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High-temperature transient surface heating experiments on carbon in Be-seeded deuterium plasmas

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ABSTRACT

A beryllium-seeded deuterium plasma and transient surface heating system is used in PISCES-B to investigate mixed-material erosion and redeposition properties of ITER relevant divertor materials. This heating can be used to investigate the effects of thermal cycling in plasma facing components expected during ELMs in ITER-like devices. An experimental investigation of the effects of thermal cycling on Be films on graphite has been conducted. It has been shown previously that Be film growth on C can form carbide layers that reduce the chemical erosion of C during deuterium ion bombardment. Results from heat cycling on the chemical erosion and on deuterium retention in C targets up to 1200 °C have shown an enhancement in layer formation. In this report, the temperature range was extended to above 2100 °C, the expected dissociation temperature of Be_2C. It has been found that even heat pulses up 0.1 s long to temperatures above this dissociation temperature, Be_2C layer formation is enhanced by the thermal cycling. This work was supported by Grant DE-FG02-07ER-54913 from the US DoE.

1. Introduction

The current ITER design employs a beryllium first wall, tungsten divertor and carbon strike points. ITER also calls for severe heat loads on these plasma facing components, with heat fluxes at the divertor of 10 MW/m^2 and increasing up to a possible 3 GW/m^2 during an ELM [1]. Beryllium sputtering from the first wall will migrate to the divertor region and the carbon strike point. The PISCES-B linear divertor simulator has been utilized to evaluate the effects of this sputtered beryllium depositing in the carbon strike points. Previous experiments [2,3] on beryllium/carbon mixed-material effects showed both chemical and physical erosion of carbon was mitigated by Be_2C layer formation when a Be concentration of less than 0.1% existed in the plasma. A predictive scaling expression has been derived for the erosion mitigation time of graphite samples due to Be_2C layer in a steady-state environment [4].

A pulsed heating system installed on the machine is employed to create heat pulses up to 3000 °C on graphite samples to simulate repetitive ELM heating [5]. This heating system uses a pulsed positive bias to draw electrons from the plasma and transiently heat the surface of the plasma-exposed sample ohmically. It has been previously reported [6] that cyclically heating graphite samples during exposure to a beryllium-seeded plasma to up to 1500 °C resulted in a significant decrease in the time it took for the Be_2C layer to form and mitigate C erosion, $\tau_{Be/C}$. In this paper, we extend this previous work on the effects of heat cycles on Be_2C layer formation by increasing the temperature of the transient pulsing to above the expected dissociation temperature of the Be_2C layer, ~2100 °C.

2. Experimental setup

Experiments are performed in the linear divertor plasma simulator PISCES-B [7], which produces a high flux (up to 10^{23} m^{-2} s^{-1}) steady-state plasma. An evaporative neutral atomic beam source is used to inject Be into the plasma ~150 mm upstream from the sample. The samples used are 1-inch diameter ATJ grade graphite 6.25 mm thick, with a 22 mm diameter face exposed to the plasma due to the boron–nitride cap. A figure of the experimental setup is given in Fig. 1. These samples were exposed to a Be-seeded deuterium plasma. The total exposure time was 2000 s. To facilitate comparison, the samples were exposed to similar deuterium plasmas used in previous experiments, with $n_e = 3.0 \pm 0.6 \times 10^{18}$ m^{-3}, and $T_e = 6 \pm 1$ eV as measured with a reciprocating double probe. The singly ionized beryllium concentration in the plasma, $c_{Be} \sim 0.05\%$, is obtained from Be II ($\lambda = 467.3$ nm) line intensity measured with an absolutely calibrated spectroscopic system. A potential bias of −50 V was applied to the samples to achieve low-energy-ion bombardment with an impact energy of ~40 eV.

