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GENERAL ATOMICS

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ABSTRACT

Prior heat pulse testing of plasma facing components (PFCs) has been completed in vacuum environments without the presence of background plasma. Edge localized modes (ELMs) will not be this kind of isolated event and one should know the effect of a plasma background during these transients. Heat-pulse experiments have been conducted in the PISCES-A device utilizing laser heating in a divertor-like plasma background. Initial results indicate that the erosion of PFCs is enhanced as compared to heat pulse or plasma only tests. To determine if the enhanced erosion effect is a phenomena only witnessed in the laboratory PISCES device, tungsten and graphite samples were exposed to plasmas in the lower divertor of the DIII-D tokamak using the Divertor Material Evaluation System (DiMES). Mass loss analysis indicates that materials that contain significant deuterium prior to experiencing a transient heating event will erode faster than those that have no or little retained deuterium.

I. INTRODUCTION

Gases trapped in plasma facing components of tokamaks could cause an increase in the erosion of the surface during plasma operations, specifically transients such as edge localized modes (ELMs). Heat-pulse experiments have been conducted in the PISCES-A device utilizing laser heating in a divertor-like plasma background. Initial PISCES results [1] indicate that the erosion of surfaces exposed simultaneously to plasmas and heat transients is enhanced as compared to heat pulse or plasma only tests. This enhanced erosion may be caused by trapped gases released during a heat pulse. Also self-sputtering of material that is ejected during the transient, ionized by the plasma near the surface and subsequently driven back to the surface may occur. Gas retention in plasma facing components (PFCs) and ELM energy are currently indicated as the cause. Current tokamak devices don't exhibit the damage witnessed in the lab because the sample (divertor) has a lower fluence before seeing an ELM, disruption, or glow cleaning. This will not be the case for ITER as one can expect fluences of 10^{25} D/m^2 between ELMs (2 Hz). To determine if the enhanced erosion effect is a phenomena only witnessed in the laboratory, tungsten and graphite samples were exposed to D plasmas in PISCES and then exposed to ELMing He and D plasmas in the lower divertor of the DIII-D tokamak using the Divertor Material Evaluation System (DiMES) [2]. PISCES exposures were conducted to load samples with D prior to exposure in DIII-D. The tokamak experiments were conducted during two separate campaigns as piggybacks to normal experiments and hence plasma conditions could not be fully controlled. Helium exposures in DIII-D were chosen so isotopic exchange could be evaluated and deuterium exposures were conducted most recently to confirm initial results.

II. APPARATUS AND EXPERIMENT

A. Materials

Two types of tungsten were used in this study. For the primary exposures during the He campaign, several mechanically polished tungsten samples measuring 6 mm in diameter and 2 mm thickness were generated by vapor-plasma spray technique (hereafter referred to as WA Samples). Pure VPS-W samples were prepared at Guangzhou Research Institute of Nonferrous Metals with a purity of 99.6 wt.% and relative density of 92% [3]. Additional tungsten samples (hereafter referred to as WB Samples) were exposed to a few D plasmas as a piggyback experiment most recently. These samples were Plansee ITER Grade tungsten that was machined by Midwest Tungsten (IL), and following, polished and outgassed in house. All samples were weighed on a high precision microbalance before and after exposure to laser and/or plasma irradiation. Table I lists the sample type and designation for the experiments.

TABLE I. Summary of materials and exposures of tungsten samples in PISCES A to D plasma and subsequently in DIII-D to He/D plasma.

