Modeling, analysis, and code/data validation of DIII-D tokamak divertor experiments on ELM and non-ELM plasma tungsten sputtering erosion

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Abstract

We analyzed recent DIII-D tokamak tungsten divertor probe experiments using advanced, coupled, sputter erosion/redeposition, plasma, and surface response code packages. Modeling is done for ELMing H-mode, and L-mode plasmas, impinging on various size tungsten deposits on Divertor Material Evaluation System (DiMES) carbon probes. The simulations compute 3D, full kinetic, sub-gyromotion, impurity sputtering and transport, including changes in tungsten surface composition and response due to mixed deuterium and carbon ions irradiation. Per our analysis, ELM (edge localized mode) plasma sputtering in DIII-D mostly involves free-streaming high energy (~500–1000 eV) D⁺ and C⁺ ions, with high near-surface plasma density. L-Mode sputtering is due to impurity sputtering (C, W) only, with lower density. All cases show complete redeposition of tungsten on the divertor, with significant redeposition on the tungsten spots themselves, and low self-sputtering. Comparison of ELM plasma gross tungsten erosion simulation results with in-situ spectroscopic data is good, as are code/data comparisons of net erosion using post-exposure Rutherford backscattering (RBS) data for the L-mode probes. The analysis, extrapolated to a full tungsten divertor, implies low net erosion and negligible plasma contamination from sputtering. These results support the use of high-Z plasma facing surfaces in ITER and beyond.

Keywords: tungsten sputtering, erosion/redeposition, ELM erosion, DIII-D DiMES Probe

(Some figures may appear in colour only in the online journal)
There is a long history of experiments and associated modeling using the 5 cm diameter removable DiMES divertor probe in the DIII-D tokamak at General Atomics—to study plasma/material interactions, particularly sputtering erosion, for numerous candidate surface materials, and to predict/validate performance for ITER and future fusion reactors, e.g. [3, 4]. The past focus has been for non-ELMing plasmas but understanding of high energy transfer edge localized mode (ELM) sputtering response is important for future tokamak operation. In particular, ELMs could possibly be suppressed in ITER but this is uncertain. Continued understanding of non-ELM and inter-ELM performance is also of obvious major importance. Another issue for ITER is performance of the low-Z-wall/high-Z-divertor mixed-material Be/W system—DIII-D simulations can provide insight into this by virtue of the analogous DiMES C/W system.

We therefore analyzed a series of DIII-D experiments in which tungsten-on-carbon deposited spots on DiMES divertor probes were exposed to both H-mode ELMy plasma [5] and L-mode (low confinement, relatively high turbulence) plasmas, with a range of near-surface electron temperatures and densities. The ELM experiments exposed a fully tungsten coated DiMES probe to multiple plasma shots, with different ELM sizes, measured gross erosion via in-situ photon emission, and used analytical models to assess results. The L-mode experiments used the ‘big spot’ (1.5 cm diameter) and ‘small spot’ (1 mm diameter) technique of Stangeby et al [6], with multiple repeat-shot exposure and post-exposure lab measurements, to assess net (big spot) and approximate gross (small spot) tungsten erosion. We performed advanced computational simulations for both experimental series and compare with available data. The code/data comparisons are generally good and add to the model’s validity. The simulation outputs can thus provide insight into the physical processes of sputter erosion and transport, and aid analysis of subsequent experiments at DIII-D and elsewhere.

2. ELM plasma erosion analysis

The DIII-D ELM experiments are described in detail in [5]. Briefly, time-dependent, in-situ spectroscopic measurements were made of gross erosion of a tungsten coated DiMES probe, for well-characterized ELMy H-mode plasma shots. The tungsten coating consisted of a ~200 nm magnetron sputter-deposited layer on top of a finely polished ATJ graphite substrate. W-coated DiMES probes were inserted into the divertor plasma just outboard of the outer strike-point (OSP). The spectroscopic emission intensity from the WI 400.9 nm line was monitored via the DIII-D WI filterscope diagnostic with 50 kHz time resolution, cross-referenced against the high-resolution multichannel divertor spectrometer for absolute intensity calibrations [7]. This measurement was converted into absolute gross erosion of tungsten atoms via the ionizations/photon (S/XB) method. The background plasma density, temperature, ion flux, and heat flux to the DiMES location were also measured concurrently via Divertor Thomson Scattering, Langmuir probes, and IR thermography, respectively.

