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Beryllium containing plasma interactions with ITER materials

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Abstract. A beryllium-seeded deuterium plasma is used in PISCES-B to investigate mixed-material erosion and redeposition properties of ITER relevant divertor materials. The beryllium containing plasma simulates the erosion of first wall material into the ITER sol plasma and its subsequent flow toward the carbon divertor plates. The experiments are designed to quantify the behavior of plasma created mixed Be/C and Be/W surfaces. Developing an understanding of the mixed material surface behavior is crucial to accurately predicting the tritium accumulation rate within the ITER vacuum vessel. The temporal evolution of the plasma interactions with the various mixed surfaces are examined to better understand the fundamental mechanisms in play at the surface and to allow scaling of these results to the conditions expected in the ITER divertor. A new periodic heat pulse deposition system is also installed on PISCES-B to simulate the transient temperature excursions of surfaces expected to occur in the ITER divertor during ELMs and other off-normal events. These periodically applied heat pulses allow us to study the effects of transient power loading on the formation, stability and tritium content of mixed-material surfaces that are created during the experiments.

1. Introduction

A bilateral US(DOE)-EU(EFDA) collaboration, focused on experiments performed in the PISCES-B linear divertor simulator [1,2], utilizes a beryllium-seeded deuterium plasma to investigate mixed-material erosion and codeposition properties of ITER relevant divertor materials. The experimental program is designed to reduce uncertainties in the prediction of tritium retention in codeposited mixed-materials in ITER and other future burning plasma devices. The beryllium-containing plasma simulates the erosion of first wall material into the ITER sol plasma and its subsequent flow toward the carbon and tungsten material located in the ITER divertor region.

This paper will summarize the primary, significant results that this collaboration has produced. It will relate these results to the operating conditions expected in ITER and attempt to predict what the consequences of mixed materials on the ITER plasma-facing surfaces might be.

The first, most dramatic result obtained from this collaboration was the suppression of carbon erosion, both physical sputtering and chemical erosion, at very low levels (~0.1%) of incident beryllium impurity ions [3,4]. This result was confirmed using both spectroscopic as well as weight loss measurements. These initial measurements focused on the equilibrium state of the plasma-exposed surface. In other words, long fluence plasma exposures were performed, after which the surfaces of the plasma bombarded targets were examined. In addition, during these large fluence exposures material collectors (referred to as witness plates) were positioned outside the plasma column to collect eroded material [5].

Subsequent experiments have documented the temporal evolution of the mixed beryllium-carbon plasma-created surface [6,7]. Through focusing on the time-dependent

evolution of the surface and its associated plasma-material interactions, we believe we have been able to identify the fundamental mechanisms responsible for the mitigation of carbon erosion from the mixed-material surface. An ongoing series of experiments is examining the response of the mixed-material surface to periodically applied thermal transients [8] with the goal of understanding how such thin surface layers might react to off-normal events in ITER.

In addition to mixed Be/C studies, the issue of alloy formation between beryllium and tungsten is under investigation [9]. Various beryllide (Be_xW) alloys have been observed to form during different plasma exposure conditions. Again by understanding the formation conditions of these alloys, it will increase the confidence in predictions regarding their importance to the ITER design.

2. Present understanding of mixed Be/C surfaces

Our present understanding of mixed Be/C surface formation and implications is as follows:

- Be ions incident in the bombarding plasma become implanted into a carbon surface and due to the energy of the incoming particles, the implanted berrylium will tend to bond with carbon atoms to form beryllium carbide (Be_2C)
- The formation of Be_2C in the surface acts to inhibit the reaction chain responsible for chemical erosion of carbon and also reduces physical sputtering of carbon atoms from the surface
- The Be_2C surface layer thickness saturates after a time that depends on the plasma interaction conditions
- Once a protective Be_2C layer forms on the surface, subsequent beryllium ion bombardment will produce an enrichment of the surface with beryllium that will be easier to erode (compared to beryllium bonded as the carbide)
- After the Be_2C layer forms, the primary species eroding from the plasma bombarded mixed-material surface, and codepositing with hydrogenic species on non-plasma-exposed surfaces, is beryllium.