Sample	Type	Fluence in PISCES	DIII-D Plasma
WA-B1	VPS-W	2×10^{26} D/m^2	He
WA-B2	VPS-W	2×10^{26} D/m^2	–
WA-C	VPS-W	1×10^{26} D/m^2	He
WA-D	VPS-W	0 D/m^2	He
WA-G	VPS-W	5×10^{25} D/m^2	He
WB-1	Plansee IG	2×10^{26} D/m^2	D
WB-2	Plansee IG	2×10^{26} D/m^2	D
WB-3	Plansee IG	2×10^{26} D/m^2	D
WB-4	Plansee IG	2×10^{26} D/m^2	D
WB-5	Plansee IG	2×10^{26} D/m^2	–
WB-6	Plansee IG	0 D/m^2	D
WB-7	Plansee IG	0 D/m^2	D
WB-8	Plansee IG	0 D/m^2	D
WB-9	Plansee IG	0 D/m^2	–

B. Initial plasma exposure — deuterium loading

To load the material to various gas levels, samples of tungsten were bombarded with deuterium ions ($E_{ion} \sim 125$ eV) in the PISCES-A device prior to introduction to the tokamak. The PISCES-A plasma device [4] has parameters similar to the edge plasma in tokamaks. The 7.5 cm diameter plasma is generated by electron emission from a large area LaB_6 disc cathode and is transported along the 1-2 kG magnetic field to produce a high density ($\sim 10^{13}$ cm^{-3}), low energy (5-15 eV) deuterium plasma. The ions can be accelerated to the sample by biasing the sample to produce 50-250 eV ion energy at a flux on the order of a few 10^{18} cm^{-2} s^{-1}. Samples in this experiment were biased to -125 V, held near 50°-100°C and exposed to a fluence up to 2×10^{26} D^+/m^2. Table I lists the sample designation and exposure in PISCES A for the experiments.

C. DIII-D exposure

For the first exposures (WA) variably saturated and unsaturated samples were loaded onto the DiMES head and inserted. Figure 1 shows the initial DiMES head (a) and location in DIII-D (b). For 48 shots during the He campaign of 2009, the strike point (SP) was swept onto the DiMES system at some point during the shot for duration up to 3 s. The DiMES holder was lowered between shots so that it was not exposed to He glow discharges. Figure 2 shows the flux incident on Langmuir probes on the floor in the vicinity of DiMES. ELMs during this period are evident in the flux trace shown. ELMs in DIII-D can heat the surface to neary 1000°C in less than a few milliseconds. The total fluence to the (WA) samples for all exposures was approximately 5×10^{23} He^+/m^2. Table I lists the sample designation and DIII-D plasma environment for the experiments.

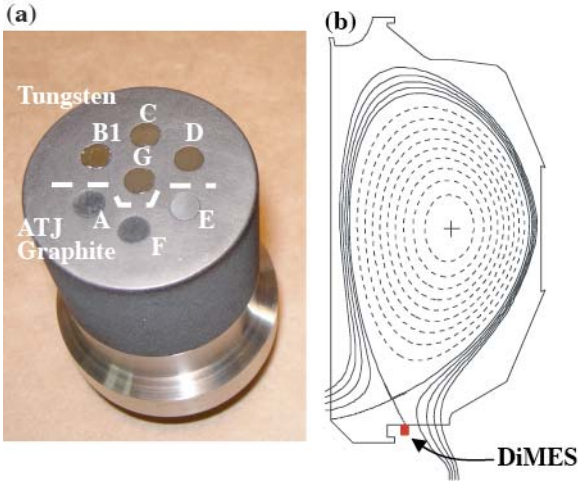

Fig. 1. (a) DiMES Head loaded with W and C samples. (b) Cross-section of DIII-D with location of DiMES indicated.

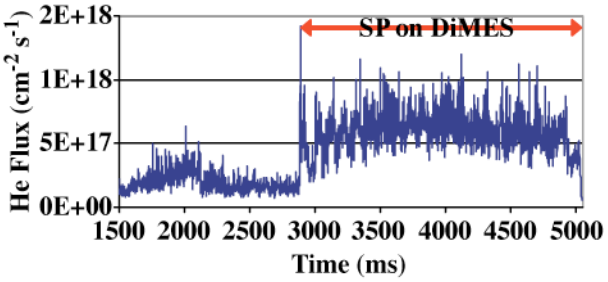

Fig. 2. Flux incident on Langmuir probes on the floor in the vicinity of DiMES. The strike point (SP) is moved onto DiMES near 3 s into the shot and remains there for more than 2 s. ELMs during this period are evident in the flux trace shown.