In these discharges, the inter-ELM WI filterscope signals were too noisy to make a robust comparison of the relative contribution of the intra-ELM and inter-ELM phases to the total tungsten erosion rate. Previous analysis of a database of W erosion measurements from the DIII-D Metal Rings Campaign demonstrated that the intra-ELM W sputtering is small (~10%) relative to the inter-ELM phase at low ELM frequency (~10 Hz) but the two phases produce comparable amounts of W sputtering at higher frequencies (~50 Hz) [8]. We note that this is different from the JET-ILW result that the JET intra-ELM W sputtering dominates in all ELM regimes [9] because of: (a) the higher physical sputtering yield of C on W, in DIII-D, relative to Be on W, at the low impact energies of the inter-ELM phase; and (b) the higher C impurity content in DIII-D (1%–2%) than Be impurity content in JET (0.5%).

We performed simulations for the ELM experiments involving plasma surface interaction with the full 5 cm diameter tungsten coated probe, for the highest erosion, intra-ELM period, peak power loading time. Our analysis computes the tungsten sputtering and transport, at the fixed peak time, using the REDEP/WBC [1, 2] 3D, full-kinetic, Monte Carlo, sub-gyro-orbit, erosion/redeposition code package, coupled with DiMES mixed-material surface response simulations from the ITMC-DYN (Ion Transport in Materials and Compounds-Dynamics) [10, 11] dynamic surface mixing and sputter code. Plasma near-surface parameters (Ne, Te, Ti, flow velocity, pre-sheath electric field, etc.) and impinging particle fluxes and energies are given by the ‘free-streaming model’ and related models of [5, 12, 13] and REDEP/WBC models (e.g. oblique magnetic field incidence sheath structure and potential) as applicable.

Following the approach of [5], the plasma conditions at the target during ELMs are inferred via the free-streaming model, which assumes that a flux tube from the plasma pedestal top detaches into the scrape off layer directly to the divertor. We define a reference ELM plasma model for our analysis with free-streaming D+ flux of 5.0 × 10^{22} m^{-2} s^{-1} and 2% C^{+6} flux, both with impinging ion energies of 1000 eV; a 2% flux of recycling-based 250 eV C^{+2} ions; and near-surface 25 eV plasma temperature and 1.2 × 10^{20} m^{-3} density—corresponding to peak ELM conditions for the ‘Case 1’ high temperature pedestal, strongly attached divertor conditions of [5].

The free-streaming model implies significant sputtering of tungsten by the majority plasma deuterium ions, unlike non-ELM cases where D+ energies are typically below the W sputtering threshold, and as further explained in [5]. Sputter yields and atom velocities are given by ITMC-DYN, for all incident particle species, for carbon saturated tungsten. (Such C saturation results from exposure of the W surface prior to the ELM experiments.)

ITMC-DYN simulations have been benchmarked against laboratory experiments as well as NSTX experiments [14]. The code uniquely integrates all collisional and near surface thermal processes to study the effect of impurities, surface segregation, and erosion on hydrogren isotope retention in plasma facing materials under multiple mixed ions irradiation during steady state and transient events. The general
physics picture of carbon impingement on a tungsten surface, from ITMC-DYN simulations of various DIII-D experimental conditions, shows C implantation to ~15 nm depth, peaking along a ~1–5 nm zone, of order 50% C/W, reached in several seconds. For the present studies the ITMC-DYN simulations compute the self-consistent DiMES surface C/W ratio profile based on incident particle fluxes, and include ion/atom collisional interactions, D diffusion, retention, and desorption, and considering traps concentration during implantation and material heating. As noted in [5], the 2% carbon flux used in ITMC-DYN for the coupled code-package ELM simulations is in good agreement with measurements from the DIII-D edge charge exchange recombination spectroscopy system for discharges with a similar shape to those studied here. Per these inputs, surface equilibrium is found by ITMC-DYN to be reached before the ELM measurements in question, with ITMC-DYN computing the ELM-period W sputtering yields and velocity distributions (energy, elevation angle, azimuth angle) for each incident D, C, and W ion species. These are then used in WBC to launch W atoms from the probe surface, on a particle-by-particle basis using Monte Carlo.