In PISCES-B one can investigate the bonding patterns of atoms in plasma-exposed using in-situ X-ray Photoelectron Spectroscopy (XPS). Figure 1 [from 10] shows the C1s and Be1s signals from several samples exposed to beryllium-containing deuterium plasma at different temperatures. Also included in the figure are similar XPS signals from ‘standard’ carbon and beryllium samples exposed to deuterium only plasmas. The figure shows a clear shift in bonding toward the carbidic bonds, with essentially all carbon in the surface being bound as carbides after the higher temperature exposures.

The effect of carbidic bonding of impurities in graphite has been shown to reduce the rate of chemical erosion in a variety of doped graphites [11]. The difference in these PISCES experiments is that the doping of the graphite with beryllium impurities occurs as a consequence of having metallic impurities entrained in the plasma flow toward the graphite target. A similar effect might be expected in the divertor of ITER. Measurements of the effects of beryllium doping of graphite show similarities to those exhibited by boron doped graphite, namely an increase in the hydrogenic species retained by the doped material and a shift in the release patterns of the retained deuterium to lower temperature [10]. This behavior, in an indirect way, shows the impact of beryllium doping of graphite. Direct measurements of the amount of

chemical erosion of carbon from a graphite surface with varying amounts of beryllium imbedded in the surface also shows the impact of beryllium doping, as shown in Figure 2.

Rutherford Backscattering (RBS) data have been obtained at the University of Wisconsin on targets that were exposed to beryllium-seeded plasma in PISCES [10]. This data is shown in Figure 3 and reveals the saturation in the thickness of beryllium on the surface of two samples exposed for different times to identical plasma conditions. In the case of the sample exposed to a beryllium ion fluence of 3×10^{22} m^{-2}, virtually all of the beryllium incident on the sample from the plasma can be accounted for in the surface layer. When the exposure time, under identical plasma conditions, is increased on a different sample (to 1×10^{23} m^{-2}), the same amount of beryllium is found in the surface, indicating that the subsequent beryllium deposited on the sample has been eroded. These two traces in Figure 3 are compared to a RBS spectrum acquired from a graphite sample exposed to identical deuterium plasma, expect with no beryllium seeding, in PISCES-B.

The beryllium eroded from the sample surface can be observed by monitoring the neutral beryllium line emission (at 457.3 nm) from directly in front of the exposed target [12]. By examining, in detail, the temporal evolution of a typical beryllium seeded plasma exposure in PISCES-B, one can clearly see the increasing beryllium erosion from the sample surface. Figure 4 shows this behavior along with the temporal behavior of the chemical erosion decay (measured by the CD band emission from directly in front of the target surface). Although the mitigation time of the chemical erosion of a surface depends on the plasma conditions during the exposure [6], in this particular exposure the CD band is measured to decay in approximately the first 60 seconds of the exposure after the beryllium oven shutter has been opened (t = 0 sec.). A small amount of neutral beryllium line radiation is detected within the line of sight of the spectrometer when the oven shutter is opened at t = 0 sec. In fact, one observes a slight drop in this initial intensity during the first 10 seconds, or so, of the exposure due to a few degree drop in the oven temperature when the shutter is initially opened. After the beryllium oven temperature has re-equilibrated, the beryllium line radiation remains constant throughout the decay of the CD band intensity, indicating that the beryllium erosion from the target surface is not changing. Once the chemical erosion from the sample has been suppressed, the beryllium erosion from the target is observed to increase (after 60 seconds under these conditions) until at about 200 sec. into the discharge (for these conditions) the beryllium erosion from the surface reaches equilibrium with the incoming Be ion flux from the plasma.