For the second experiment (WB) samples were loaded into a new DiMES head rotated 30°. This head was created to allow loaded and unloaded samples to be exposed on the same flux surface on the divertor shelf and provide a better comparison. Half of the samples were bombarded by D plasma in PISCES A to a fluence $\sim 2\times10^{26}$ D/m^2, the remainder was only outgassed. In these experiments, the X-point started on the shelf within 10 cm of DiMES and was moved off approximately 800 msec into the discharge.

III. NUCLEAR REACTION ANALYSIS AND THERMAL DESORPTION SPECTROSCOPY

Following exposure to PISCES and DIII-D plasmas, each sample was analyzed by nuclear reaction analysis (NRA) to determine the depth profile of trapped deuterium. NRA was performed with 2.5 MeV ^{3}He ion beam, $D(^3He,p)^4He$ reaction, spectra analysis by SIMNRA, and calibration with ErD_2 film (0.5 μm thick). Figure 3 shows the net difference in retention of samples exposed to DIII-D He plasmas as measured by NRA. Additionally, the initial loading profile of deuterium in a tungsten button (*B1*) is shown for reference.

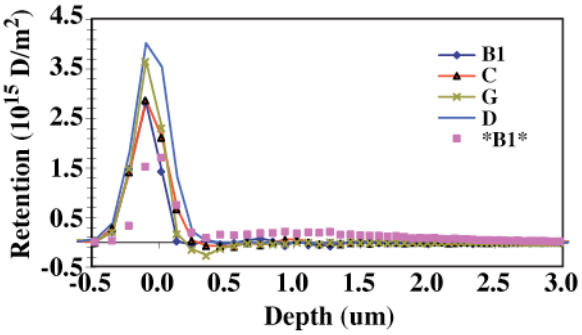

Fig. 3. The difference in retention of samples exposed in DIII-D to He plasmas based upon NRA. Sample *B1* is the NRA result following PISCES exposure and is representative of initial loading of deuterium.

TDS was employed to analyze the trapping and retention of deuterium and helium in the samples. Two separate quadrupole mass spectrometers (QMS) were used in this study. A high-resolution QMS, MKS Instruments–Micro Vision+ was utilized to accuarately distinguish all masses lower than 6 AMU during desorption. This system is capable of resolving ^{4}He: $m = 4.0026$ and D_2: $m = 4.0282$, a requirement to study isotope exchange. A standard SRS RGA300 was also employed to study "mass 4" evolution and monitor other gases produced. A standard D_2 leak at 1.4×10^{-9} mol/s was used to calibrate the systems prior to measurements. He leaks were not available so a calibration was developed based upon the deuterium results, the responsiveness of the QMS to He versus D_2, and the pumping speed of the chamber. Infrared heaters were used to heat the irradiated samples at a ramping rate up to 5 K/s. Results of TDS and NRA are shown in Table II.

TABLE II. Summary of NRA and TDS analysis of W samples exposed in PISCES A (PA) and subsequently in DIII-D. NRA was conducted following exposure in PA and after exposure in DIII-D. TDS was completed in the final step.

	NRA Analysis D (10^{16} at/ cm^2)		**NRA Analysis C (10^{16} at/ cm^2)**		**TDS Analysis D (10^{16} at/ cm^2)**	**TDS Analysis He (10^{16} at/ cm^2)**
	PA	**DIII-D**	**PA**	**DIII-D**	**DIII-D**	**DIII-D**
B1	0.95	1.54	2.08	2.66	7.94	4.37
B2	0.91	0.8	1.04	1.56	1.68	0.00
C	0.95	1.67	2.22	3.48	1.2	4.65
D	–	1.15	–	3.46	0.3	2.70
G	0.80	1.51	2.11	3.75	1.06	3.06

