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An experimental comparison of gross and net erosion of Mo in the DIII-D divertor

P.C. Stangeby [a,*,1], D.L. Rudakov [b], W.R. Wampler [c], J.N. Brooks [d], N.H. Brooks [e], D.A. Buchenauer [f], J.D. Elder [a], A. Hassanein [d], A.W. Leonard [e], A.G. McLean [g], A. Okamoto [h], T. Sizyuk [d], J.G. Watkins [c], C.P.C. Wong [e]

[a] University of Toronto Institute for Aerospace Studies, Toronto, Canada M3H 5T6
[b] University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0417, USA
[c] Sandia National Laboratories, Albuquerque, NM 87185, USA
[d] Purdue University, West Lafayette, IN 47907, USA
[e] General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA
[f] Sandia National Laboratories, P.O. Box 969, Livermore, CA 94551-0969, USA
[g] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
[h] Tohoku University, Sendai, Japan

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ABSTRACT

Experimental observation of net erosion of molybdenum being significantly reduced compared to gross erosion in the divertor of DIII-D is reported for well-controlled plasma conditions. For the first time, gross erosion rates were measured by both spectroscopic and non-spectroscopic methods. In one experiment a net erosion rate of 0.73 ± 0.03 nm/s was measured using ion beam analysis (IBA) of a 1 cm diameter Mo-coated sample. For a 1 mm diameter Mo sample exposed at the same time the net erosion rate was higher at 1.31 nm/s. For the small sample redeposition is expected to be negligible in comparison with the larger sample yielding a net to gross erosion estimate of 0.56 ± 12%. The gross rate was also measured spectroscopically (386 nm MoI line) giving 2.45 nm/s ± factor 2. The experiment was modeled with the REDEP/WBC erosion/redeposition code package coupled to the ITMC–DYN mixed-material code, with plasma conditions supplied by the OEDGE code using Langmuir probe data input. The code-calculated net/gross ratio is =0.46, in good agreement with experiment.

1. Introduction

Net erosion of high-Z plasma-facing surfaces in a tokamak is expected to be reduced by local redeposition due to sputtered atom collisions with the impinging plasma [1]. In earlier experiments on ASDEX Upgrade [2] and DIII-D [3,4], samples of W, Mo and V were exposed to divertor plasmas, and post-mortem analysis found redeposited material mostly within a few mm from the samples, supporting the local redeposition picture. Reduction of net compared to gross erosion has been demonstrated for W in ASDEX Upgrade [5]. However, in Alcator C-MOD the measured campaign-integrated peak net erosion of Mo divertor tiles was found to be ~10× higher than that computed using the REDEP/WBC code, while the gross erosion predicted by the code was a reasonable match to the gross erosion rate measured spectroscopically using a MoI emission line [6]. The present experiment was aimed at measuring both net and gross erosion of Mo under stable well-diagnosed plasma conditions allowing more accurate comparison with the modeling.

The standard method for measuring gross erosion rates in tokamaks is spectroscopic: the intensity of an atomic line of the sputtered impurity is measured and converted to a particle influx rate using an inverse photon efficiency value, $S/XB(T_e)$, obtained from atomic theory or calibrated experiment. This method involves a number of uncertainties. It is therefore desirable to develop a non-spectroscopic method as a check. Such a method is reported here based on post mortem IBA analysis of the net erosion of a sample that is small enough that, for the plasma conditions involved, redeposition on the sample of particles sputtered from the sample is unlikely, thus gross erosion ~ net erosion.

2. Experiment

Three separate experiments were carried out, see Table 1, using slightly different plasma conditions. In the 1st experiment a silicon disk 1 cm in diameter coated with a 24 nm thick film of Mo and mounted in a graphite Divertor Material Evaluation System (DiMES) holder, Fig. 1, was inserted flush with the lower divertor tiles of DIII-D and exposed to a series of 7 reproducible lower single

* Corresponding author. Address: General Atomics, P.O. Box 85608, San Diego, CA 92186-5608, USA
E-mail address: stangeby@fusion.gat.com (P.C. Stangeby).
[1] Presenting author.

