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Measurements of Tungsten Migration in the DIII-D Divertor

W.R. Wampler[a,*], D. L. Rudakov[b], J. G. Watkins[a] , A. G. McLean[c], E. A. Unterberg[d], P. C. Stangeby[e]

[a]*Sandia National Laboratories, Albuquerque, NM, USA*
[b]*University of California, San Diego, CA, USA*
[c]*Lawrence Livermore National Laboratory, Livermore, CA, USA*
[d]*Oak Ridge National Laboratory, Oak Ridge, TN USA*
[e]*University of Toronto Institute for Aerospace Studies, Toronto, Canada*

Abstract

An experimental study of migration of tungsten in the DIII-D divertor is described, in which the outer strike point of L-mode plasmas was positioned on a toroidal ring of tungsten-coated metal inserts. Net deposition of tungsten on the divertor just outside the strike point was measured using the Divertor Materials Evaluation System (DiMES) sample exposure system. Tungsten coverage, measured by RBS, was found to be low and nearly constant with both radius and exposure time closer to the strike point, whereas farther from the strike point the W coverage was much larger and increased with exposure time. Depth profiles from RBS show this was due to accumulation of thicker mixed-material deposits farther from the strike point where the plasma temperature is lower. These results are consistent with a low near-surface steady-state coverage on graphite undergoing net erosion, and continuing accumulation in regions of net deposition.

1. Introduction

The interaction between a magnetically confined plasma and plasma-facing components results in erosion and redeposition of material. Understanding this process is necessary for predicting component lifetime, tritium retention and the influence of impurities on plasma conditions. Codes such as ERO [1] and WallDYN [2] are being developed to simulate plasma-wall interactions in tokamaks, but this is a challenging task due to the complex physical mechanisms, coupling between distant source and sink regions due to long-range transport by the plasma, and the large temporal and spatial variations in both plasma and wall conditions. Development of such codes is guided by comparison to experimental studies in which the effects on the plasma, and/or the materials, from known plasma exposure conditions can be quantified [2, 3, 4, 5].

Such an experiment was recently conducted in DIII-D in which the migration of tungsten from a toroidal ring source in the divertor was studied. Deposition of tungsten onto adjacent regions of the graphite divertor was measured using the DiMES sample exposure system [6]. In the experiment described here, the outer strike point (OSP) of L-mode lower single-null deuterium plasmas was positioned on a toroidal ring of tungsten-coated tiles, and net deposition of tungsten on a DiMES collector probe, located just outside the strike point, was measured by Rutherford backscattering (RBS). Spatial and temporal variations in W deposition were characterized by analyzing graphite inserts in the DiMES probe which were replaced a few times during the experiment. Plasma conditions were kept constant during the exposure and were characterized in the region of the OSP and DiMES probe by Langmuir probe and Thompson scattering measurements. Here we summarize the results of the measurements of tungsten deposition and discuss their implications for modeling. Contrary to preliminary ERO modeling [6], tungsten coverage was observed to be high and increase with exposure time on the outboard side of the probe (i.e. farther from the stride point and W source), versus low and independent of exposure time on the inboard side. Depth profiles by RBS show this is due to accumulation of thicker mixed-material deposits from net deposition farther from the strike point where the plasma temperature is lower. This suggests that net erosion nearer the strike point quickly produces a low steady-state coverage of W which migrates across the surface by successive erosion/redeposition, to regions of net carbon deposition where it is buried. The preliminary ERO simulations apparently did not reproduce the transition from net erosion to net deposition of carbon with increasing distance from the strike point.

2. Experiment and discussion

Figure 1 illustrates geometry of the DiMES probe and tungsten source during the experiment. Figure 1 also shows the electron density and temperature of the plasma determined by divertor Thompson scattering (DTS) and Langmuir probe measurements. The graphite DiMES probe had its inboard edge 1 cm away from the outboard edge of the W ring and featured two thin inserts 1 mm wide, i.e. toroidal extent, by 5 cm in radial extent that were changed a few times during the experiment. Plasma exposure consisted of 23 similar L-mode lower single null plasmas with the OSP located 2.7 cm inside the outboard edge of the W insert for 3.7 seconds per shot. These were DIII-D shots 167196 through 167219, with no plasma on shot 167206 and with no disruptions. Post-exposure RBS analysis of the inserts provided measurements of W coverage versus radial position over the extent of the probe for various plasma exposure durations. Both inserts (A1 & B1) were replaced prior to the first shot of the experiment to characterize the initial condition. Inserts B2, B3, B4 were replaced after shot numbers 8, 12 and 16 respectively. Both inserts (A2, B5) and the half-shells of the DiMES assembly were removed after shot 23.

