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Analysis of a tungsten sputtering experiment in DIII-D and code/data validation of high redeposition/reduced erosion☆

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ABSTRACT

We analyze a DIII-D tokamak experiment where two tungsten spots on the removable DiMES divertor probe were exposed to 12 s of attached plasma conditions, with moderate strike point temperature and density (~20 eV, ~4.5 × 10^{19} m^{-3}), and 3% carbon impurity content. Both very small (1 mm diameter) and small (1 cm diameter) deposited samples were used for assessing gross and net tungsten sputtering erosion. The analysis uses a 3-D erosion/redeposition code package (REDEP/WBC), with input from a diagnostic-calibrated near-surface plasma code (OEDGE), and with focus on charge state resolved impinging carbon ion flux and energy. The tungsten surfaces are primarily sputtered by the carbon, in charge states +1 to +4. We predict high redeposition (~75%) of sputtered tungsten on the 1 cm spot—with consequent reduced net erosion—and this agrees well with post-exposure DiMES probe RBS analysis data. This study and recent related work is encouraging for erosion lifetime and non-contamination performance of tokamak reactor high-Z plasma facing components.

1. Introduction

Plasma facing component (PFC) sputtering erosion is a critical issue for fusion power. The General Atomics DIII-D tokamak with the Divertor Material Evaluation System (DiMES) manipulator probe [1] is a valuable facility for erosion/redeposition experiments and code validation, in particular due to enabling short duration (~1–5 plasma shots) controlled test surface exposures with well diagnosed near-surface plasmas, and with post-plasma exposure DiMES sample analysis capabilities at Sandia National Laboratories, Albuquerque. Accordingly, there has been a long history of modeling/analysis of DIII-D/DiMES sputtering/erosion experiments, with numerous surface materials and plasma conditions, e.g. [1,2].

A current world-wide fusion research focus is high-Z material PFC surfaces. Recent studies at DIII-D have examined molybdenum test sample sputtering and resulting Mo transport and Mo/C mixing [3–5]. A DIII-D/DiMES experiment with tungsten on a carbon substrate was also performed [5]. In terms of other devices, Ref. [6] analyzed a long exposure campaign at Alcator C-MOD using a 3 cm wide poloidal by full toroidal tungsten divertor. These and other research efforts for a tungsten divertor, e.g. ASDEX Upgrade modeling and experiments [7–9], ITER simulation [10], and JET modeling [11], generally show negligible high-Z material sputtering by the main hydrogen isotope plasma, sputtering by plasma impurities only, high redeposition rates, and resulting low net erosion rates.

Such high redeposition/low erosion is needed for ITER, where only very low plasma contamination by sputtered tungsten can be tolerated, and critically for DEMO and commercial fusion reactors where, additionally, multi-year sputter erosion *lifetime* of PFCs is required. Although the above cited and other work is encouraging in this regard, issues remain including the effects of plasma turbulence on sputtered high-Z material transport, relative contributions of the different transport mechanisms, and redeposited material properties. Continued experiments, simulation, and code/data validation of sputter erosion/redeposition, is thus a major need for fusion power research.

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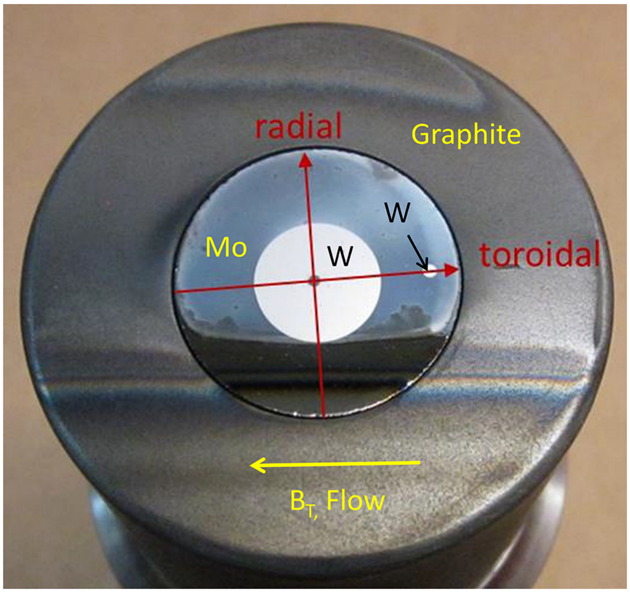

Fig. 1. DiMES-61 5 cm diameter probe containing 1 cm and 1 mm diameter tungsten spots deposited over a molybdenum inter-layer on a silicon substrate. (Central 1 cm spot has a 1 mm diameter non-coating.)

The DiMES-61 experiment [12] analyzed here had relatively high near-surface plasma density, moderate temperature, and significant plasma carbon impurity content, with resulting well-measurable tungsten sputtering erosion. Also, as mentioned for the DiMES system in general, DiMES-61 has a major advantage for modeling purposes, of short duration, well-controlled/near-constant exposure conditions. The experiment used the two-spot deposited metal technique where a very small—in relation to sputtered particle transport distances—1 mm diameter spot is expected to have low redeposition of sputtered material, and thus permits a good measure of *gross* erosion, and where a larger 1 cm spot has higher redeposition, enabling code/data comparisons of the *net/gross* erosion ratio. Also, in contrast to other experiments, the DiMES-61 tungsten films were deposited on a molybdenum inter-layer, reducing complications from near-spot high-Z/low-Z material (W/C) surface mixing.