To measure the chemical erosion of C from the surface, the difference in CD band emission, (for molecular energy state transition $A^2\Delta - X^2\Pi$) around $\lambda \sim 430$ nm, in the plasma near the sample and far from the sample is measured spectroscopically [4]. In Ref. [3],

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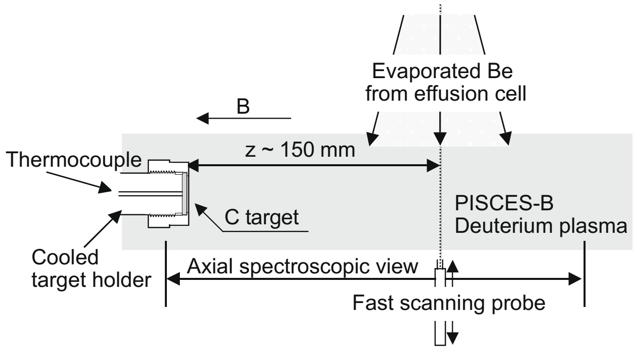

Fig. 1. A schematic view of the target region in the linear divertor plasma simulator PISCES-B.

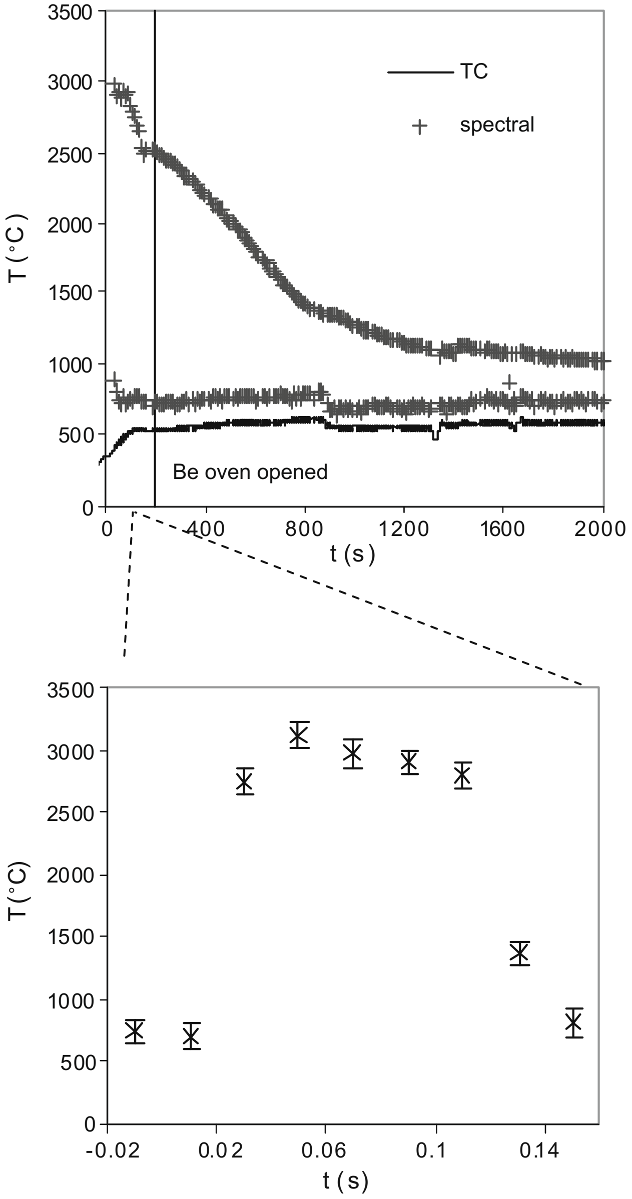

Fig. 2. Surface temperature profile from the spectral pyrometer and bulk temperature from the thermocouple over an entire 2000 s exposure. The Be oven was opened at 187 s. The blow-up is the surface temperature from the pyrometer for a single pulse of 0.1 s.

the CD band intensity decay is found to correlate closely with beryllium layer formation on a graphite sample.