Monitoring the D_{gamma} line radiation from the plasma is also used to normalize the two other signals, thereby accounting for any possible changes in the optical properties of the detection system, for example coating of the optical windows. Figure 4 also shows the D_{gamma} signals as a function of time throughout the plasma discharge. During the first 80 seconds of the discharge the D_{gamma} signal does not change, however once the beryllium erosion from the sample increases, the D_{gamma} signal is seen to decrease monotonically throughout the remainder of the exposure. In other words, the optical windows in the PISCES-B vacuum system coat up due to the beryllium erosion of the incident beryllium plasma ion flux.

This interpretation of the D_{gamma} signal is corroborated by the analysis of witness plate samples located outside the plasma column during the discharge [5]. Typical depth profiles of material collected on such witness plates are shown in Figures 5a and 5b. In these cases the collector plate was tantalum and is located under approximately 100 nm of codeposited material collected during the plasma exposure. In both cases, beryllium is the predominant material

collected. The depth profile of material on the witness plate samples can then be interpreted as the temporal dependence of erosion from the plasma-bombarded target.

As has been previously reported, the suppression time of chemical erosion is much shorter when the temperature of the exposed target is higher [6]. The material collected initially during low-temperature carbon target exposure (300°C), Figure 5a, between 70 – 100 nm into the witness-plate layers, contains a significant amount of carbon. As the exposure continues in time, the carbon material collected on the witness plate decreases (50 –70 nm into the layer), until eventually all the material eroding from the targets is beryllium (0 – 50 nm into the layer). During a high-temperature target exposure (700°C), Figure 5b, the suppression of chemical erosion is much more rapid [6] and virtually no carbon is detected throughout the layer of collected material on the witness plate.

3. Transient temperature excursion experiments

An important issue related to the formation of mixed-material surfaces in the ITER environment will be their response to off-normal events, such as ELMs and possibly disruptions. Although these events do not occur in the PISCES devices, certain aspects of their occurrence can be simulated. The impact of periodic surface temperature excursions is being investigated during beryllium-seeded plasma discharges by applying a short-duration positive bias to the targets exposed in PISCES-B [8]. Typically, targets are biased negatively in PISCES to provide the ion bombarding energy, however a positive pulsed bias can be applied to collect electron current, and thereby heat, to the targets repetitively during the plasma exposure. Varying the voltage of the positive bias controls the power flux to the target.

Although these systematic experiments are just beginning, a few observations have already been documented. First, during power fluxes that vary the target temperature from the steady-state value of 500°C, up to 1200°C during the heat pulse (with a heat pulse duty cycle of 1%), the mitigation time of the chemical erosion of the target is seen to decrease dramatically [8]. This behavior is understandable from the mitigation time scaling studies [6] described above (at higher surface temperature the beryllium and carbon atoms in the surface react more readily to form beryllium carbide, thereby reducing chemical erosion). The second result is that the amount of deuterium retained in the targets increases, by roughly 50%, during heat pulse experiments when compared to identical exposures without the application of the positive bias heat pulses. This indicates that the high temperature excursions of the surface are acting to increase the diffusivity of deuterium into the sample, rather than increasing the recombination and release of deuterium from the target surface. The pulsed-power supply system has recently been upgraded to allow the application of higher positive bias voltage pulses to the targets.

4. Summary

The understanding of plasma-created mixed-material surfaces has increased dramatically due to this US-EU collaboration. The fundamental mechanisms responsible for the mitigation of chemical erosion from graphite surfaces exposed to beryllium containing deuterium plasma have been identified. A scaling law for the mitigation time of chemical erosion, based on data from PISCES-B, has been developed to predict the time needed to suppress chemical erosion of the graphite dump plates in the ITER divertor. The scaling law predicts the chemical erosion in the ITER divertor suppression time to be approximately 10 msec. [6], based on typical ITER divertor

plasma parameters [13]. This indicates that the beryllium carbide layer should form readily between expected ELMs in ITER. The consequence of beryllium carbide formation on the graphite dump plates in ITER is that beryllium based codeposited material should be expected, rather than carbon based codeposits.