Figure 2 shows the areal density of tungsten on the inserts and one of the half-shells, versus radial position. There was visible evidence of deposition on the outboard side of the half-shell as shown in the insert photograph in figure 2. On the inboard side nearer the OSP, the W coverage was nearly the same on the various samples at about 1.5×10^{14} W atoms/cm^2, hence was insensitive to the duration of the exposure. In contrast, on the outboard side the W coverage was much higher and increased with exposure time.

Figure 3 shows the W concentration versus depth at the various radial locations on the inserts and the half-shell. These depth profiles were obtained from the RBS spectra by transforming the energy scale to a depth and the yield scale to a W concentration relative to simulations of RBS spectra for W in carbon using the SMINRA program [7]. The RBS spectra showed that the concentrations of other elements were inconsequential, apart from oxygen at ~0.04 atom fraction and deuterium which only weakly influences the RBS spectra. Results for insert B4 are not shown but were similar to those for B3. On the region of low coverage on the inboard side, the W is at the surface, within the depth resolution of the measurement (~ 3×10^{17} C atoms/cm^2 FWHM), consistent with a surface undergoing net erosion. On the outboard side the W concentration is around 0.0015 W/C atomic fraction, extending to depths of 5-6×10^{18} C atoms/cm^2. Values of depth are given here in units of C atoms/cm^2 because the deposited material is mostly C and the depth scale comes from the energy loss which depends on the number of atoms per cm^2. The physical thickness scales inversely with density. At the density of graphite, the thickness would be about 100 nm per 10^{18} C atoms/cm^2, however since deposited material is less dense than graphite, its thickness is likely to be about one micron on the outboard side of the half-shell. Estimating the deposit thickness from the depth profiles on the various samples in figure 3 and dividing by the exposure times, we find that the thickness increases with exposure time at a rate of approximately

$4x10^{16}$ C atoms/cm^2/s. This rate of carbon deposition is similar to that seen in a previous experiment in which a DiMES probe was exposed at the OSP of L-mode plasmas [8]. The low ratio of W/C in the deposit indicates that the ratio of W to C flux onto the surface, and hence the relative concentrations of W to C in the plasma are also very low, even with the OSP on the tungsten ring.

Due to the short (~1mm) mean-free path for ionization, eroded tungsten is locally redeposited with high probability. This reduces the net W erosion rate and suppresses long-range direct transport of W by the plasma. However, on surfaces undergoing net erosion, tungsten may migrate across the surface by successive erosion-redeposition steps. This would cause a rapid approach to a low steady-state W coverage on surfaces undergoing net erosion and cause migration of W to regions of net carbon deposition, qualitatively consistent with the results of this experiment. The transition from net erosion to net deposition with increasing radius is consistent with the decreasing electron temperature of the plasma with increasing radius as shown in figure 1. Lower electron temperature gives lower incident ion energy and less sputtering. The unanticipated results from this experiment give new insights into physical mechanisms of impurity migration on plasma-facing materials. Quantitative comparison between these results and models should lead to improvement of the models.