IV. DISCUSSION

All samples show similar He retention but an increase in D retention from exposure to DIII-D He plasmas, a confusing result. NRA reveals (Fig. 3) that the increase is near surface and is accompanied by an increase in carbon areal density. This indicates that this trapped D could be in the form of a carbon co-deposit. Comparing the TDS spectrum of samples B1 and B2 (Fig. 4) and evaluating the net increase in deuterium, one can easily see that the release is very different. Deuterium released up to about 450°C is most likely from tungsten [5,6] while D released above this is likely to come from co-deposits of C frequently seen in DiMES experiments [7]. It is possible that co-deposits were laid down on the samples in the later half of shots which had less impact on DiMES but eroded material from nearby surfaces. Analysis of the TDS spectrum for He release indicates that nearly all of the retention comes from tungsten and not carbon co-deposits. This conclusion is made based upon the temperature of release and previous studies [5,8]. It is likely that most of the He retained came from the initial part of the campaign when the strike point was swept onto DiMES repeatedly for 20 shots.

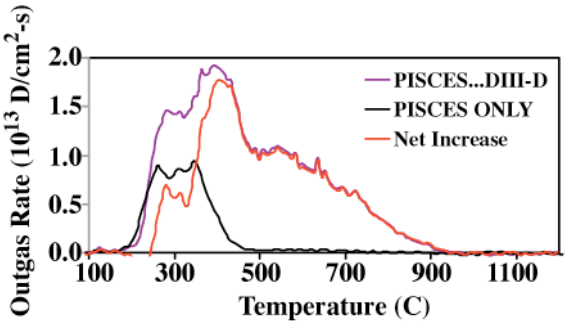

Fig. 4. Thermal desorption spectra of VPS-W samples B1 and B2. The increase in retention is significant and thermally different from that retained after exposure to pure D plasmas in PISCES A and is attributed nearly entirely to carbon codeposits on the sample.

SEM images of the samples (Fig. 5) illustrate the difference in damage to the loaded and unloaded surfaces. Sample B1 which shows blistering after exposure in PISCES A has cracks and dislocations following DIII-D exposure. C which had no visible blistering shows signs of exfoliation. The grain boundaries visible on the surface of Sample D have disappeared after exposure to ELMing He plasmas.