Measurements have also begun in PISCES-B to understand the response of the mixed-material surface layers to transient temperature spikes, similar to those that might be expected during an ITER ELM.

References

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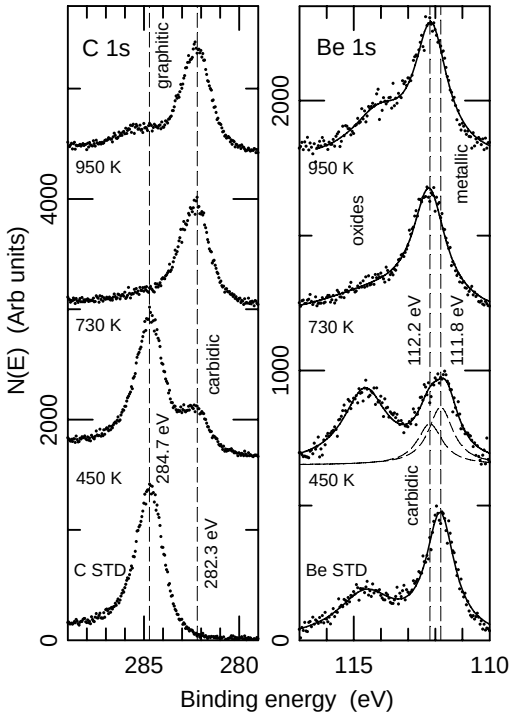

Figure 1 – XPS analysis of beryllium and carbon binding on the surface of carbon targets exposed to a beryllium containing plasma at different target temperatures. The Be-C bond is seen to be primarily carbidic in nature, suggesting the formation of a beryllium carbide surface layer.

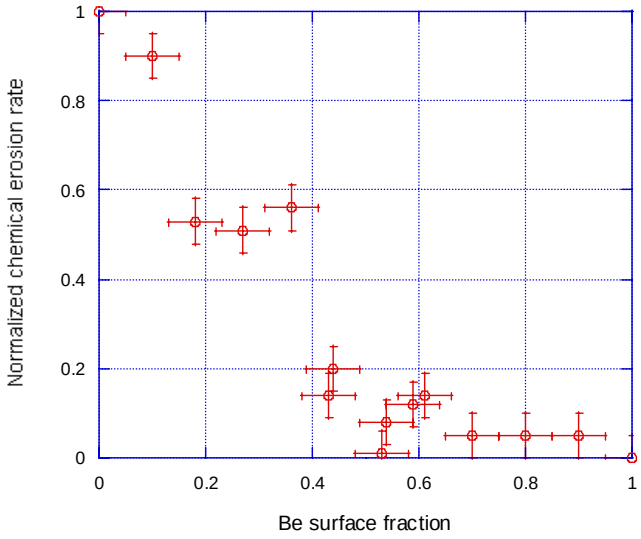

Figure 2 – Variation of normalized chemical erosion rate (CD band intensity) with beryllium surface coverage (from Auger Electron Spectroscopy) of mixed Be/C surface.