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Table 1
Features of the three experiments.

Date	Exposure time (s)	Initial thickness of 1 cm sample (nm)	Probe data. T_e-max (eV), n_e-max (10^{19} m^{-3})	MoI filter passband (nm)	With 1 mm sample	Net erosion rate[a] (nm/s)
8/1/2011	28	24.16	30, 1.5	10	No	0.42 ± 0.02
4/23/2012	12	23.81	No data	1	No	0.50 ± 0.05
5/1/2012	4	16.13	40, 1.2	1	Yes	0.73 ± 0.08

[a] Measured by ion beam analysis.

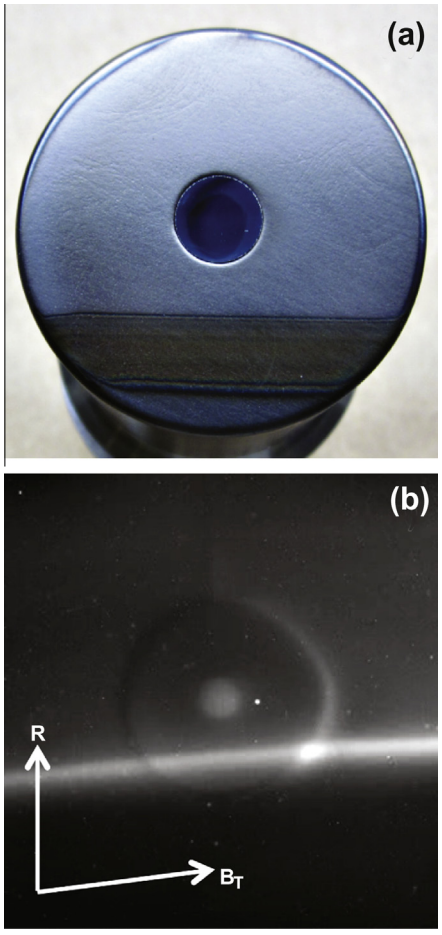

Fig. 1. Post-exposure photograph of the DiMES holder with Mo sample (a); image of the sample taken during the exposure by a CCD camera with MoI 390 nm filter (b). First experiment.

null L-mode deuterium plasma discharges. The exposure was performed near the attached outer strike point (OSP) for a total flattop time of ~28 s. The plasma density and temperature near the strike point were measured by the divertor Langmuir probes, Fig. 2. The gross erosion rate of Mo, essentially completely due to a ~1% plasma carbon background, was measured spectroscopically, using an absolutely calibrated CCD camera with MoI filter centered around 390 nm and having a bandwidth of ~10 nm. A sample image from the camera is shown in Fig. 1b. The 10 nm bandwidth passed several non-MoI lines (identified using a high resolution spectrometer which was not, however, intensity calibrated for this wavelength), including some CII lines. The bright strip in Fig. 1b is due to CII, while the illuminated circle is MoI light plus emission of several other lines in the passband; the bright strip corresponds to the location of the strike point, as identified by magnetics, thus conveniently confirming the location visually. The dark strip in Fig. 1a was identified by ion beam analysis to be deposited carbon, and evidently occurred in the cold plasma region just inside the strike point location. By correcting for the contributions of the non-MoI lines passed by the filter, a first estimate of 0.68 nm/s for the gross erosion rate was made using the inverse photon efficiency, S/XB, for the MoI line measured on PISCES by Nishijima et al. [7]. Allowance was also made for (i) the transmission of the 10 nm filter, (ii) the transmission of a 2nd filter used to block the intense D_α line, (iii) the transmission of the vacuum window, (iv) reflection from the Mo surface and (v) the fact that only part of the MoI triplet near 390 nm was passed by the filter. The combined uncertainty was estimated to be a factor of ~4×. Therefore in the 2nd and 3rd experiments, a 1 nm bandwidth filter centered on the MoI line at 386 nm was used, reducing the uncertainty estimate to a factor of 2. The high resolution spectrometer showed no emission in the 1 nm passband other than the MoI line and the camera view no longer registered the bright CII band along the strike point location.