Figure 1 shows typical computed sputtered W neutral and ion trajectories—in this figure to better show distances involved—from the central 1 mm diameter portion of the probe. The trajectories involve initial ionization of W atoms, ionization to higher charge states, velocity-changing collisions with the incident plasma, and Lorenz force motion due to magnetic fields and sheath and pre-sheath electric fields. As shown, there is high tungsten redeposition within a range of several millimeters. We also note that the transit time for the redeposition process (<10^{-6} s) is much shorter than an ELM duration time or characteristic time for change in plasma parameters.

Table 1 summarizes results for the reference case as well as for an experimental case conducted with smaller ELMs, ‘Case 3’ of [5], resulting in lower free-streaming and recycling energies, with differences in near-surface plasma parameters, and with slightly higher (20%) free-streaming flux (scaling with pedestal density and plasma sound speed). Both simulation cases show a similar qualitative picture. The fractional contributions to tungsten sputtering by the reference ELM case are found to be 50% by free-streaming D\(^+\) ions, 40% by C\(^+\)\(^+\) ions, and the remainder by recycling C\(^+\)\(^+\) ions. Such fractional contributions determine the energy distribution of the sputtered tungsten atoms. The sputtered tungsten atom energy, averaged over all sputtered particles, is 24 eV for the reference case and 16 eV for the smaller ELM case. Sputtered flux differs by about a factor of two between the two ELM conditions, obviously due to the different free-streaming energies and resulting sputtering coefficients.

There is very high redeposition of sputtered tungsten on the probe itself, approaching unity. This high fraction is a major result of the high near-surface electron density for the DIII-D ELM plasmas. Tungsten ions redeposited on the probe tend to be those that were ionized within the ~1 mm magnetic sheath region. Another finding is that W self-sputtering by redepositing ions is low, ~3%–8%, due to the moderate redeposited ion average energy, primarily from sheath acceleration, of order 100 eV, (as shown, however, with high variance). Of major significance is that redeposition on the entire divertor, for all cases, is 100%, i.e. with ~5% W deposition on the non-DiMES part of the DIII-D divertor. No tungsten (for 10\(^6\) histories per case) leaves the (~0–5 cm) near-surface region.

A key result is that the computed tungsten gross sputtered fluxes, per table 1, are a reasonable match to the relevant peak rates seen in the time-varying WI spectroscopic data [5]. This and the other simulation outputs tend to provide reasonable validation of the model/assumptions of the Abrams et al analytical type analysis [5].

Although analysis of peak ELM power/particle loading erosion is the most critically needed and cost-effective modeling activity, we performed some analysis of other portions of the ELM discharges, for the Case 1 experiment. We find the same qualitative features of the erosion/transport process, with some differences in redeposition rates but high in any event. For example, for a near-surface electron density of half the peak value (i.e. for N\(_e\) = 0.6 \times 10\(^{20}\) m\(^{-3}\) occurring at 2 ms after the peak, the probe redeposition fraction is 91%, down from the peak-conditions 95. This would tend to increase the net erosion, however, the particle flux is much lower at this time. Also, in terms of sensitivity to changes in the plasma near-surface temperature, we found little difference in redeposition fractions for a T\(_{e}\) range of 20–30 eV.