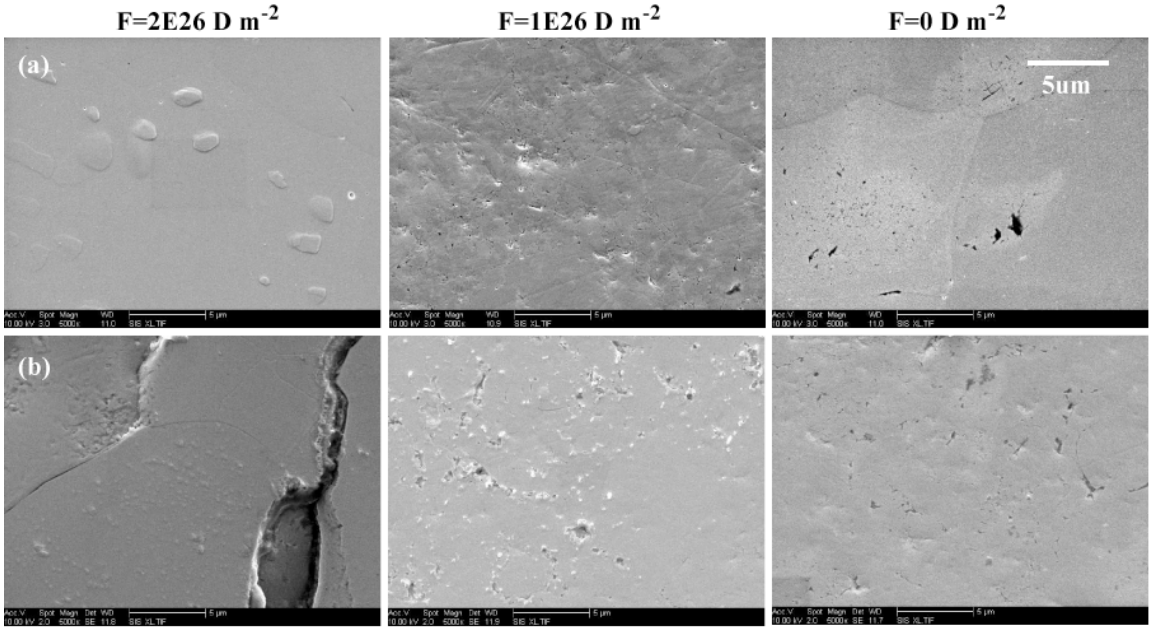

Fig. 5. SEM images of the WA samples exposed to PISCES-A D plasmas (a) and subsequently to DIII-D He plasmas (b).

Previous experiments [1] demonstrated that the D absorbed by the samples prior to significant transient heating (laser pulse) directly effects the erosion of the PFC surface. That data also indicated that this effect only occurs for W samples that have been exposed to fluences $\sim 5\times10^{25}$ D/m^2. A summary of mass loss experienced by all samples is summarized in Table III. Mass analysis here reveals a clear trend in enhanced erosion.

WA samples pre-exposed to a fluence $\geq 10^{26}$ D/m^2 (B1 and C) lost two to five times the mass lost by those pre-exposed at lower or no fluence (G and D). Specimens B1 and D are on the same flux surface and hence should have received the same ELMing plasma exposure. Prior D retention is the leading cause of mass loss in these samples as only preloading differentiates the conditions experienced. It is not clear whether the difference in mass loss between C and B1 was due to different He exposure or pre-exposure D fluence.

A new DiMES head was constructed that would allow exposure of pre-exposed and unexposed samples on the same flux surface. These WB samples exposed most recently during deuterium shots showed a similar trend where those loaded with D prior to exposure lost at least three times more mass than those unloaded when exposed. These samples experienced less exposure in DIII-D than those exposed during the He campaign. So the difference was expected to be small. TDS of these samples has not yet been completed. Evaluating each row independently, it appears that the location of samples

affects the flux and ELMs that are incident and hence here, the enhanced erosion. Future experiments will be sure to include this effect in their design.

TABLE III. Summary of mass loss of all samples exposed. Samples in the same row should have received the same flux during exposure in DIII-D.

Sample	Mass Loss (mg ±0.02)	Pre-Exp	Location
WA-B1	0.35	Y	Row b
WA-B2	0.00	Y	
WA-C	0.13	Y	Row a
WA-D	0.07		Row b
WA-G	0.07	Y	Row c
WB-1	0.21	Y	Row b
WB-2	***	Y	Row c
WB-3	0.20	Y	Row b
WB-4	0.10	Y	Row a
WB-5	–	Y	–
WB-6	0.01		Row a
WB-7	0.06		Row b
WB-8	***		Row c
WB-9	–		–

V. CONCLUSION

It is difficult to comment on isotopic exchange based upon the measurements made. Deuterium co-deposition with carbon during helium plasmas prohibits a clear determination of helium replacement of deuterium in tungsten. We plan to complete additional analysis of the samples that have been exposed. Furthermore, experiments in PISCES and DIII-D are planned to determine the effect of co-deposits on isotope exchange.

We have shown that the enhanced erosion effect is not phenomena only witnessed in the laboratory PISCES device. Tungsten samples were exposed to plasmas in the lower divertor of the DIII-D tokamak using DiMES. Mass loss analysis indicates that materials that contain significant deuterium prior to experiencing a transient heating event such as ELMs and disruptions will erode faster than those that have no or little retained deuterium. This effect is a concern for longer pulse and steady state fusion reactors and should be taken into consideration when evaluating the lifetime candidate materials for the divertor.

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