Net erosion of Mo was measured by comparing the Mo layer thickness measured by Rutherford backscattering (RBS) before and after the exposure, Fig. 3. Measured toroidal and poloidal profiles of the net Mo erosion across the sample are shown in Fig. 3a. The reduction of Mo thickness was 11.6 ± 0.6 nm on the average, corresponding to an average net erosion rate of 0.42 ± 0.03 nm/s for the plasma in the 1st experiment.

The distribution of Mo redeposited on the graphite holder was also measured by RBS, Figs. 3b and 4. As expected, Mo deposits were concentrated near the Mo-coated sample edge, with an e-folding length of ~2 mm. Concentration of the deposited Mo was a factor of 8–10 larger on the downstream side of the sample compared to the upstream side. Contrary to what had generally been expected, the total amount of Mo found on the holder was only 19% of the net amount of Mo eroded from the sample. This initially surprising result is discussed in modeling Section 3.

^{3}He nuclear reaction analysis was used to measure the coverage of carbon on the Mo/Si sample, which was low, and of deuterium on the sample and adjacent graphite [8]. Deuterium coverage was low, consistent with net erosion, over most of the DiMES head except for a narrow band just inside of the OSP (see Fig. 1a), where net deposition occurred at a rate of 1.8×10^{17} carbon atoms/cm^2/s with a relatively high deuterium content of D/C = 0.8 atom ratio.

The 2nd experiment was used to establish that (i) the 1 nm filter passed enough light to provide an adequate spectroscopic measurement and (ii) a single shot is sufficient to give an adequate IBA measurement. Accordingly both were employed for the 3rd experiment where the Langmuir probe measurements indicated that the plasma was somewhat different than in the 1st experiment: the peak T_e was 40 eV instead of 30 eV and the peak density was 1.2×10^{19} m^{-3} instead of 1.5×10^{19} m^{-3}. For the 3rd experiment a 1 mm diameter Mo sample was included on the graphite head, 0.5 cm upstream of the 1 cm diameter Mo sample where it would receive negligible Mo deposition from the 1 cm sample, Figs. 3b and 4. For such a small sample and these plasma conditions, simple estimates of the sputtered neutral ionization distance – order mm – indicate that very few of the Mo particles sputtered from the

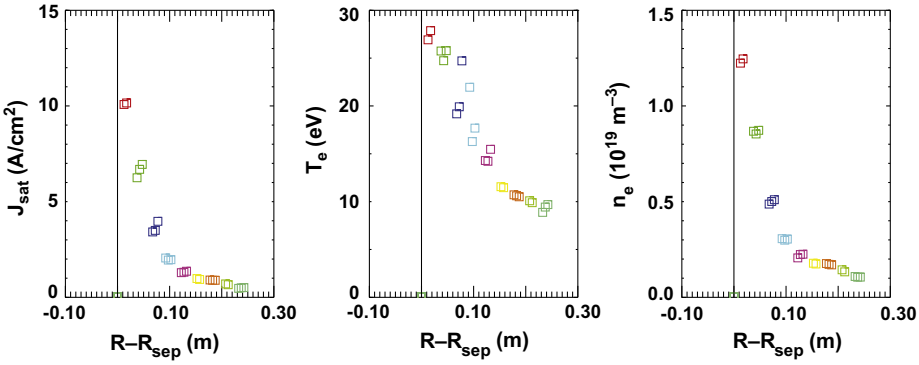

Fig. 2. Langmuir probe profiles across DiMES. The 1 cm sample is centered about 1 cm from the outer strike point. First experiment.