Extrapolating the present and past modeling results, e.g. [2, 15], to a divertor with complete tungsten coverage, the net erosion rate would be much smaller (up to two orders of magnitude) than the gross rate, and with negligible core plasma contamination by sputtering. As with the present DiMES experiments, this would be due to very short W atom ionization distances, resulting intense redeposition via electric and magnetic field acceleration, and impurity/plasma collisions. Such high redeposition of tungsten and other high-Z divertor materials has been likewise predicted by various past studies, such as REDEP/WBC code package analysis for tokamaks.
in general e.g. [1, 2], DIII-D e.g. [3], and ITER [15]; ERO code modeling of JET ELM effects [16], and DIII-D [17]; and SOLPS code package modeling of ITER [18]. In view of the critical importance of this issue, the present additional findings for the DIII-D ELM experiments and code/data validation are encouraging.

Regarding plasma contamination however, our findings apply to the studied main plasma/divertor interaction area—there are other potential sources of core contamination, in DIII-D, ITER, etc., such as from sputtered or plasma-transient vaporized W, transported from the divertor to more remote boundary regions, and then re-emitted into a lower density near-surface plasma with significantly longer ionization distances.

We also studied the effect—for both the ELM simulations and the L-mode analysis to be described—of some model changes such as in WI ionization rate coefficients (which rates are somewhat uncertain), and magnetic field and sheath related changes in impinging ion azimuthal angle distributions (e.g. isotropic incidence vs. the reference non-isotropic). No significant qualitative change in the results was seen, i.e. with the simulation outputs still showing high redeposition, low self-sputtering, and in related parameters. Likewise, substantially increasing the temperature gradients of the near-surface plasma, affecting the so-called thermal force, showed essentially no change in results. These insensitivities are due to the small tungsten transport distances, for both the ELM and L-mode plasmas studied, where strong Lorentz forces and plasma collisions dominate the impurity transport.

3. L-mode plasma analysis

Further model benchmarking activity was performed on L-mode DIII-D experiments conducted at high divertor electron density to roughly simulate, in steady state, the divertor plasma conditions that are present transiently during ELMs. The plasma discharge scenarios were similar to those described in [3], but at higher heating power and gas puffing rate to produce high density L-mode divertor plasmas with sufficiently high electron temperature to cause measurable amounts of tungsten gross and net sputter erosion. The diagnostic setup was effectively identical to the H-mode cases discussed above and in [5].

Figure 2 shows the probe structure and geometry for the L-mode experiments. In addition to the central 1.5 cm diameter big W spot there are two 1 mm diameter small spots each in the toroidal and radial directions. The idea is that the small spots exposure gives a good indication of gross erosion, i.e. having minimal redeposition, whereas the big spot data will show net erosion [6]. To interpret the data it is then vital to have highly accurate computations of the redeposition rates and the related self-sputtering contribution.

We analyzed two DIII-D L-mode experiments that had well defined near-constant plasma conditions. These were a higher near-surface plasma temperature case, DiMES ‘Cap #3’, using 3 discharges with 10.80 s total exposure; and a ‘Cap #1’ case with lower Te, higher Ne, with 5 discharges and 13.25 s exposure.

Table 2 shows Rutherford backscattering (RBS) erosion data for the two L-mode experiments. Also measured by RBS were toroidal and radial tungsten erosion profiles on the DiMES probe through the 1.5 cm spot center. A key goal for our analysis is to predict/explain the central spot observed net erosion—for code validation purposes and to assess, for example, ITER divertor performance with full tungsten coverage. A secondary goal is to provide insight into the toroidal small spots erosion. An issue for the latter is the asymmetry in the T1, T2 data. In theory, toroidal symmetry should be obtained in a tokamak. As shown in table 2, however, there is a 31% difference in T1, T2 erosion, oddly enough the same for both cases (although measurement uncertainty percentage is high for the Cap #1 data). One contributor to asymmetry is different transfers of central spot material to the small spots. As discussed below we computed this and it explains some of the asymmetry.
Figure 2. Photo of DiMES probe Cap #1 after L-mode plasma exposure in DIII-D. The 5 cm diameter carbon-base probe has a 1.5 cm diameter deposited central tungsten spot, and four 1 mm deposited tungsten small spots. Arrows show the lines along which W coverage was measured in the toroidal (T) and radial (R) directions. R1, R2, T1, T2 show the locations of the 1 mm spots, centers of which are 1.565 cm from the probe center. Direction of the toroidal magnetic field $B_T$ is indicated. A band of toroidally symmetric carbon deposition is also visible just inboard of the OSP location. Cap #3 has identical geometry.

