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Alcator C-Mod divertor**

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A study of tungsten migration in the Alcator C-Mod divertor

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Abstract

A toroidally-continuous row of bulk tungsten (W) tiles was installed near the typical location of the outer strike-point in the Alcator C-Mod divertor and was removed for analysis after two campaigns (3151 plasma discharges). External beam (in-air) particle induced X-ray emission (PIXE) analysis has been used to observe campaign-integrated W migration patterns in the otherwise Mo divertor using the W as a tracer for divertor erosion and transport. With a set of high spatial resolution PIXE measurements (~ 3 mm resolution), poloidal profiles of W migration have been constructed. Redeposition of up to 1.5×10^{21} atoms/m² (~ 20 nm equivalent thickness) is observed on the outer and inner divertor, and in the private-flux region. The campaign-integrated deposition on the analyzed tiles corresponds to net W erosion of ~ 60 nm (> 0.014 nm/s). The migration profiles indicate sputtering and prompt redeposition in the outer divertor, neutral and ion transport through the private-flux region, and transport in the scrape off layer.

Keywords:

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1. Introduction

The core plasma performance in tokamaks is strongly affected by complex plasma surface interactions (PSI) at the edge. The plasma facing components (PFC) are exposed to extreme conditions including high mechanical stress, high heat loads, exposure to energetic particles, and radiation damage. High-Z refractory metals have high melting points and are among the most resilient materials against physical and chemical sputtering [1]. They are therefore a desirable choice for PFCs and are used in Alcator C-Mod and many other tokamaks. Plasma exposure still causes sputtering of high-Z surfaces which results in erosion and the introduction of impurities into the plasma. Since high-Z impurities in the core plasma degrade energy confinement due enhanced radiation, boron coatings are frequently used in C-Mod. Boronization is often performed daily and deposits ~ 100 nm of boron (B) which has been shown to improve performance until its effectiveness is diminished, usually after tens of plasma discharges, due to erosion. The introduction of B however further complicates the PSI because B becomes the primary impurity in the edge plasma which contributes significantly to high-Z sputtering [2]. Since net erosion and migration of material can, over time, cause macroscopic changes and damage the integrity of PFCs, it is important to study these effects so they can be minimized. A study of erosion and poloidal migration of tungsten (W) and molybdenum (Mo) is described in the following sections.

2. Experiment

Alcator C-mod has a plasma facing first wall made from closely packed Mo tiles with $\sim 2 \times 2$ cm surfaces. In 2007, a toroidally-continuous row of bulk W tiles was installed in the outer lower divertor of C-Mod at one poloidal location near the typical position of the outer divertor strike-point. Since all of the plasma-eroded W originated from one toroidally symmetric row and no W melting was observed, the W could effectively be used as a tracer to observe campaign-integrated W erosion and migration patterns [3] in the otherwise Mo divertor.

After two experimental campaigns which exposed the PFCs to a total of 3151 plasma discharges, a set of Mo tiles from a single toroidal location, spanning the poloidal extent of the lower divertor were then removed for analysis. In addition, a W tile from this toroidal location and one adjacent were removed for analysis. These tiles were examined for W and Mo using external beam (in-air) particle induced X-ray emission (PIXE) analysis.

PIXE analysis was chosen because of its sensitivity to high-Z elements. Since X-ray production cross sections for K and L emission are typically very large for high-Z elements (10-1000 barns) and vary smoothly with energy PIXE can be used to effectively measure average areal densities of trace amounts of surface deposition [4]. An external beam was used to simplify and expedite measurements and sample handling.

Analysis was performed with the tandem accelerator at the MIT PSI Center using an external beam produced by a 2 MeV proton beam passing through 3 mm diameter aperture supporting a 7.5 μm thick vacuum tight kapton exit foil. The Mo-L, W-L $_{\alpha}$, and W-L $_{\beta}$ X-ray peaks were measured using an Si(Li) detector. A detection geometry with 45 $^{\circ}$ incidence and detection angles was used to allow for beam access to the sample and line-of-sight access to the detector.

3. Results and Discussion

Tungsten migration due to erosion of W at the outer strike-point has important implications for high Z impurity transport. The W that is deposited in the divertor originates from a toroidally continuous row of tiles at one poloidal location in a high erosion region of the outer divertor. This effectively creates a toroidally symmetric tungsten source. Symmetry simplifies the analysis to two dimensions, allowing predictions to be made regarding the mechanisms that cause W migration. In addition, it was shown with Rutherford backscattering spectroscopy that the W was not localized at any depth and was distributed throughout the B surface films, verifying that the W deposition resulted from sputtering over many plasma discharges.