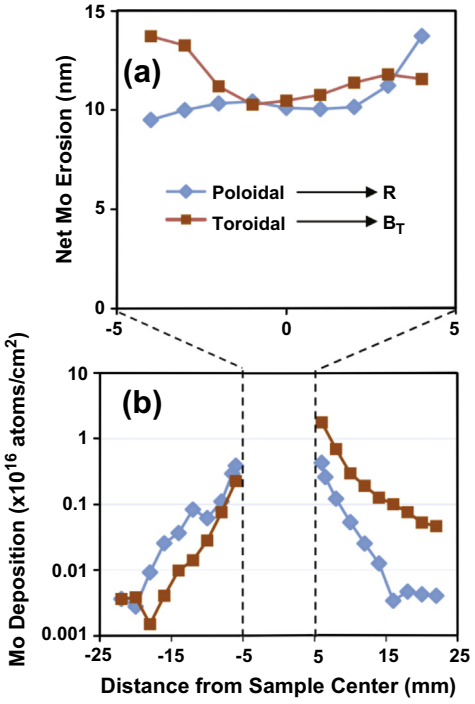

Fig. 3. RBS measurements of net erosion of Mo from the sample (a) and Mo deposition on the graphite holder (b). First experiment. Upstream is to the left.

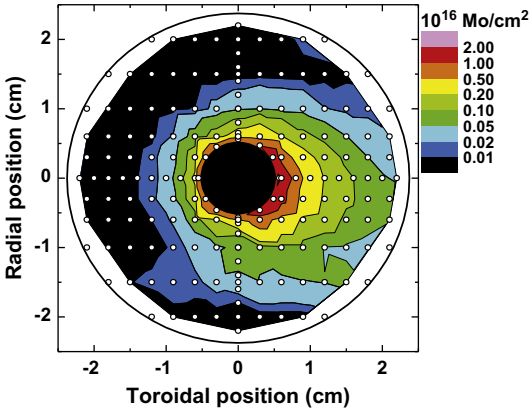

Fig. 4. As Fig. 3b but a 2D map of Mo deposited on the complete 5 cm diameter graphite surface. First experiment.

1 mm spot would be expected to return to and deposit back on the 1 mm spot. This was confirmed by detailed REDEP-ITMC code package modeling, Section 3, which found only ~5% redeposited. Thus gross erosion ~ net erosion and so by measuring the net erosion of the 1 mm Mo sample using IBA, a non-spectroscopic method for measuring gross erosion can be carried out.

For the 3rd experiment IBA showed that the thickness of the 1 cm Mo spot reduced from 16.1 nm by 2.93 nm (average values over the spot) for the 4 s plasma exposure, while the 1 mm Mo spot was reduced from 12.9 nm by 5.26 nm, giving a net/gross erosion ratio of 0.56 ± 12%, or correcting for the 5% deposition on the 1 mm spot, 0.59 ± 12%. This ratio was close to the code calculated result of 0.46, Section 3. The gross erosion rate of the 1 cm sample was thus 1.31 nm/s, or correcting for the computed 5% deposition on the 1 mm spot, 1.38 nm/s. For the same experiment the spectroscopic method gave a gross erosion rate of 2.45 nm/s, with uncertainty about a factor of 2, therefore in good agreement with the non-spectroscopic method.

3. Modeling

Molybdenum sputtering and transport from DiMES was modeled with the REDEP/WBC erosion/redeposition code package coupled to the HEIGHTS package ITMC–DYN mixed-material evolution/response code, and with plasma conditions supplied by the OEDGE code with Langmuir probe data input. As described in e.g. [9,10] WBC computes the 3-D, sub-gyro-orbit, full-kinetic motion of sputtered atoms/ions, subject to the Lorentz force motion, and velocity-changing and charge-changing collisions with the plasma. Major new simulation capability involves the Mo/C mixed-material evolution and re-sputtering of Mo deposited in the carbon divertor surface, per coupled REDEP/ITMC–DYN calculations, as described in [11]. Focus of the modeling was on the first experiment.

Modeling inputs include a D plasma with 1% carbon, with nominal at-probe sheath/plasma boundary conditions for the first experiment, $T_e = T_i = 30$ eV, $n_e = 1.5 \times 10^{19}$ m^{-3} (essentially uniform over the Mo sample surface), sound speed flow at the sheath boundary, and with measured magnetic field components. The BHI-3D sheath code [12] was used to verify WBC models for the dual structure, magnetic + Debye sheath, including incident carbon ion impingement energy/angle for the studied DIII-D conditions. The surface geometry is of course that of a spot and not toroidally symmetric: this is fully taken into account in the 3-D modeling.