Table 2. Net tungsten erosion fluence on DiMES L-Mode experiments measured by Rutherford backscattering (RBS). (Measurement uncertainty is $\pm 2 \times 10^{19}$ at m$^{-2}$.)

| 1 mm spots | 15 mm central spot average |
|------------|---------------------------|
| Cap # 1    | 7.2 9.4 −1.7 1.6 1.6     |
| Cap # 3    | 79.1 103.9 78.3 71.1 28.7 |

The general methodology for DiMES experiments and our associated modeling is described in several publications, e.g. [3, 4]. We note that the ref [3]. experiment used a 1 cm big spot and a single 1 mm small spot of W on a DiMES probe with Mo substrate; thus the new probe experiments analyzed here have more than twice the central spot area, use four vs. one small spots, with carbon substrate, also with L-mode exposure vs. previous H-mode plasma. We expect, however, that general sputtered impurity transport features, i.e. role of plasma collisions, electric and magnetic fields, etc, should be similar, and new modeling results here should be highly useful to compare and extend past results and conclusions.

The above described coupled code modeling technique for the ELM analysis is likewise used for the L-mode simulations, with the ITMC-DYN code supplying sputter yields and sputtered velocity distributions to REDEP/WBC. The L-mode plasma background inputs to WBC are from data-calibrated OEDGE/DIVIMP code calculations. and various direct DIII-D B-field, geometry etc data.

OEDGE uses a 1D fluid equation solver along individual flux surfaces (parallel to the field lines) starting from the target surface. The code uses Langmuir probe measurements.
of the target condition profiles ($J_{\text{sat}}$, $T_e$) as boundary conditions for the 1D fluid solver. Divertor Thomson scattering measurements of electron density and temperature along the field lines are used to further constrain the reconstruction of the experimental plasma conditions. Monte Carlo simulations of carbon erosion, transport and deposition, incorporating both physical and chemical sputtering of carbon, are then run using DIVIMP to determine profiles of carbon fluxes/fluences, charge state and average impact energy across DiMES.

The DIVIMP computation of absolute C/D ratio, however, is relatively uncertain, involving large area, less clear, far-boundary plasma parameters, in contrast to the relative C ion fluxes and energies to the DiMES probe, involving the better characterized plasma scrapeoff layer region near the small DiMES probe. We therefore use a preferable, data-based method, to be described, using the OEDGE/DIVIMP relative carbon ion state flux profiles, and impinging energies, with the absolute C fluence calibrated to the RBS data.

The resulting plasma inputs to WBC are the 2D near-surface (~0–5 cm above the divertor) temperature, density, magnetic and pre-sheath electric field, etc spatial profiles, data-calibrated carbon ion fluxes, and incident energy profiles—for each carbon ion charge state—across DiMES. In contrast to the ELM plasma case, for the L-mode plasma all sputtering is by carbon ions and self-sputtering, because $D^+$ energies are below the W sputter threshold.

Summarizing some key background plasma inputs to WBC, plasma electron temperature at the DiMES probe center is 25 eV for the Cap #1 experiment and 11 eV for Cap #2, with corresponding pre-sheath electron densities shown in table 3. Ion temperature is about the same as electron temperature near the surface but is moderately higher elsewhere. Plasma flows to the divertor surface at the sound speed. Plasma parameters are nearly constant in the radial direction, at the divertor along the 1.5 cm central spot. Temperatures and density fall off radially outside this DiMES central region. Impinging carbon-on-tungsten ion charge states vary from $+1$ to $+4$, with energies mostly determined by sheath acceleration, e.g. at the Cap #3 center the average $C^{+3}$ impinging energy is $\sim 300$ eV, of which 225 eV is due to sheath acceleration.

