

# Sputtering of lithium and lithium compound films under deuterium and helium ion bombardment



L. Buzi<sup>a</sup>, A.O. Nelson<sup>b</sup>, Y. Yang<sup>a</sup>, R. Kaita<sup>c</sup>, P.S. Krstić<sup>d</sup>, B.E. Koel<sup>a,\*</sup>

<sup>a</sup> Department of Chemical and Biological Engineering, Princeton University, A311 EQuad, Olden Street, Princeton, NJ 08544-5263, United States

<sup>b</sup> Department of Astrophysical Sciences, Princeton Program in Plasma Physics, Princeton University, Princeton, NJ 08544, United States

<sup>c</sup> Princeton Plasma Physics Laboratory, Princeton, NJ 08540, United States

<sup>d</sup> Institute for Advanced Computational Science, Stony Brook University, NY 11794, United States

## ARTICLE INFO

### Keywords:

Deuterium retention  
Lithium carbonate  
Lithium deuteride  
Sputtering  
Thin films

## ABSTRACT

Conditioning of plasma facing components (PFCs) using lithium (Li) evaporation has shown to improve plasma performance in fusion devices by imposing low recycling boundary conditions. It is important to understand the retention and sputtering dynamics of deuterium (D) in Li and Li compound (Li–O and Li–C–O) films to most efficiently make predictions on plasma performance. Energetic  $D_2^+$  incident on thin Li films is shown to readily form LiD leading to a lower Li sputtering yield than the sputtering yield of pure Li. Measured sputtering yields for thin LiD films agree with previous simulations and bulk erosion measurements. The  $He^+$  sputtering yield of pure Li was 2–3 times higher than the sputtering yield of  $D_2^+$  on LiD. Incident 1000–1200 eV/ $D_2^+$  sputtered Li–O films at a slower rate than  $D_2^+$  on LiD and Li–C–O films.

## 1. Introduction

Lithium (Li) coated plasma-facing components (PFCs) have been successfully utilized to enhance the operational plasma performance in the National Spherical Torus Experiment (NSTX) and the Lithium Tokamak Experiment (LTX) by exploiting the impurity gettering and deuterium (D) retention properties of Li [1,2]. Enhanced D retention from Li reduces D recycling and therefore leads to hotter plasma edge and reduced instabilities, which in turn improves the overall plasma performance [3,4].

However, Li PFCs can also undergo significant erosion and sputtering by energetic ion bombardment, both limiting the material lifetime and contaminating the plasma [5]. An understanding of the complex dynamics of Li sputtering is thus valuable when characterizing Li as a potential PFC on fusion reactors. In current fusion experiments the presence of oxygen and carbon inevitably creates Li oxides and carbonates (Li–O and Li–C–O compounds) [6–8]. Investigating the mechanisms of D retention and sputtering for these Li compounds is crucial for the application of Li as a plasma-facing material. Additionally, Li–C–O compounds may be of interest as new fusion-relevant materials. For example, lithium carbide has recently been proposed as a prospective breeder material for fusion reactors [9].

It is difficult to study the details of Li PFC behavior in-situ since tokamaks inherently create a complex environment for plasma and

material characterization. Sputtering and reflection rates of D and tritium (T) into Li, along with associated self-sputtering yields, were originally calculated with Monte Carlo simulations by László and Eckstein [10]. Measurements and modeling of solid phase bulk Li and of liquid Li showed that the Li sputtering yield decreases significantly upon D saturation of the surface due to preferential sputtering of D atoms [11,12]. Further first-principles molecular dynamics simulations have suggested that rock-salt like LiD precipitates quickly in liquid Li under D bombardment [13], and corresponding measurements have shown that surface erosion rates are reduced in the presence of LiD for low (20–40 eV) incident ion energies [14]. Additional in-situ [5] and laboratory studies [15–17] strengthened the case that the chemical state of Li in the surface has a strong effect on Li erosion rates. What remains is to characterize this effect on thin Li films where chemical processes can be observed experimentally.

In this work, as a representation of Li PFCs in a tokamak [3], the D retention and sputtering characteristics of thin Li and Li compound (Li–O and Li–C–O) films on a nickel (Ni) substrate were studied in the well-controlled environment of a surface science apparatus. By working in an ultrahigh vacuum (UHV) chamber with a base pressure of  $1 \cdot 10^{-10}$  Torr ( $1.33 \cdot 10^{-10}$  mbar), thin ( $\sim 5$  nm) Li films can be created and studied with minimal oxidation and contamination (oxygen and carbon content as measured by AES remained below 2 at.% for up to 2 h) and Li compounds can be formed under controlled conditions.

\* Corresponding author.

E-mail address: [bkoel@princeton.edu](mailto:bkoel@princeton.edu) (B.E. Koel).