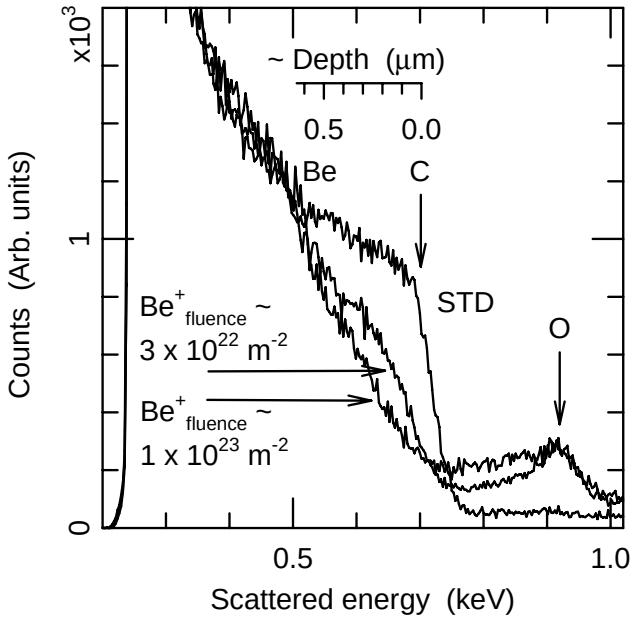

Figure 3 – RBS spectra for an unexposed graphite target STD, and two graphite targets exposed to beryllium-seeded plasma. The beryllium ion concentration during plasma exposures was ~0.15 %, and the exposure times, 1600 s and 4600 s corresponding to beryllium fluences of 3×10^{22} m^{-2} and 1×10^{23} m^{-2}.