The major modeling goal is to compute sputtered tungsten transport/redeposition parameters, and resulting net erosion, for the central spot. This requires first determining the gross carbon-on-tungsten sputtering rate, i.e. before any redeposition. One way of doing this is first-principles computation of sputtering from the input plasma model but this requires very accurate knowledge of the impinging plasma carbon content, in terms of the C/D fraction. Direct C/D data is unavailable for the L-mode plasma shots in question, however, as mentioned, we use a different procedure based directly on the RBS W erosion data. Namely, we use the average T1 and T2 measured gross tungsten erosion fluence—with a small adjustment—as the data-based carbon sputtering of the central spot, on the basis of assumed constant plasma parameters along the tokamak toroidal direction. The adjustment is made due to the small spots actually having some redeposition as well as some self-sputtering. Using this approach, the inferred small spot gross tungsten erosion fluence, due to carbon sputtering is given by:

$$F_{C-W} = \frac{F_{\text{RBS}} (1 - R_3 Y_{ZS})}{(1 - R_5)}$$

for measured fluence $F_{\text{RBS}}$ (table 2) averaged over the T1 and T2 spots, small spot redeposition fraction $R_5$, and small spot self-sputtering yield $Y_{ZS}$; with $R_3$ and $Y_{ZS}$ computed by WBC.

To summarize, the WBC code tungsten atom launch velocities are determined by the ITMC-DYN code, per the incident carbon ion distributions (and a small self-sputtering contribution), and W atom/ion trajectories are computed using the background plasma profiles. Redeposition is computed. The central spot net tungsten erosion fluence is then determined by the computed big spot redeposition fraction and self-sputter yield applied to the data-based C–W erosion, per the relation:

$$F_{\text{NET}} = \frac{F_{C-W} (1 - R_B)}{(1 - R_6 Y_{ZB})}$$

for big spot redeposition fraction $R_B$ and average self-sputtering yield $Y_{ZB}$. This computed $F_{\text{NET}}$ value can then be directly compared to the central spot eroded fluence RBS data.

To further describe the computational technique, the OEDGE/DIVIMP carbon ion flux fractions and energies to the big spot, for each charge state, are used in ITMC-DYN to compute the respective C–W sputter yields, sputtering fluences, and sputtered W velocity distributions. For the Cap #3 case the contribution fractions of carbon sputtered tungsten are: .037 for C$^{+1}$; .451 for C$^{+2}$; .461 for C$^{+3}$; and .051 for C$^{+4}$. For Cap #1 we have zero sputter fraction for C$^{+1}$ (impinging energy being below the W sputtering threshold); .670 for C$^{+2}$; .305 for C$^{+3}$; and .025 for C$^{+4}$. WBC launches W atoms from the spots, per these carbon sputter results, and W self-sputtering, and then calculates the resulting W ion transport and redeposition rates, using the near-surface OEDGE plasma parameters. Finally, the central spot net tungsten erosion fluence is computed using the WBC results in the above equations. To summarize, net erosion is computed using plasma, sputtering, and transport parameters from the three coupled code packages, with gross erosion calibration to the post-exposure DiMES RBS data.

Table 3 and figure 3 show selected L-mode analysis results. For central spot sputtering, tungsten ionization mean free paths and transit times are short, with low resulting redeposited charge states and energies. The critical central spot redeposition fraction is high, as shown of order 75%. Small spot redeposition is of order 15%, small but not insignificant. As for the ELM analysis, the L-mode predicted redeposition fraction for the probe/divertor as a whole is 100%. The average self-sputtering coefficient for redeposited W ions varies from ~6% to 1% for the higher and lower $T_e$ cases respectively, thus low in any event.

