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Beryllium-containing Mixed Material PMI Studies on PISCES-B

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Abstract

Carbon and Tungsten material samples are exposed to Be-seeded deuterium plasmas in the PISCES-B divertor simulator facility. The sample temperature, incident ion energy, upstream Be plasma concentration, and incident plasma flux can all be controlled independently, allowing study of ITER-relevant mixed-material PMI issues. Previous results show that the formation of Be_2C can lead to a large reduction of chemical erosion of C [Baldwin:2006]. An empirical scaling of the formation rate of Be_2C derived from PISCES-B results is then used to extrapolate to ITER divertor target conditions. The extrapolation predicts that Be_2C formation should occur at a rate much higher than the type-I ELM period, implying that C chemical erosion suppression is likely to occur in ITER.

Introduction

The long-pulse, high-power operation expected in ITER presents a new set of challenges to the design and performance of plasma facing components (PFCs). Because of the presence of more than one type of material, the composition of the plasma-facing components will evolve over time due to large-scale material migration; the resulting mixed-material surfaces may then present much different properties than the materials that were initially designed for in the machine. Developing an understanding of the interaction of a beryllium containing hydrogenic plasma with both tungsten and carbon surfaces is therefore crucial to accurately predicting PFC performance in the present ITER design. In this paper we report on experiments performed in the PISCES-B linear plasma simulator which has been equipped with a beryllium atom beam source, allowing seeding of the deuterium plasma column with controllable amounts of beryllium impurity ions (see Doerner:2004 for a description of the apparatus). The Be-containing plasma subsequently interacts with a material sample immersed in the downstream region of the plasma. Results from Be/C and Be/W mixed-material experiments are reported.

Results

We have extended previously reported results on the alteration of chemical erosion of graphite surfaces exposed to beryllium-containing plasma [Schmid:2005]. In particular, the rate at which the graphite surface chemical erosion is quenched has been studied as functions of beryllium plasma content, plasma flux, surface temperature and incident ion energy. The results show that the reduction of C-erosion due to deposition of Be from the main plasma can be expressed as a scaling for the CD-band emission quenching time τ_{CD}^{scale} in terms of the Be concentration, the incident ion energy and flux, and the surface temperature.

Using these results, we find an empirical scaling for the C-erosion mitigation time given as

$$\tau_{CD}^{scale}\,[\mathrm{s}] = 1.0\mathrm{e}{-7}\, f_{Be+}^{-1.9\pm0.1}\, E_i^{0.9\pm0.3}\, \Gamma_i^{-0.6\pm0.3}\, \exp(4.8(\pm0.5)\mathrm{x}10^3/T_s), \qquad (1)$$

where $f_{Be+} = n_{Be+}/n_e$ is the relative Be ion fraction, E_i is the ion energy in eV, T_s is the surface temperature in deg K, and Γ_i is the ion flux in 10^{22} $m^{-2}s^{-1}$. In fig. 1, the experimentally measured chemical erosion decay time obtained under a variety of plasma conditions is compared with this scaling expression. The experimental values agree well with the scaling expression over a wide range of operating conditions. The decay time has a weak negative power law dependence on the incident ion flux ($\Gamma_i^{-0.5}$), perhaps indicating that at higher fluxes, sputtered Be atoms are more likely to be ionized in the plasma, thereby increasing the re-deposited fraction of Be and thus leading to shorter decay time.

Using typical values for ITER divertor carbon target plates [Federici:1999]*: f_{Be+} = 0.05, E_i = 20 eV, T_s = 1200 K and $\Gamma_i = 10^{23}$ $m^{-2}s^{-}$]* with our scaling law for Be-C film formation, we estimate that τ_{CD} ~ 9 ms for these ITER conditions, which is much shorter than the predicted time between Type I ELMs in ITER(~ 1 s). These PISCES results suggest that protective Be layers on C targets can be formed between ELMs in ITER, which would lead to a reduction of both chemical and physical erosion of the C divertor target. However, even though we might expect protective beryllium carbide surface layers to form in the ITER divertor between ELMs, one still must investigate the response of these surface layers to the harsh conditions expected during an ITER ELM. Such studies are now underway on PISCES-B and will be reported in future publications.