The REDEP simulations show a high Mo redeposition fraction (54%) on the 1 cm Mo spot and a consequent ratio of ~2 to 1 for gross/net erosion. (For comparison, a special computation suppressing the impurity electric field acceleration and impurity/

plasma collisions showed a 20% redeposition fraction, this being roughly equal to the so-called "prompt" redeposition effect of gyromotion return of an ionized sputtered particle to the surface.)

The predicted Mo content in the carbon portion of the DiMES head is 13%, which compares well with the IBA measured 19% (for the 1st experiment in both cases). Other modeling predictions include a ~100% overall Mo redeposition on the divertor (including the DiMES head) with essentially zero core plasma Mo contamination. The initially surprising result that only 19% of the Mo removed from the 1 cm sample was found on the 5 cm DiMES graphite head is seen in the code modeling to be due to fast saturation of the Mo in C and subsequent re-sputtering. Although experiments #2 and #3 were not simulated in as much detail, initial REDEP modeling indicates similar trends.

4. Discussion and conclusions

For a specific divertor plasma condition (low density, high T_e, no ELMs) the measured ratio of net to gross erosion was found to agree well with code modeling, i.e. is in accord with the 'standard' model of prompt, local re-deposition. It should be noted that the significance of the findings reported here is not the absolute numbers for net and gross erosion, nor even their ratio – since all these numbers are specific to the particular geometry and plasma condition used; rather the significance lies in the good agreement between measurements and model. Since the latter is the 'standard picture' of net versus gross erosion, it tends to confirm that model. To achieve a definitive conclusion will, of course, require that such tests now be extended to other geometries and plasma conditions.

The large model/data discrepancy in Alcator C-MOD (gross erosion to net erosion measurement of ~3–10 versus a model prediction of >30) stands in contrast with the experiments reported here. While the discrepancy is not yet understood it must be pointed out that the C-MOD observation was based on campaign-integrated conditions (1300 s) where plasma conditions can vary greatly through the course of the campaign. Although such plasma variation was modeled, there is more room for uncertainty than in the present DIII-D, limited time exposure experiments. (The higher gross/net C-MOD ratio, whether measured or modeled, is due to both the much higher density and the use of a full Mo divertor instead of just a small sample as used in this report). On the other hand, for the plasma conditions used here there is not a great difference between net erosion and gross erosion, only a factor of 2, and therefore to be more conclusive, these studies should be extended to include higher density and/or larger samples where, according to the standard model, a lower ratio of net erosion to gross erosion is expected.

The sputtered Mo that does not promptly redeposit on the 1 cm sample apparently travels only a short distance before redepostion adjacent to the edge of the Mo sample, as evidenced by the rapidly decaying profiles of Mo on the C surface, Figs. 3b and 4. However, there is also longer range transport of some ions, as expected by the relatively low density and the near-oblique magnetic field angle to the surface, as well as longer mean-free-paths for sputtered Mo atom ionization arising from the higher energy portion of the sputtered energy distribution. Longer range transport is caused by re-sputtering from the DiMES carbon surface, involving mixed materials effects including a high sputtering rate due to shallow Mo deposition and reduced binding energy of Mo/C relative to Mo/Mo.

A new, non-spectroscopic method for measuring gross erosion rates has been demonstrated, based on post mortem surface analysis measurement of the net erosion experienced by a very small sample where gross erosion will be close to net erosion. Such a method makes optimum use of the removable DiMES facility, and provides confirmation of the spectroscopic method which is subject to a number of uncertainties, including the values of the S/XB ratio. The non-spectroscopic method provides a means of calibrating S/XB for general tokamak use.

Future studies will examine tungsten, and also aluminum as proxy for Be. As noted above, for the plasma used here, net erosion was only somewhat less than gross erosion, owing to the rather long ionization mean-free-path for the sputtered Mo atoms. In these future studies it is planned to use plasmas with higher densities and thus shorter mean-free-paths and thus lower ratios of net erosion to gross erosion.

Acknowledgments

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