The erosion fluence from the T1 ‘downstream’ 1 mm spot is reduced by 4%–5%, relative to the T2 ‘upstream’ 1 mm spot, due to transfer of sputtered tungsten from the central spot to the small spot along the toroidal magnetic field. There is negligible transport to the upstream toroidal spot. This can explain
Table 3. Summary of erosion/redeposition parameters from WBC/ITMC coupled impurity sputtering/transport code package analysis of DIII-D DiMES L-mode plasma experiments with 1.5 cm diameter central tungsten spot, and four 1 mm toroidal and radial tungsten spots.

| Parameter | DiMES Cap #3 | DiMES Cap #1 |
|-----------|--------------|--------------|
| $T_e, N_e$ at spot center (pre-sheath) | $\sim 25$ eV, $4 \times 10^{19}$ m$^{-3}$ | $15$ eV, $6 \times 10^{19}$ m$^{-3}$ |
| Mean sputtered tungsten atom energy | $17$ eV | $11$ eV |
| Mean-free-path for sputtered atom ionization (normal to surface) | .50 mm | .39 mm |
| Transit time (ionization to redeposition)$^a$ | .48 (.71) $\mu$s | .56 (.70) $\mu$s |
| Charge state$^a$ | 1.6 (.90) | 1.6 (.76) |
| Energy$^a$ | $100$ (75) eV | $56$ (39) eV |
| Elevation angle of incidence$^a$ (from normal) | $19$ (10)$^c$ | $16$ (10)$^c$ |
| Redeposition fraction, for 1.5 cm diameter central spot sputtering | .75 | .71 |
| Self-sputtering coefficient$^a$ | .057 | .013 |
| Redeposition fraction, for 1 mm diameter toroidal spots sputtering | .15 | .17 |
| Sputtered fluence transport fraction; central spot to 1 mm toroidal spots$^b$ | $\leq .001$, T1 (downstream) | $\leq .001$, T1 (downstream) |
| | $\leq .001$, T2 (upstream) | $\leq .001$, T2 (upstream) |
| Sputtered fluence transport fraction; central spot to 1 mm radial spots$^b$ | $\leq .001$ | $\leq .001$ |
| Net eroded W fluence, central spot average ($10^{19}$ m$^{-2}$) | **29.1** code **28.7 ± 2** data | **2.9** code **1.6 ± 2** data |

$^a$ Average, and where shown (standard deviation), for redeposited tungsten ions on 1.5 cm diameter spot.

$^b$ [W fluence to small spot from central spot sputtering] / [central spot sputtered fluence].

Figure 3. WBC/ITMC code package simulation of sputtering erosion/redeposition of 1.5 cm diameter DiMES probe central tungsten spot. For DIII-D DiMES Cap #3 experiment. L-mode plasma inputs from OEDGE/DIVIMP codes. Sputtered W redeposition (or ‘deposition’ for $|Distance| > 7.5$ mm) fluence profiles shown in toroidal and radial directions through spot center. Redeposition flux is normalized to central spot average gross eroded fluence. Total spot redeposition fraction is 75%. Impurity transport is higher in toroidal-downstream and radial-inboard directions than upstream/outboard directions respectively.

at least some (16% for Cap #3; 24% for Cap #1) of the experimentally observed 1 mm spots toroidal erosion asymmetry. Such asymmetrical transport is seen in our past tokamak divertor simulations as well—and is mostly due to tungsten ion collisions with the incident plasma flowing at or near the sound speed along the net magnetic field direction.

The last row of table 3 shows the code and RBS data comparisons for the 1.5 cm spot net erosion fluence. The comparisons are good for both experiments. The code values are a sensitive function of the computed redeposition rate and, in general, of the numerous simulated sputtering and transport processes. The close agreement here provides a positive indication of the simulation validity. Also, the sputtered tungsten transport profiles shown in figure 3 for the Cap #3 case—showing differences in W deposition in both the upstream/downstream toroidal and inboard/outboard radial directions—are a reasonable match to the RBS profile data, an example of which is shown in figure 4. The code/data profile trend comparisons are likewise good for Cap #1.