This paper reports on analysis of the DiMES-61 tungsten samples gross and net erosion. Other issues for this experiment such as erosion of Mo, W/Mo mixing, and off-sample W transport, remain subjects for future modeling. Although there are concerns about uncertainties in the plasma conditions we find good code/data agreement for the tungsten erosion. This adds to the confidence about predictions of acceptable sputter erosion/redeposition performance for future high-Z PFCs.

2. DiMES-61 experiment

Fig. 1 shows the DiMES-61 probe surface. The test sample was prepared by magnetron sputter deposition of Mo and W films onto a 25 mm diameter Si disk at Sandia National Laboratories. The W was deposited as 1 cm and 1 mm diameter films, both ~30 nm thick. The purpose of the smaller spot was to obtain non-spectroscopic measurement of the gross erosion of W [3]. (A 1 mm diameter spot in the middle of the 1 cm sample was left uncoated by W in order to measure gross erosion of Mo. This does not materially affect the present analysis.) Unlike a previous experiment [5], where a carbon inter-layer was used to mask the Si substrate, this time a 20 nm thick Mo inter-layer was used in order to investigate a different set of mixed material effects. The sample was installed in a graphite casing ~5 cm in diameter and inserted in the lower divertor of the DIII-D tokamak using the DiMES manipulator. During the exposure the plasma-facing side of the sample was level with the divertor tile surface within 0.1 mm.

The probe was exposed to three deuterium plasma discharges, in a lower single null magnetic configuration (see Fig. 1(b) in [5] for the magnetic configuration and diagnostic arrangement). The outer strike point was moved to near the center of the DiMES sample once stable plasma conditions were achieved, and kept there for ~4 s in each exposure discharge, giving a total exposure time of ~12 s. Discharges with reversed (counter-clockwise when seen from above) toroidal field (B_T) were used, allowing injection of 2.9 MW neutral beam heating power without transitioning into H-mode (thus avoiding a complicating effect of ELMs). Plasma flow to the divertor plates was toroidally co-directed with B_T (from right to left in Fig. 1). As in previous experiments the 1 mm spot was located upstream of the 1 cm spot, to minimize deposition of W eroded from the larger spot on the smaller one. Local electron density (n_e) and temperature (T_e) at the major radius of the sample were measured by the divertor Langmuir probes and divertor Thomson scattering (DTS) system. WI and MoI emission from the sample region was monitored by an absolutely calibrated digital CMOS camera and a high resolution Multichord Divertor Spectrometer.

Net erosion and deposition was determined by measuring the areal density of the W before and after exposure to the plasma, using Rutherford backscattering spectroscopy (RBS) with 2 MeV He^4. (In addition, erosion of Mo by RBS, and coverage of deuterium and carbon by He^3 nuclear reaction analysis (NRA) was measured, as further described in [12].)

3. Plasma model

We used the process of empirical plasma reconstruction using the OEDGE and EIRENE codes [13,14] to determine the plasma conditions at the outer divertor which best matched the available diagnostics. These diagnostics are Langmuir probe measurements of saturation current (J_{sat}) and T_e; Thomson scattering measurements of T_e and n_e, both at the divertor and upstream; as well as some limited hydrogen and carbon spectroscopic measurements.

Empirical plasma reconstruction uses the diagnostic measurements of J_{sat} and T_e across the target as input boundary conditions to the 1-D, parallel to the field line, OEDGE plasma solver or Onion Skin Model (OSM). The OEDGE code then calculates the plasma conditions (n_e, T_e, ion temperature (T_i), parallel plasma flow speed ($v_{||}$), and parallel electric field) along the field lines on the computational mesh, using the experimental boundary conditions at the target as input, and usually making the following additional assumptions; that $v_{||} = c_s$ (sound speed) at the target, and $T_i = T_e$ at the target. Toroidal symmetry of the plasma parameters is also assumed. The hydrogenic terms used in the plasma solver, typically ionization density, neutral density and energy loss terms, are calculated by the EIRENE code using the initial plasma solution from the OSM. The OSM is then run iteratively with EIRENE until convergence of the calculated plasma values. The resulting 2-D plasma values (radially across the DiMES probe and vertically 0–5 cm above the probe) are then supplied as input to the REDEP/WBC code package.

The target plasma conditions used for the tungsten erosion modeling across DIMES are shown in Fig. 2. As is typical of DIII-D shots, both Te and ne peak slightly outboard of the magnetic strike point, and hence outboard of the DiMES-61 probe center. Initial plasma solutions using the T_e values measured by the Langmuir probes did not agree well with the Thomson measurements. Since the J_{sat} measurement is considered more reliable than the Langmuir probe T_e measurement, the J_{sat} was left fixed while the target temperature was adjusted to obtain a better match between the calculated plasma and the divertor Thompson measurements. Setting the