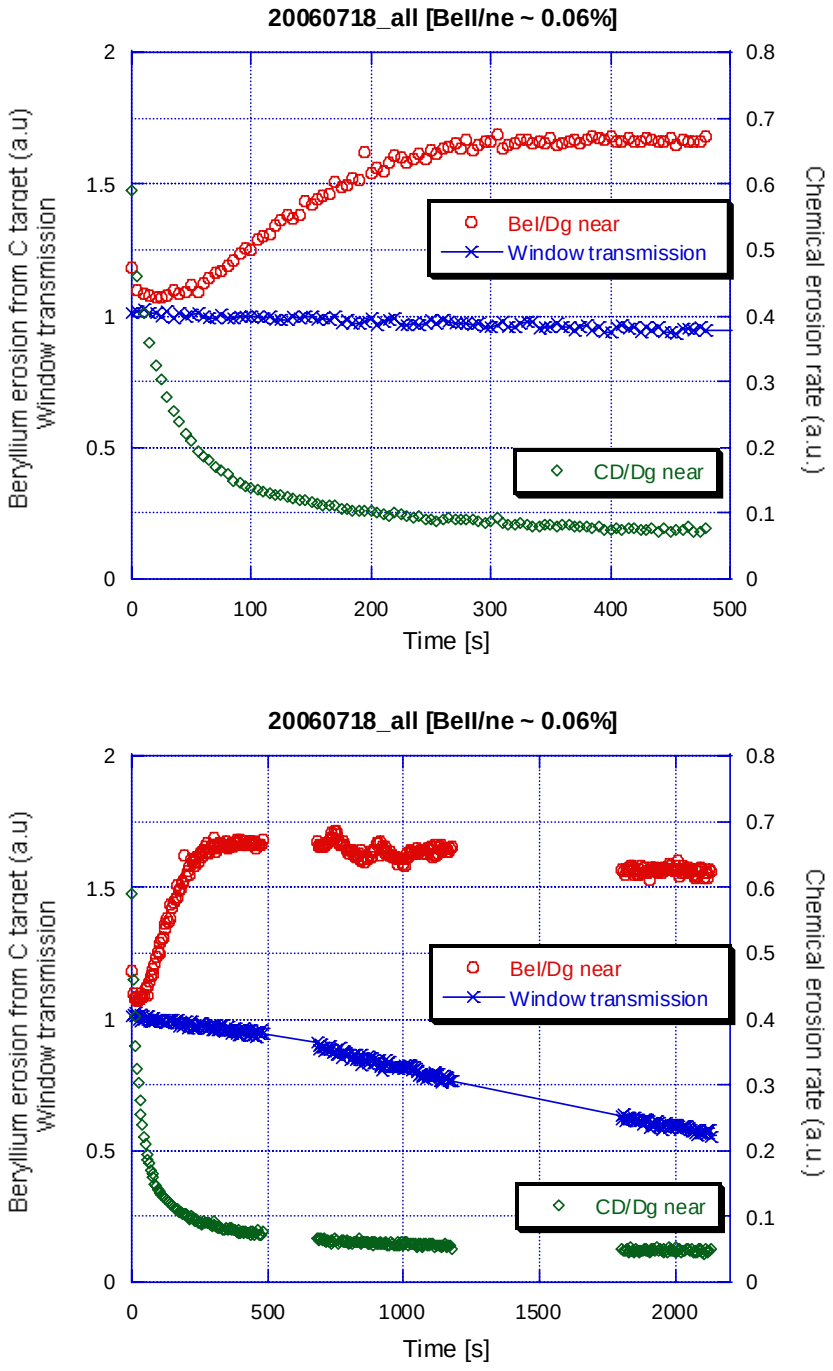

Figure 4 – Temporal evolution of the chemical erosion (CD/Dg), beryllium erosion (BeI/Dg) and the optical window transmission from a graphite sample exposed to a beryllium-seeded deuterium plasma. The top figure is an expansion of the first 500 seconds of the exposure for clarity. The beryllium oven opens at t = 0 sec.

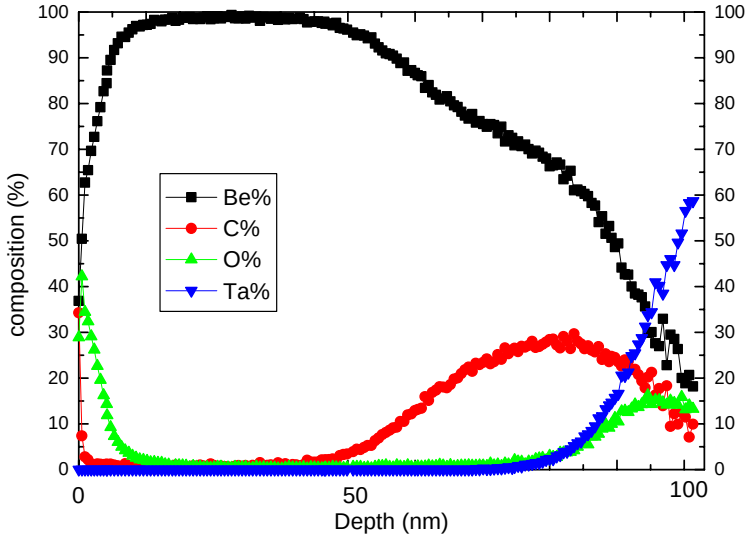

Figure 5a – Elemental depth profile of the codeposited material collected on a witness plate coupon during the exposure of a graphite target to beryllium-seeded deuterium plasma at 300 ℃.

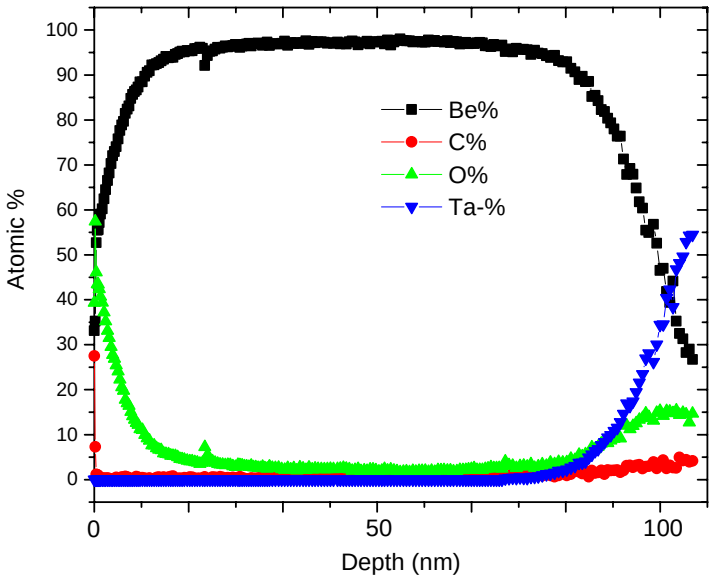

Figure 5b – Elemental depth profile of the codeposited material collected on a witness plate coupon during the exposure of a graphite target to beryllium-seeded deuterium plasma at 700 ℃.