Another modeling result is that the inferred L-mode impinging plasma C/D ratio—based again on the RBS DiMES erosion data calibration method—is about 3% for the Cap #3 experiment and 0.5% for Cap #1; unfortunately there is no carbon concentration data to compare with, but these are in
Figure 4. RBS toroidal profile data through the center of the DiMES probe for DIII-D DiMES Cap #3 experiment, showing before and after plasma exposure tungsten coverage. (Data includes erosion/transport effects of the two toroidal 1 mm W spots.)

a plausible range for general DIII L-mode shots, particularly considering the higher power Cap #3 vs. lower power Cap #1 conditions.

Although outside the main scope of our present study we expended some effort on code computations and comparisons for the 1 mm radial spots erosion. Based again on calibration to the 1 mm spots T1 and T2 RBS data, and using WBC-ITMC with OEDGE background plasma inputs, we compute net erosion fluxes very close (within experimental error) to the measured values (table 2) for the Cap #1 radial spots. However, for Cap #3 the simulation under-predicts the observed radial spots net erosion by about a factor of 2. This may reflect plasma background modeling issues with the radial spots being ~1.6 cm away from the strike point, and/or experimental issues. Further study of this is planned.

4. Discussion

Comparing one key metric for the H and L-mode plasmas in this study, for the high power cases, the peak measured gross W erosion rate for the ELM plasma is ~10 times higher than the L-mode rate (the latter derived using the average/adjusted T1 and T2 spots RBS fluence data divided by the 10.8 s exposure time.) Considering the different computed redeposition factors, ‘R’, i.e. 95% vs. 75% respectively, the predicted DIII-D net erosion rates, scaling as (1-R), are within a factor of two. For both plasma regimes, and per our earlier comment regarding extrapolation to future devices, sputtered tungsten redeposition rates for full-divertor high-Z coverage in ITER or DEMO type reactors, along the high particle/heat loading area, would likely approach unity, with consequent minimal net sputter erosion. There are other factors involved, of course, including effects of higher or lower near-surface plasma densities and temperatures.

5. Conclusions

We used advanced, rigorous, coupled code package simulations to analyze DIII-D carbon-containing tungsten DiMES divertor probe sputter response for ELMing H-mode and L-mode plasma experiments. Such ELMing plasmas, in particular, are considered likely in ITER and post-ITER tokamak fusion reactors, and with computation of DIII-D C/W mixing effects being likewise applicable to the ITER Be/W system. The simulations are believed to include all known relevant processes for sputtering, material mixing, and sputtered particle transport. They are, however, obviously dependent on accurate inputs of background plasma parameters/profiles and experimental conditions.

With that qualification we see a good code/data match for key metrics of gross tungsten sputter erosion flux for the ELM cases, and net erosion and redeposition fluence for the L-mode cases. The simulations predict 100% redeposition of sputtered tungsten on the probe/divertor and no resulting core plasma contamination from the main plasma/divertor interaction region. These are similar to past predictions—for DIII-D and other devices with high-Z plasma facing surfaces—but primarily for non-ELMing plasmas. The DIII-D ELM plasma cases studied do not cause undue sputtering erosion of a tungsten divertor segment, with the predicted net erosion rates being similar to non-ELM cases. In addition, the DIII-D DiMES modeling gives continued insight into sputtered impurity transport physics, including sub-mm W atom ionization mean free paths; strong redeposition forces due to electric and magnetic fields and impurity/plasma collisions; sub-µs W ion redeposition times; and resulting moderate redepositing energies and low self-sputtering.

For both ELMing and non-ELM plasmas the present results, extrapolated to a full tungsten divertor, imply acceptable, very low, net sputter erosion rates. These conclusions, at least for the cases studied, are encouraging for ITER and future tokamak fusion reactors using high-Z plasma-facing divertor surfaces.

There are several unresolved issues including a toroidal asymmetry in probe erosion data, and an issue for tungsten sputter response in the radial direction away from the diverter OSP. These are not highly significant in terms of our main conclusions but warrant further analysis. We plan further study of ongoing DIII-D/DiMES experiments, in general, and with particular focus on ELM exposures.

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