Pulsed surface heating is achieved by reversing the sample bias and drawing electrons from the plasma through the sample. This electron impact then heats the surface in a sub-ms timescale to up to 3000 °C. A bias of +150 V was used that typically drew 25–35 A from the plasma for an absorbed power density of ~13 MW/m^2. The pulse timescales of duration and frequency are both adjustable. We have investigated heat cycles of 0.1, 0.05 and 0.025 s every 10 and 5 s. Surface temperature is measured with two pyrometers during and between pulses [5]. Typical temperature profiles of a sample from the spectral pyrometer and the thermocouple at the back of the sample over the full exposure and during a single pulse are given in Fig. 2. It can be seen from Fig. 2 that the surface temperature achieved during heat pulses tends to decrease over time with cyclic heating. The temperature drop at the beginning of the experimental run in this figure is due to changes in the plasma before the Be oven is opened. The surface temperature and plasma become stable about 30 s prior to Be seeding. After Be is introduced into the plasma, the surface temperature begins to drop with successive heat cycles even though the plasma parameters stay constant and there is no change in the power load on the sample. Even though this leads to the surface temperature during a heat cycle dropping below the 2100 °C we are interested in maintaining, it does stay above this temperature for the duration of the measured C erosion mitigation. For these plots the cyclic heating was 0.1 s every 10 s, the voltage during the pulse was 144 V and the current drops from 44 A to 33 A once the plasma stabilizes, before the Be oven is opened. Between heat pulses, the voltage was −50 V and the current was −3 A.

To investigate the relative effects of single pulses, two experimental runs were done in which the sample was exposed to a Be-seeded plasma without pulsing long enough to establish the C erosion mitigation timescale, $\tau_{Be/C}$, and then a single heat cycle was applied and $\tau_{Be/C}$ re-measured. For the second run, two cycles were applied 10 s apart.

Following exposure runs in PISCES-B, each sample was removed from the machine and a Thermal Desorption Mass Spectrometer (TDS) system was used to analyze deuterium retention in the sample [8]. The samples are heated linearly in vacuum over 1 h

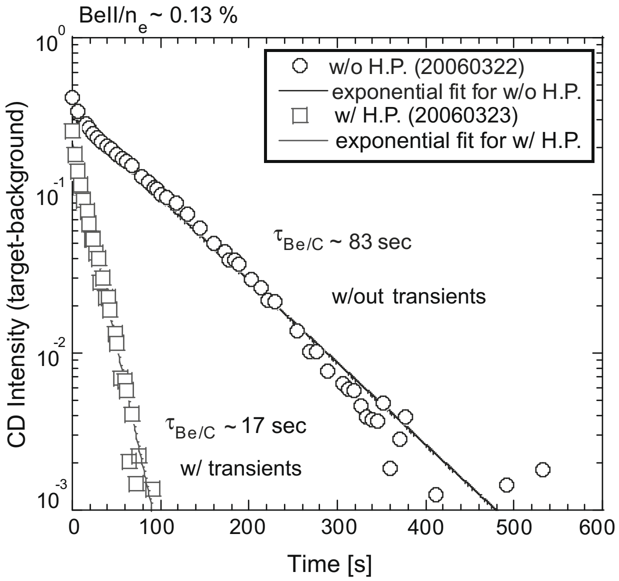

Fig. 3. Spectroscopic measurement of the decay in C chemical erosion for a sample with and without temperature cycles applied. The time to chemical erosion mitigation is approximately decreased by a factor of 5 when cycling is applied.

to 1050 °C, while the partial pressure of deuterium is monitored using a residual gas analyzer. A calibrated deuterium leak is used to convert the experimental integrated deuterium partial pressure signals into total retention values.

3. Analysis and results

Fig. 3 shows the decay in the CD band emissions from the plasma over time for samples without and without cyclic heating. $\tau_{Be/C}$ is found by fitting to the slope of the exponential [4]. The decrease in the erosion mitigation time due to cyclic heating is apparent. Fig. 4 presents the CD emissions for the samples exposed to single and double heat pulses as explained above. It can be seen here that although there is a momentary increase in CD emission directly after the pulse, $\tau_{Be/C}$ is then shorter after the pulse. In the case of the pair of transients, there is a delay time before the erosion resettles. For similar plasma conditions and heat cycle temperatures, a single pulse decreased $\tau_{Be/C}$ by 18% and a series of two pulses decreased $\tau_{Be/C}$ by 39%. This leads one to believe that each individual pulse for these experimental parameters decreases $\tau_{Be/C}$ by another ~20%.