Tungsten is also known to interact chemically with Be forming the stable alloy phases Be_2W, $Be_{12}W$ and $Be_{22}W$, which have melting points below 2250 ºC, significantly lower than that of pure W (~3400 ºC). A consequence of these alloys forming in ITER could be a dramatic reduction in the maximum heat load capabilities of ITER tungsten armor. PISCES-B experiments have determined the plasma conditions which give rise to the formation of beryllium-tungsten alloys on W targets exposed to Be seeded deuterium plasma. A simple zero-dimensional surface particle balance model can be used to predict formation of a 100% coverage Be layer by examining when the incident flux of Be exceeds that lost by plasma-induced and surface processes. The incident flux, $\Gamma_{Be,}$ is given by $\Gamma_{Be}=f_{Be}\,\Gamma_{plasma}(1-R_f)$, where f_{Be} is the fraction of Be in the plasma, Γ_{plasma} is the ion flux and R_f is the surface reflection coefficient for Be on W. The flux of Be lost from the surface, $\Gamma_{Loss,}$ is described by physical erosion and evaporation, $\Gamma_{Loss}=Y_{D\text{-}Be}\Gamma_{plasma}(1-R_d) + f_{Be}Y_{Be\text{-}Be}\Gamma_{plasma}(1-R_d) + \Gamma_{evap}(1-R_e)$ where $Y_{D\text{-}Be}$ and $Y_{Be\text{-}Be}$ are sputter yields, R_d are the corresponding the redeposition fractions and R_e is the probability for evaporated Be to ionize and return to the target surface. Equating these two expressions and solving for f_{Be} leads to a simple equation describing the critical value of f_{Be} for which a deposited Be layer will form. Fig. 2 shows the critical f_{Be} value needed for 100% Be surface coverage as a function of surface temperature for a set of constant ion energies 10, 25, 50 and 100 eV. The formation of a deposited Be layer in PISCES-B (solid lines) occurs at low ion energy bombardment and surface temperatures below ~1200 K; as these parameters are increased, evaporation and re-erosion from the surface requires large plasma f_{Be} values to support the growth of a deposited Be layer on the W substrates. Under the ITER conditions described above (dashed lines) the model predicts that tungsten beryllide can form if the W surface temperatures are below~1300 K and $f_{Be}>0.04$. Studies are underway on PISCES-B to further validate this simple model, which is only applicable to plasma exposed normal surfaces, and thus cannot be applied e.g. to Be trapped within tile gaps; transient heat loads from ELMs also require additional physics.

Conclusions

Controlled mixed material Be/C and Be/W PMI experiments are being carried out on the PISCES-B facility. The results suggest that Be/C mixed material surfaces will have time to form between type-I ELMs on ITER. As a result, the suppression of C chemical erosion is expected to occur under conditions in ITER. Be/W experiments are used to develop a 0-D model for tungeten beryllide formation. This work indicates that Be/W alloys can form under some anticipated ITER divertor conditions.

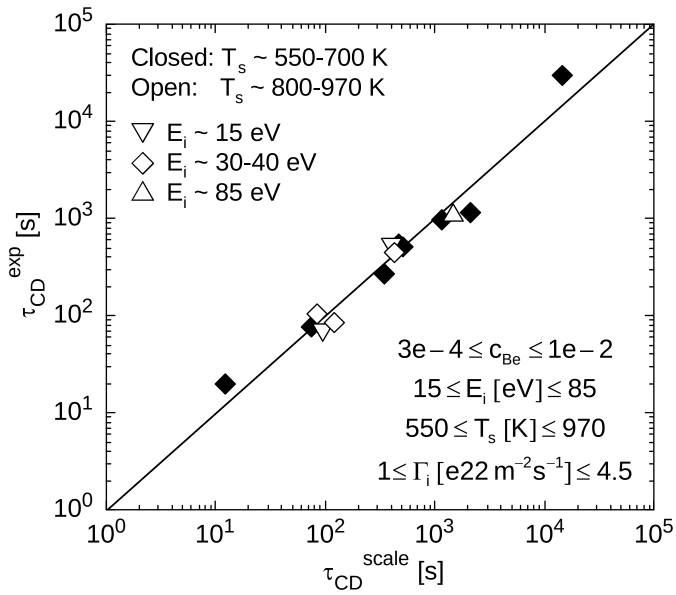

Fig. 1: Measured CD-emission decay time vs. empirical scaling given by eqn 1.

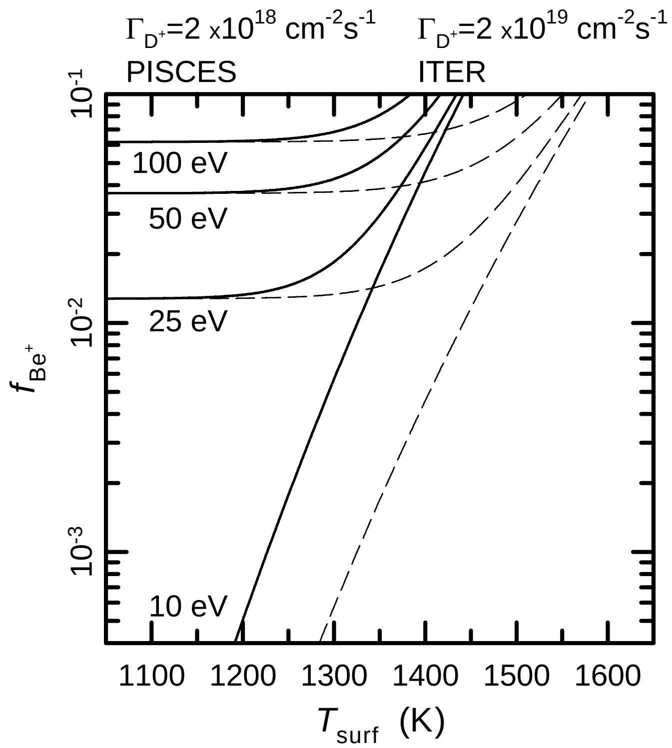

Fig. 2 – Conditions for tungsten beryllide formation in PISCES (solid lines) and predicted for ITER conditions (dashed lines). Beryllide formation occurs for conditions that lie above the ion energy curves.

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