PIXE spectra were measured systematically at 160 locations across 22 Mo tiles spanning the lower C-Mod divertor in one poloidal plane. In addition, spectra were measured on a W tile from the same poloidal plane and a second toroidally adjacent W tile. On the outer divertor and divertor dome, measurements were taken along the center of each tile every 3 to 5 mm in the poloidal direction. The sides of outer divertor tiles showed visible signs of deposition where plasma entered the gap, so measurements were made on the side of these tiles near the edge closest to the plasma facing surface. The inner divertor tiles have sloped surfaces to shadow bolt holes in their centers from direct plasma exposure so measurements were made on all three of the sloped surfaces on these tiles.

The data presented are measurements of the W and Mo areal density [atoms/m²] derived from the PIXE spectra. For convenience, areal density is represented as an effective thickness: 1.59 nm \approx 10²⁰ W atoms/m² and 1.55 nm \approx 10²⁰ Mo atoms/m² assuming that each element is at its solid the density at the surface (6.31×10^{28} W atoms/m², 6.45×10^{28} Mo atoms/m²). These deposition patterns are indicative of the possible mechanisms of plasma edge transport and are described in the following sections.

3.1. Global W Migration

Tungsten is sputtered from the W tiles by plasma particles from the scrape off layer (SOL) which often have temperatures of > 10 eV. Though the vast majority of the particles in the SOL are deuterons (D^+), boron ions $B^{+1,+2,\dots}$ are the major cause of W and Mo sputtering [2] since the W and Mo sputtering yields are negligible for D^+ ions from a 10eV plasma ($E_i < 50$ eV). Significant amounts of this sputtered W were detected at specific locations of the lower divertor, while W was not observed in others. These results are summarized in the W profile shown in figure 1.

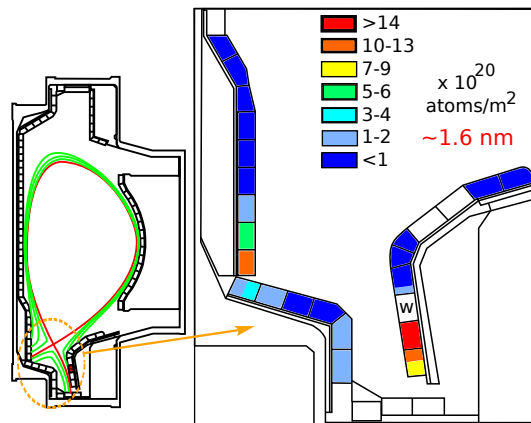


Figure 1: Eroded tungsten from the W row forms a distinct migration pattern with deposition on the C-Mod outer divertor, inner divertor, and divertor dome.

3.2. W and Mo Deposition on the Outer Divertor

The largest quantities of W were observed on the outer divertor tiles located directly below the row of W tiles while a negligible amount was observed above (figure 2). It appears that the sputtered W particles become

ionized in the SOL and are confined to the flux surface until they intercept a PFC surface where they are redeposited. This is consistent with the measured net downward migration because the magnetic geometry is such that all of the flux surfaces with line-of-sight to the sputtering location intercept a lower position on the vertical target.

