-2} at 500K. Eight additional W buttons were unexposed to plasma, but were polished in the same fashion as the pretreated buttons. The mass of each sample was recorded prior to installation in DIII-D using a microbalance with +/- 30 μg resolution.

Three sets of W button samples were exposed to the DIII-D He plasma. The configuration of the samples loaded into the DiMES head is shown in Figure 1. One set of samples was exposed to only a single set up discharge in DIII-D, whereas the other two sets were exposed to four discharges each. The strike point was located slightly (~5 cm) to the inboard side of the DiMES location to maximize the ELM energy density striking the W samples. The divertor plasma parameters were measured using the divertor Thompson scattering system located approximately 80 cm toroidally away from the DiMES location. The ECH system was used to achieve H-mode to reduce the amount of D that would have been injected into the discharge if deuterium neutral beam heating had been used. The achieved ELM frequency was 30-50 Hz with each ELM lasting about 2-3 msec. The divertor plasma density and temperature of 1 x 10^{19} m^{-3}, ~ 50 eV and 2 x10^{19} m^{-3}, ~250 eV, were measured between and during ELMs, respectively, resulting in a total helium ion fluence of ~ 1x 10^{24} m^{-2} per shot. Typical DIII-D discharge parameters are shown in Figure 2.

The fast IRTV diagnostic (2894 frames/sec and 6 pixels/button) and the W I filtered DiMES TV directly viewed the DiMES head during the exposure. For these two diagnostics samples 4, 7 and 1 (see Figure 1) were all effectively exposed to identical plasma conditions at an identical radial location. The IRTV was calibrated before the He discharges using the DiMES internal heater. The deposited ELM energy density was measured using the temperature rise of a graphite region of the DiMES head at the identical radial location as samples 4, 7 and 1. Although the ELMs varied in size, a typical temperature rise measured from the graphite was ~ 140K due to the ELM. This equates to a typical ELM energy density of 60 kJ/m^{-2}. Unfortunately, difficulties with changing emissivity of the W buttons during the plasma exposures made absolute measurements of their temperature changes problematic.

Erosion of each button, between and during ELMs, was monitored using a W I (429.4 nm) filter in front of the DiMES TV camera. Figure 3a shows the W I light emission from each button between ELMs, and 3b during an ELM. The most striking aspect of the images is the reduction of W I emission from the fuzzy W button. This is consistent with previous measurements of a reduction in erosion from fuzzy W surfaces [13]. A closer look at line scan data of these images reveals consistently reduced erosion from the W button pre-exposed to He plasma at 973K, as compared to the adjacent untreated, virgin button. Unfortunately, the mass loss resulting from the DIII-D plasma exposure is not outside of the resolution of the microbalance, so further experiments to verify this effect are planned in PISCES.

3. Ex-situ surface analysis results

Neither SEM imaging, nor confocal microscope roughness measurements, was able to detect any significant change, due to the DIII-D plasma, to the surfaces of the untreated W buttons, nor those pretreated with He plasma at 773K or 973K. This implies that repetitive transient power loads in the range of 0.04 – 0.1 MJm^{-2} to W surfaces containing He nano-bubbles is likely below the threshold for surface roughening and damage production. This is significant, as 0.1 MJm^{-2} is the present design estimate for mitigated ELMs in the ITER He campaign [14]. Of the three fuzzy buttons exposed in DIII-D, 2 exhibited arc damage to the surface; however the third fuzzy button did not experience any arcing [15].

The only observable change in surface morphology occurred to the buttons that were pre-treated with D plasma. SEM images of the sample surface before, and after, DIII-D plasma exposure are shown in Figure 4 a & b. Before the DIII-D exposure, only a few sparsely scattered blisters are evident on the sample, whereas after the DIII-D exposure, many more blisters are seen populating the surface. Again, there is no measureable mass change to the sample due to the DIII-D He plasma fluence, so there is likely another cause for the sudden appearance of the blisters. NRA will be performed on the samples to determine the change in the deuterium depth profile resulting from the DIII-D He plasma to try to understand this phenomenon.