Acknowledgments

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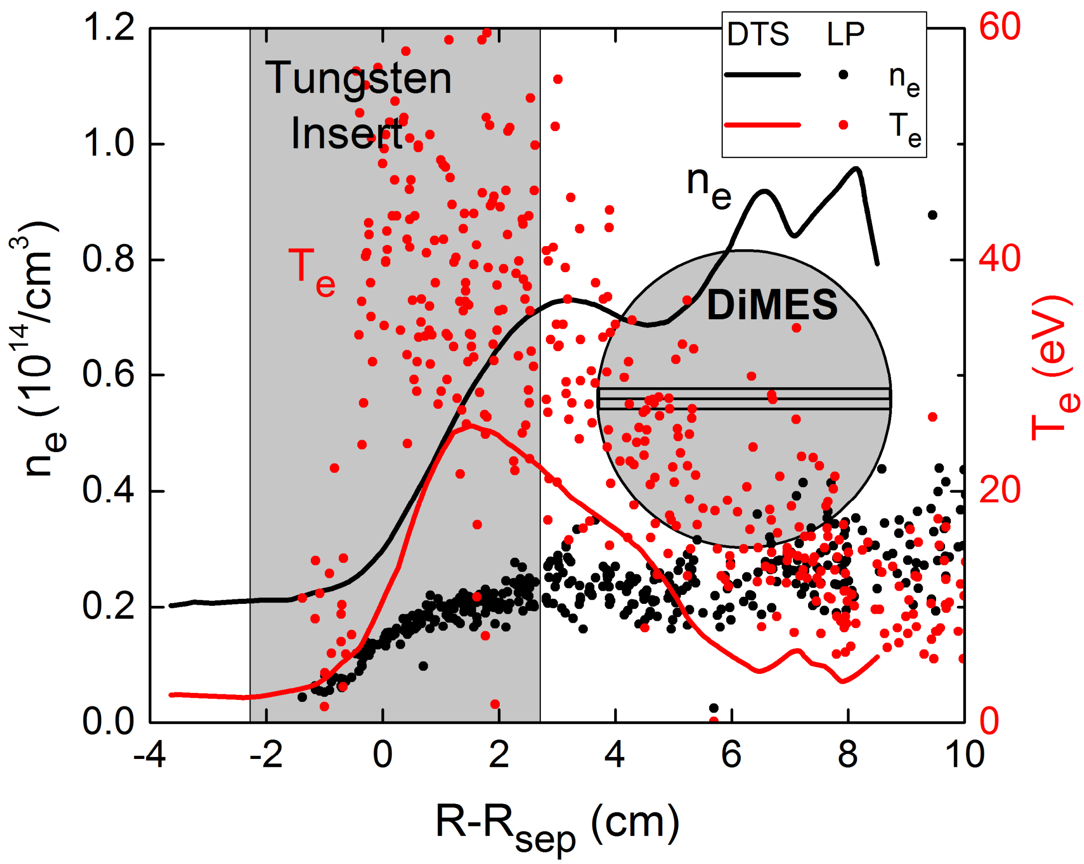

Figure 1. Illustration of the geometry of the DiMES probe and tungsten source relative to the radius of the outer separatrix on the divertor (R_{sep}). The black and red curves show averaged values of n_e, T_e near the divertor versus distance from the OSP from the divertor Thompson scattering diagnostic for shots 167193-167195. The points show n_e, T_e from Langmuir probe measurements during a strike point sweep on shot 167195.

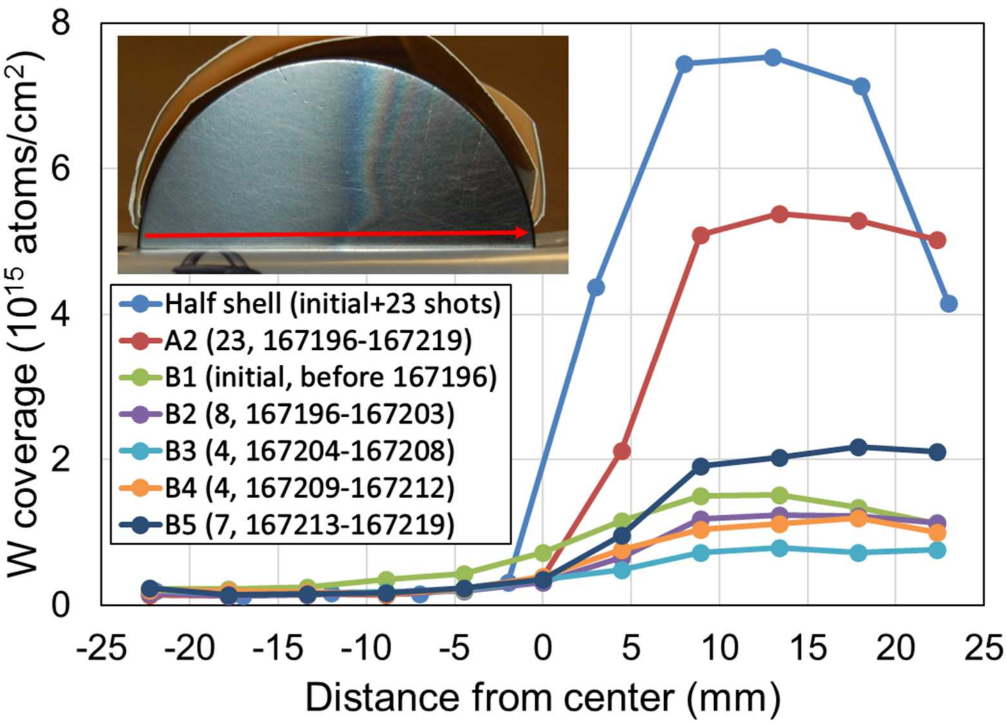

Figure 2 Areal density of tungsten on the DiMES probe half shell and inserts measured by RBS versus distance from the center of DiMES along a radial scan indicated by the red arrow in the insert. The insert photo shows visible evidence of deposition on the outboard side of the half-shell. The legend indicates the sample; in parenthesis are the number of shots and the shot number sequence as described in the text.