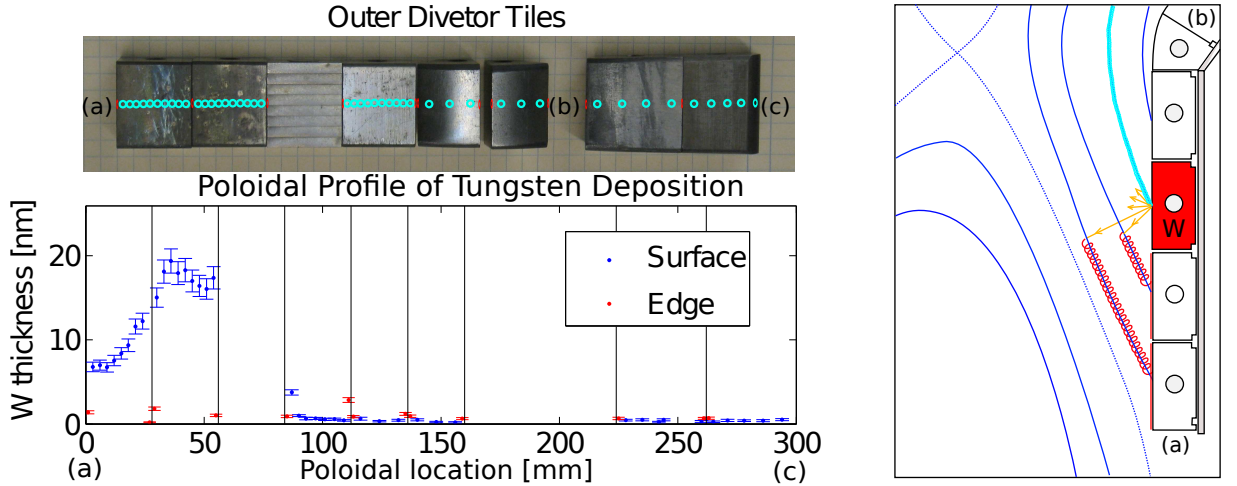


Figure 2: Sputtered W is ionized and redeposited causing net downward migration of W (right). An image of analyzed tiles (top left). PIXE measurements of W deposition thickness(lower left).

A similar quantity of Mo is also observed on the surface of both of the analyzed W tiles (figure 3). A significant fraction of Mo was likely sputtered onto the W tiles above (in the poloidal dir.), and redeposited as in the model just described, however its is possible that the Mo originated elsewhere since nearly all PFCs are Mo. The Mo deposition on W data shows a trend which decreases toward the top of the tile surface. This trend is not predicted by the model, however it can be attributed to a higher net erosion towards the top of the tile due to longer plasma exposure at higher temperatures throughout the tile's life time. This was confirmed by statistical data described in section 3.5.

3.3. Deposition in the Private Flux Region

Deposition in the private flux (PF) region is seen in two areas: on the vertical surface of the divertor dome, and adjacent to the inner divertor. The distribution pattern shows relatively large deposition on tiles adjacent

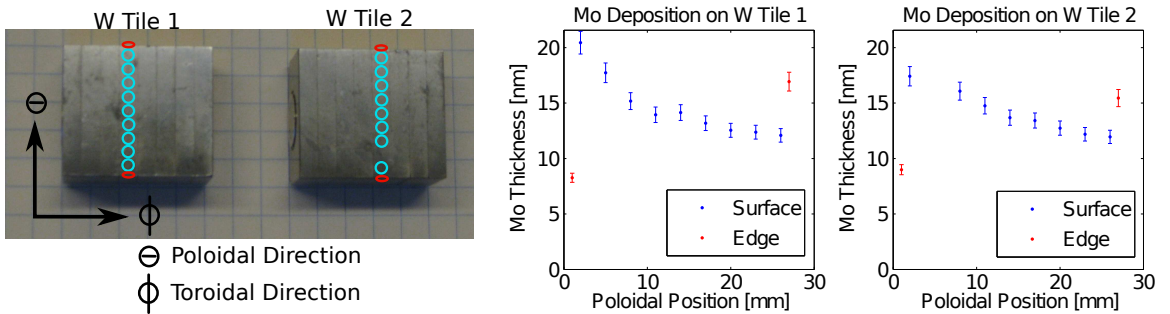


Figure 3: Sputtered Mo is ionized and transported from above tiles onto the tiles in the W row. An image of analyzed tiles (left). PIXE measurements of Mo deposition thickness (right).

to the inner divertor, and less deposition the vertical surface which increases smoothly toward the bottom (figure 4).

The vertical surface of the divertor dome has line-of-sight access to the W tiles and is not connected by field lines. The W therefore must migrate as sputtered neutrals that pass through the plasma across the ~ 25 mm gap. More W however, is observed toward the bottom of the dome rather than on the surface directly across from the W row which intercepts the largest solid angle. There are several possible explanations for this result. Since the ions strike the PFCs with oblique incidence, the sputtering distribution may have a preferred ejection angle. This is likely because sputtering angular distributions, usually approximated by a simple cosine distribution, tend to shift strongly in the forward direction with oblique incidence [5]. Another possibility is that, due to the oblique angle made between the flux surfaces and the tiles, sputtered particles with an ejection angle normal to the surface must travel further through the SOL than those with downward angles thus producing the observed deposition pattern.

The tiles on the horizontal surface that are near the inner divertor do not have line-of-sight access to the W row. Therefore, the deposition must occur from ions that flow along the magnetic field in the PF region. The sputtering however, occurs in the hotter SOL and must cross the separatrix. If the W ionization mean free path is long enough, it is possible that some W can cross the separatrix and enter the PF region before being ionized. It is also possible that transport of ions across the separatrix into the PF region could be enhanced due to the $\vec{E} \times \vec{B}$ drift [6].