Measurements using GISAXS of the sub-surface He nano-bubbles also revealed a surprise result. Analysis of the scattering data from the DiMES samples exposed to the single set-up discharge showed evidence of He nano-bubbles in the un-pretreated W buttons. Details of the measurements and their interpretation can be found in [16]. Figure 5 shows the interpretation of the scattering results from buttons exposed during the set-up shot. The button that was not pre-treated with He plasma in PISCES before exposure in DIII-D contains nano-bubbles of approximately the same size as those observed in the pretreated buttons. The He ion fluence in the PISCES exposures, however, was one hundred times larger than the He fluence in the single DIII-D H-mode discharge. This implies that the nano-bubbles form quickly in the surface and once formed their size saturates, at 1.5 -2 nm diameter, with increasing fluence. This result is in good agreement with recently published model of the incubation fluence required for the formation of W fuzz [17] and could explain some of the difficulty with changing emissivity affecting the surface temperature changes of the buttons.

The button that was only exposed to PISCES He plasma, in Figure 5, showed an average bubble diameter of 1.5 nm and a bubble layer extending 30 nm deep into the W surface [16]. FIB/TEM analysis of a similar sample exposed only to He plasma in PISCES also reveals a modified layer extending rough 25 nm below the button surface [18].

4. Summary

A series of measurements coupling plasma exposures in PISCES and DIII-D have been conducted to examine the response of W samples, with various surface morphologies, to high power ELMing H-mode He plasma. No damage, or roughening, of the sample surfaces is observed after subjecting the buttons to 600 repetitive ELMs with energy densities in the range of 0.04 – 0.1 MJ/m^2. In-situ erosion measurements clearly show a reduction in tungsten sputtering from the fuzzy W button. Post exposure materials analysis reveals the rapid formation of the He nano-bubble layer, which appears unchanged with increasing fluence.

Acknowledgements

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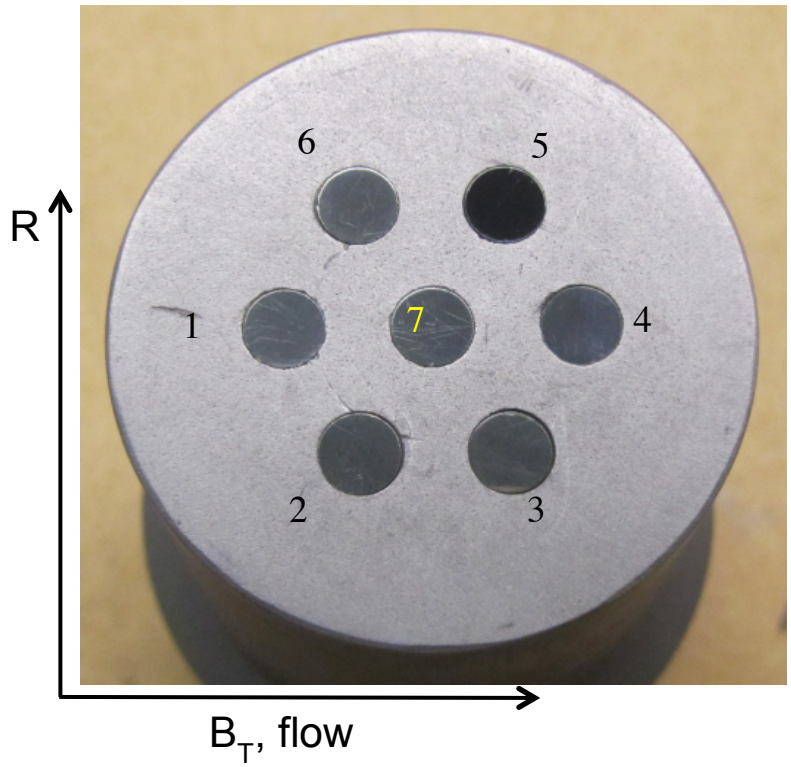

Figure 1 – Geometry of the tungsten buttons arranged in the graphite DiMES head. Button types are: 1) pre-treated with He plasma at 773K, 2) pre-treated with D plasma at 500K, 3) untreated W, 4) pre-treated with He plasma at 973K, 5) fuzzy W sample, 6) untreated W and 7) untreated W.