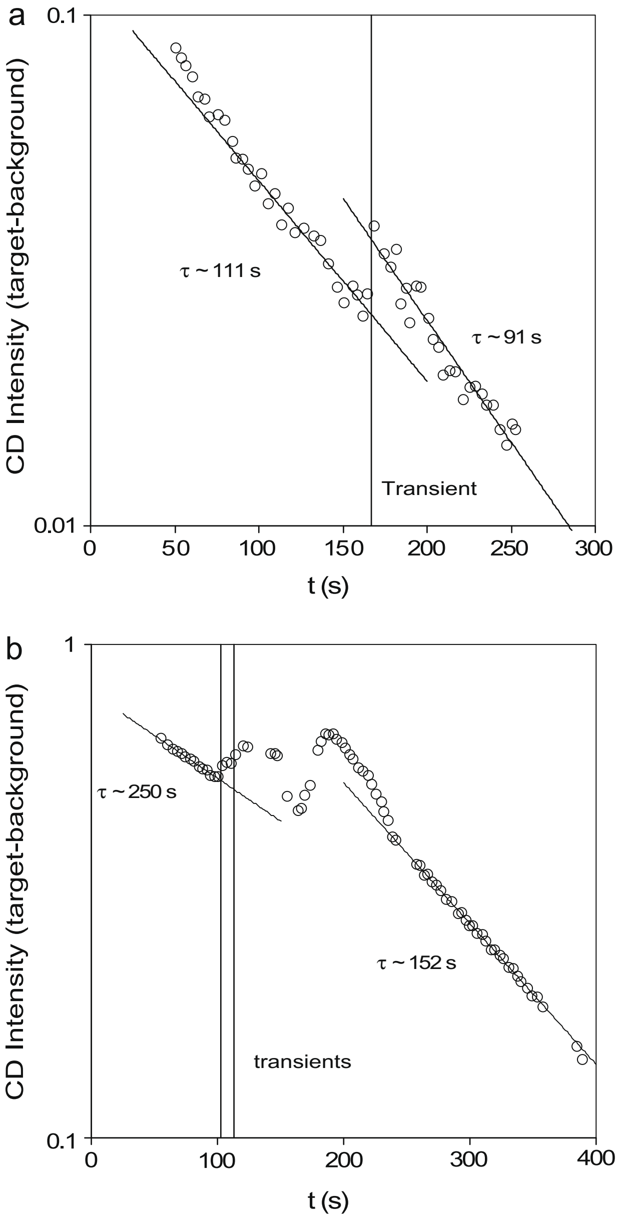

Fig. 4. Spectroscopic measurement of the decay in chemical erosion for a sample with (a) a single heat pulse applied, and (b) two heat pulses applied with a separation of 10 s.

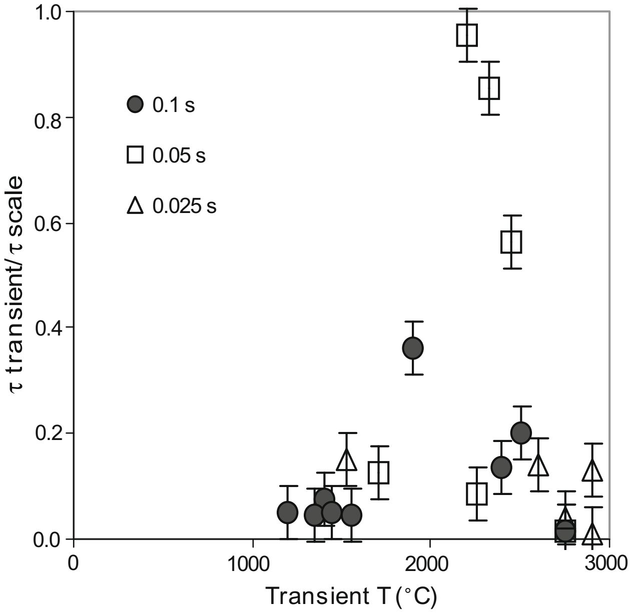

Fig. 5. A plot of the decrease in chemical erosion mitigation time given by $\tau_{transient}/\tau_{scale}$, where τ_{scale} is the expected mitigation time for a sample at the same plasma exposure with no heat cycles applied. This mitigation ratio is plotted as a function of peak pulse temperature when the Be injection is started.