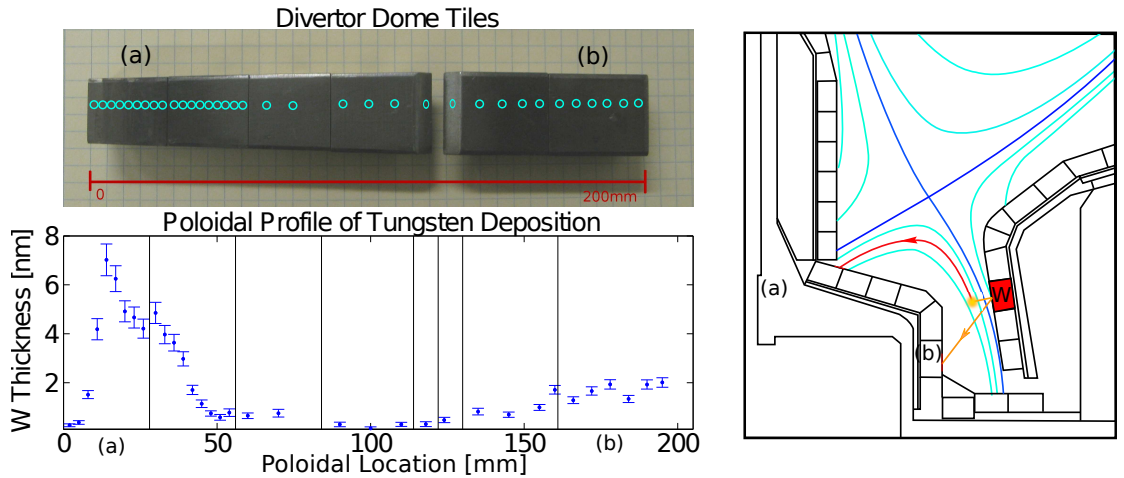


Figure 4: Tungsten was observed to migrate to the divertor dome to regions with line-of-sight access as neutrals to location (b) and as ions along flux surfaces to location (a). An image of analyzed tiles (top left). PIXE measurements of W deposition thickness (lower left).

3.4. Deposition on the Inner Divertor

A significant amount of tungsten is observed to accumulate at or near the inner divertor strike-point but is negligible elsewhere (figure 5). Since the inner strike-point intercepts the divertor both above and below this region of deposition during the campaign, there are several transport mechanisms that may cause this migration.

It is possible that this deposition originates from the W ions that flow along the field across PF region through the same mechanism as the deposition that is observed on the horizontal surface of the divertor dome (section 3.3). The other possibility is that the W could be transported around the core plasma in the SOL. Significant amounts of W in the SOL would likely diffuse into the core plasma. Migration through the SOL would seem to be a smaller effect than PF transport since the C-Mod soft X-ray diagnostics do not typically observe W in the core plasma.

3.5. Plasma Statistics

Statistical data was collected on the strike-point location and plasma conditions from C-Mod data from the 2007 and 2008 campaigns to help interpret the erosion patterns on the outer divertor. The strike-point location was determined from the location of the radial flux coordinate ρ at

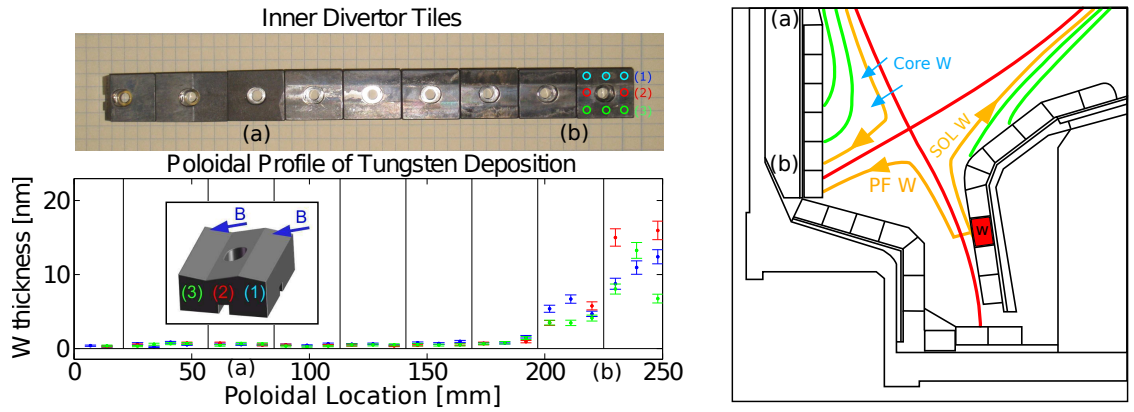


Figure 5: Tungsten was observed to migrate from the outer divertor to the location at/near the inner divertor strike-point through the private flux region and/or in the scrape-off layer (right). An image of analyzed tiles (top left). PIXE measurements of W deposition thickness (lower left). Illustration of the sloped tile surface geometry (lower middle)

the midplane from EFIT equilibrium reconstruction data, projected onto the divertor. Plasma conditions throughout each plasma discharge such as density n_e , temperature T_e , etc. were determined from flush mounted Langmuir probe data. A histogram of the strike-point data binned for various threshold temperatures is shown figure 6.