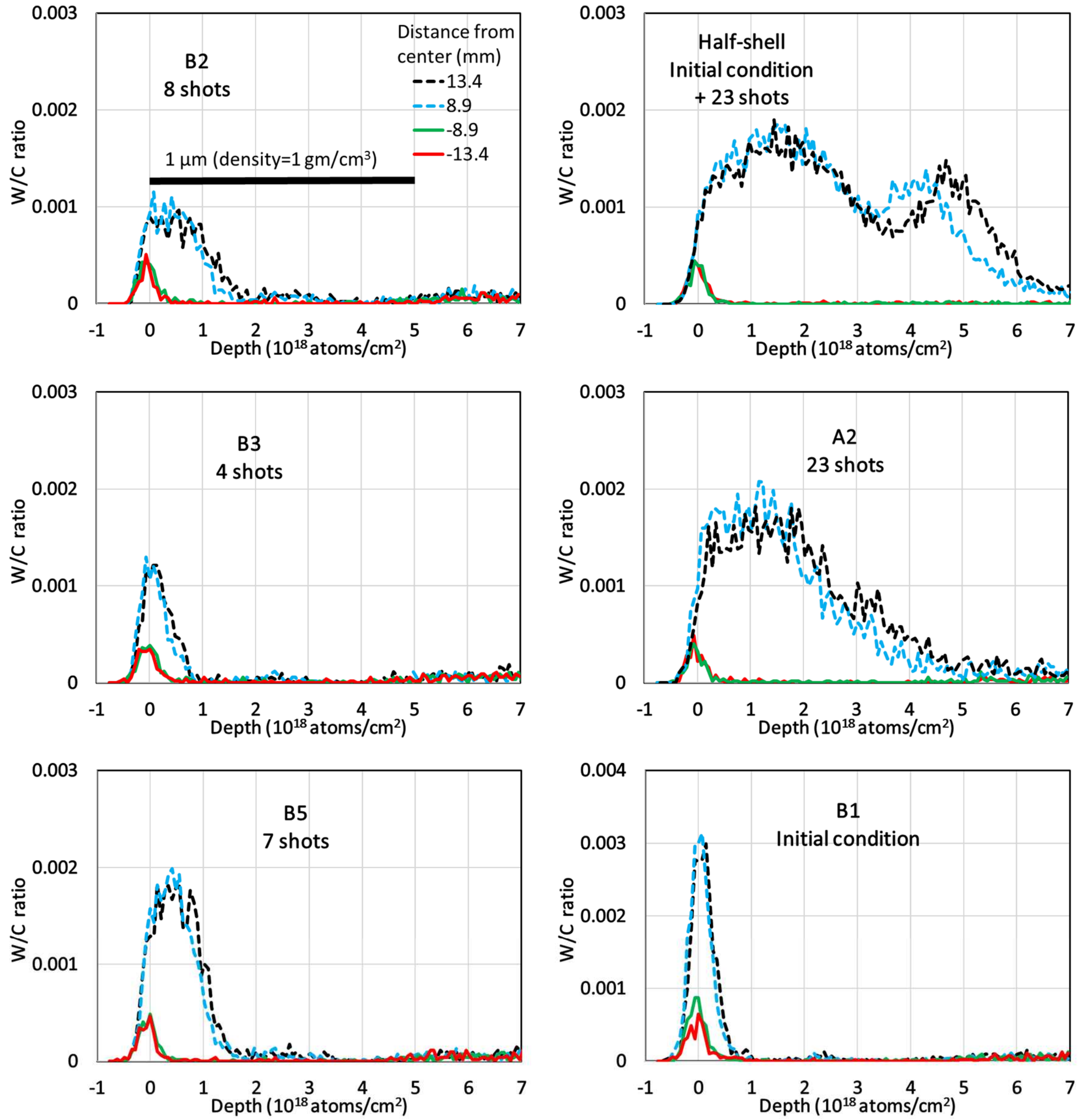

Figure 3. Tungsten to carbon atomic fraction versus depth on the various samples measured by RBS at locations near -13, -9 mm (red, green solid) and 9, 13 mm (blue, black dashed) from the center of DiMES. The scale bar in the upper left panel indicates the physical thickness for a density of 1 gram/cm^3 for the deposited material.