Fig. 5 shows the decrease in $\tau_{Be/C}$ due to cyclic heating as a function of pulse temperature. The temperature of the first pulse after the Be oven is opened is used here. The subsequent drop in pulse temperature may play a role in lowering the effect on $\tau_{Be/C}$ for later pulses and is still being investigated. Even for heat cycles starting

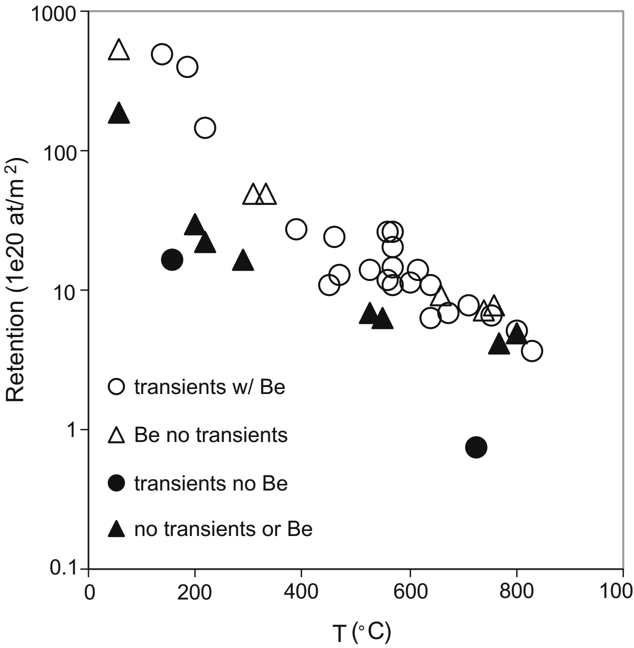

Fig. 6. A plot of the deuterium retention in the samples as a function of background surface temperature.

above 2100 °C, the erosion mitigation time drops significantly with increasing pulse temperature.

TDS results for samples exposed to cyclic heating are presented in Fig. 6 along with samples exposed to similar plasma conditions without heating [9]. Data from pulsed samples with no Be exposure are also presented. Deuterium retention values are plotted as a function of background (i.e. between cycles) surface temperature. It can be seen here that high temperature heat cycles have no real effect on deuterium retention in the Be_2C coated graphite samples. For cyclic heating on graphite without Be seeding, the retention is much less than with Be or steady-state without Be. This difference may be due to the surface temperature during heat cycles on C with no Be staying at the initial high temperature for all subsequent cycles, while for Be coated samples, the temperature decays.

4. Conclusions

Cyclic heating of graphite samples exposed to a Be-seeded plasma in PISCES-B has been implemented to temperatures above the expected dissociation temperature of Be_2C. It has been found that with these high temperature cycles, C erosion mitigation due to the formation of Be_2C layers on the surface is seen to be dramatically enhanced, as seen previously [6] for lower temperature excursions. Deuterium retention in samples with cyclic heating up to 3000 °C is found to be nearly identical to those of samples exposed in a Be-seeded steady-state environment [9].

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References

[1] G. Federici et al., Plasma Phys. Control. Fusion 45 (2003) 1523.
[2] R.P. Doerner et al., Phys. Scripta T128 (2007) 115.
[3] M.J. Baldwin, R.P. Doerner, Nucl. Fusion 46 (2006) 444.
[4] D. Nishijima et al., J. Nucl. Mater. 363–365 (2007) 1261.
[5] J. Hanna et al., Rev. Sci. Inst. 77 (2006) 123503.
[6] R. Pugno et al., J. Nucl. Mater. 363–365 (2007) 1277.
[7] R.P. Doerner et al., Phys. Scripta T111 (2004) 75.
[8] M.H. Mintz, I. Jacob, D. Shaltiel, Topics in applied physics, in: L. Schlapbach (Ed.), Hydrogen in Intermetallic Compounds II, vol. 67, Springer, New York, 1988.
[9] M.J. Baldwin et al., J. Nucl. Mater. 358 (2006) 96.