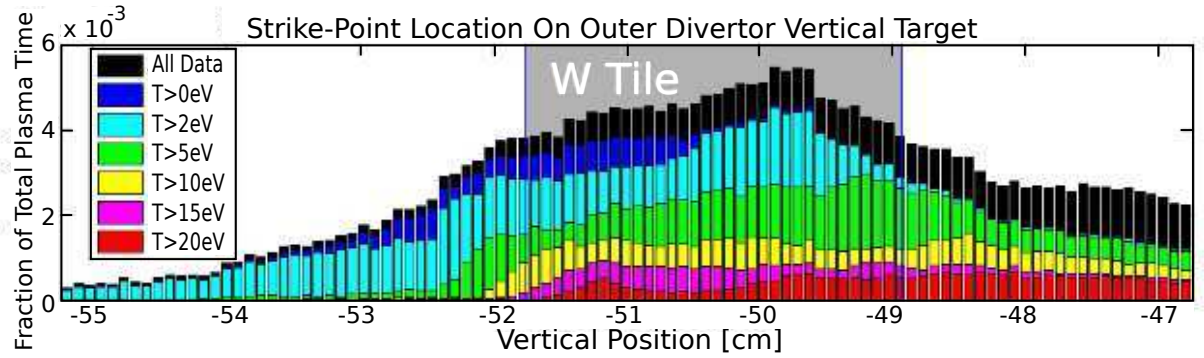


Figure 6: Statistics on the outer divertor's exposure to the strike-point were collected for several plasma temperature ranges for all available plasma data using EFIT and Langmuir probe data.

4. Summary and Conclusions

PIXE proved to be a very effective method for measuring trace amounts of tungsten deposition on PFCs. These measurements made it possible to observe campaign integrated tungsten migration in the C-Mod divertor and infer possible mechanisms for W and Mo migration including sputtering and prompt redeposition in the outer divertor, neutral and ion transport through the private-flux region, and transport in the scrape off layer.

From the tungsten deposition profile an estimate was made for net tungsten erosion assuming toroidal symmetry. The measured tungsten areal density was integrated and normalized to the plasma facing area of the W tiles to give the net erosion $\Delta W_{measured} = 58 \pm 3$ nm during 3151 plasma discharges. From the net erosion, the erosion rate $\Delta W/\Delta t$ was estimated using the total lower divertor plasma exposure time Δt . Since the plasma conditions vary substantially throughout each plasma discharge, Δt was defined as the sum of time during which the strike-point was located on the lower divertor with strike-point temperature above a threshold value. The divertor in C-Mod was exposed to plasma with $T_e > 5$ eV for 4218 s and 2317 s with $T_e > 10$ eV corresponding to erosion rates 0.014 nm/s ($T_e > 5$ eV) and 0.025 nm/s ($T_e > 10$ eV). These results represent a lower bound on the net tungsten erosion because it is possible that tungsten was transported elsewhere in C-Mod and it is also likely that the W is embedded deeply in the boron films where the sensitivity of the PIXE technique is decreased. These two effects suggest that the areal densities of deposition and net erosion are slightly higher than was measured with PIXE analysis.

In a previous study by Wampler et al. [7] a net erosion of ~ 100 nm of molybdenum was measured at the same poloidal location as the position of the W tiles. This measurement was from a campaign with 1090 discharges, meaning that the equivalent Mo erosion rates is roughly 0.09 – 0.1 nm/s. Therefore, the measured erosion rate for tungsten appears to be more a factor of ~ 5 lower than the erosion rates for molybdenum which is consistent with W's lower sputtering yield.

References

- [1] G. Federici et al 2001 Nuclear Fusion **41** 1967
- [2] B. Lipshultz, Physics of Plasmas **13**, 056117 (2006)

- [3] Y. Ueda et al, Journal of Nuclear Materials 363-365 (2007) 66-71
- [4] S. A. E. Johansson, et al, Particle Induced X-Ray Emission Spectrometry (PIXE), John Wiley and Sons, Inc., 1995
- [5] W. Eckstein, Journal of Nuclear Materials 248 (1997) 1-8
- [6] C. Boswell et al, Journal of Nuclear Materials 290-293 (2001) 556-560
- [7] W. R. Wampler, Journal of Nuclear Materials 266-269 (1999) 217-221