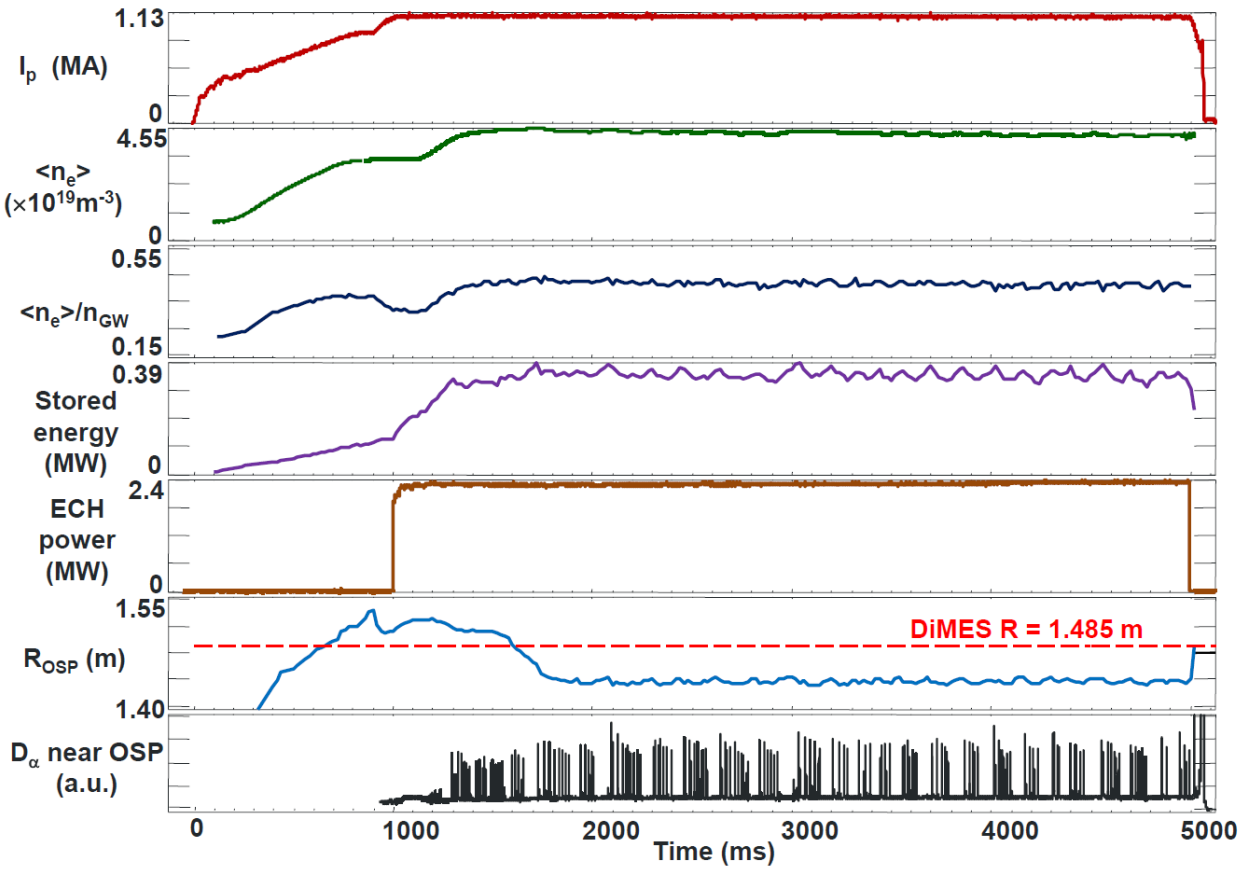

Figure 2 – Time history of DIII-D He plasma, bottom most signal shows ELM frequency.

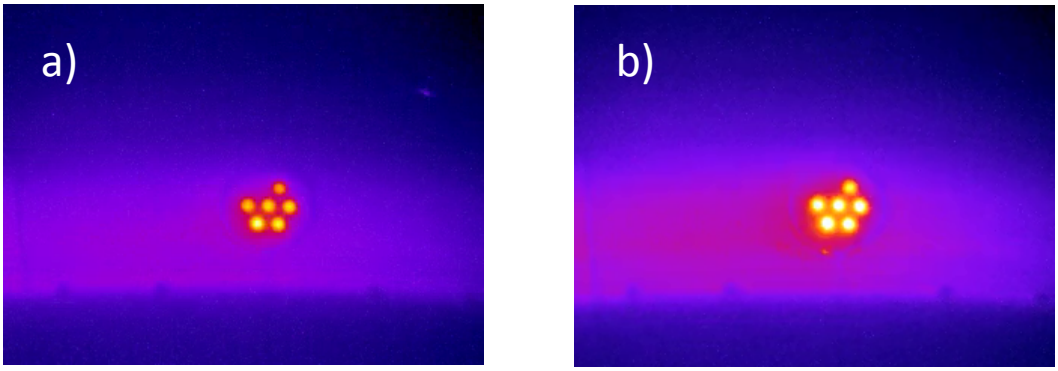

Figure 3 – W I emission images from the buttons in the DiMES head; a) between ELMs and b) during an ELM.

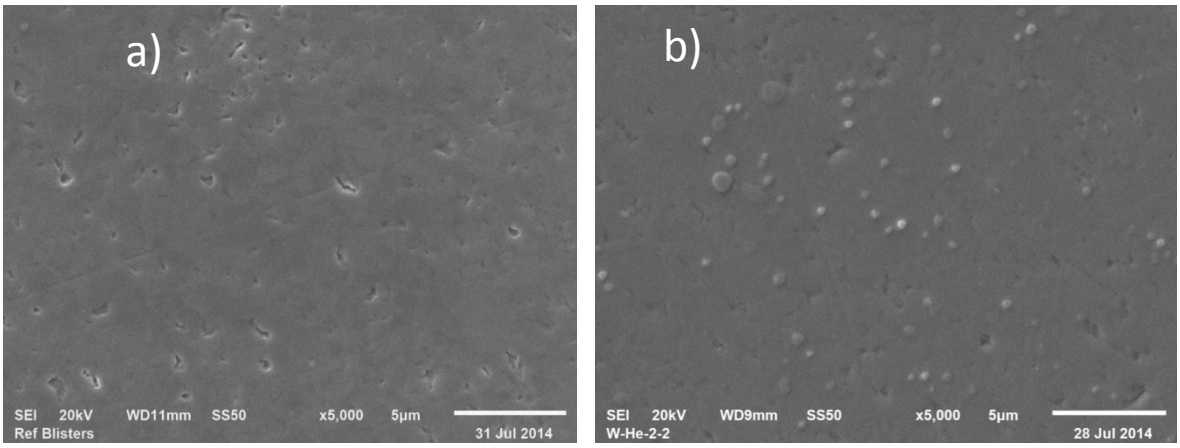

Figure 4 – SEM images of button pre-treated with D plasma: a) before exposure in DIII-D and b) after He plasma exposure in DIII-D.

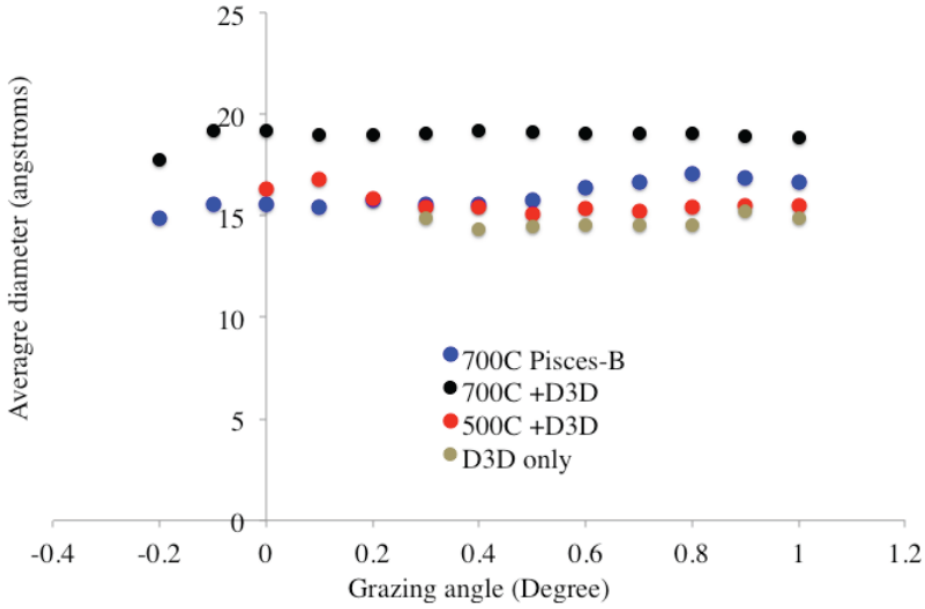

Figure 5 – GISAXS measurements of He nano-bubble diameter after different plasma exposure conditions.