<https://doi.org/10.1016/j.nme.2019.02.037>

Received 14 August 2018; Received in revised form 8 February 2019; Accepted 27 February 2019

Available online 02 April 2019

2352-1791/© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

However, operation of the ion gun for sputtering measurements does introduce additional background gas into the chamber causing oxidation and contamination beyond this level, e.g. an oxygen content of 20 at.% was measured by AES after 60 min of sputtering. Contaminates (C and O) can be added in controlled amounts to replicate surfaces likely to be found in a tokamak environment. The chemical state of these films was monitored with Auger electron spectroscopy (AES) and Temperature Programmed Desorption (TPD) as a function of  $D_2^+$  and  $He^+$  fluence and of incident ion energy to determine surface evolution properties and Li sputtering yields. The investigation of D retention and Li sputtering in thin Li films in a surface science apparatus elucidates the mechanisms involved in Li PFCs, strengthening their candidacy for application as a tokamak PFCs. The main questions addressed here are related to the sputtering of Li, Li–O, and Li–C–O films with  $D_2^+$ / $He^+$  and retention, D retention at a monolayer level, and the role of the Li–substrate (Ni) interface.

## 2. Experimental methods

All experiments were performed at 300 K in a UHV chamber with a  $2 \times 10^{-10}$  Torr base pressure as described in detail in Ref. [17]. TPD and AES were used to measure D retention and sputtering rates under various irradiation conditions. For TPD, the sample was positioned in line-of-sight of the ionizer of a Hiden UHV 301 mass spectrometer (QMS), with the nozzle located 10 mm from the sample, using a linear heating rate of 4 K/s. A K-type (chromel-alumel) thermocouple was spot-welded directly on the sample to monitor the temperature. The QMS signals, the sample temperature, and the time were recorded simultaneously. We simultaneously followed  $m/q = 1, 2, 3, 4, 7, 9, 12, 16, 18, 20, 25, 28, 32, 35, 44$  signals in our TPD measurements. The Ni (110) single crystal (8 mm square,  $\pm 0.5^\circ$  orientation) sample was suspended in space with two 0.015" tantalum (Ta) wires used for resistive heating. The Ta wires were attached to two Ni rods at least 1 cm away from the sample. No sample platen was used; and the Ta wires and Ni rods should not appreciably affect the current reading on the sample.

A Ni (110) single crystal was used as a substrate throughout these experiments to avoid possible effects due to grain boundaries, intrinsic defects, and impurities diffusing from the bulk to the surface. Additionally, Li and Ni are immiscible due to the low solubility of alkali metals in Ni, and thus do not form either bulk alloys or two-dimensional surface alloys [18,19]. The crystal was cleaned using cycles of 1.5-keV  $Ar^+$  ion sputtering and annealing in vacuum at 1100 K in oxygen and hydrogen backgrounds. While performing this work we discovered that an atomically clean Ni surface could be achieved by evaporating a thin Li layer on Ni and heating it to 1000 K. The desorbing Li binds with remaining C and O upon leaving the surface.

Li films were deposited on the Ni crystal surface using a commercial Li metal dispenser (Li/NF/7.3/17/FT, SAES Group) by thermal evaporation. Li–O and Li–C–O compounds were formed by dosing  $O_2$  and CO on pure Li films at room temperature. After surface preparation, Li films were exposed to a high-energy (450–1600 eV) ion beam composed of either  $D_2^+$  or  $He^+$  ions from a differentially pumped ion gun (PHI 04-303 A). The  $D_2^+$  beam is nominally composed of 90%  $D_2^+$  and 10%  $D^+$  [20].  $D_2/He$  gas was introduced into the ion gun through a high precision variable leak valve, and a liquid nitrogen trap was used in the  $D_2/He$  gas line to mitigate  $H_2O$  contamination. The incident ion flux was defocused over the sample surface to provide uniform irradiation at  $\sim 1 \mu A$  integrated current. The spot size of the beam was 8 mm, as measured by scanning the beam across the sample in the x and y directions and observing sharp cut-offs at the crystal edges. The irradiation time and thus fluence was varied at these conditions to allow for measurements of the sputtering yield.

The absolute amount of Li was obtained by comparing the integrated area under a Li TPD curve, corrected for the mass spectrometer sensitivity to the translational energy of the desorbed species, to the

area under a pre-calibrated monolayer Li TPD curve. This pre-calibrated Li monolayer corresponds to one atomic layer of hexagonal close packed Li adatoms on a Ni (110) substrate ( $3.02 \cdot 10^{15}$  atoms/cm<sup>2</sup>) [21]. The absolute amount of Li before and after exposure to a known fluence of incident ions were obtained via TPD, and subsequently the sputtering yield was calculated as (initial number of Li atoms - final number of Li atoms) / number of incident ions.

## 3. Results and discussion

Four sets of experiments were conducted to gain insight into Li sputtering rates and retention properties upon  $D_2^+$ / $He^+$  irradiation of pure Li and Li compound films. First, a thin Li film at 300 K was repeatedly exposed to a  $D_2^+$  ion beam with 450–1200 eV/ $D_2^+$  incident energy at various ion fluences. The initial Li coverage before  $D_2^+$ / $He^+$  irradiation was checked with TPD and was found to be reproducible within 5%. The reproducibility of the initial Li coverage on the Ni substrate was checked by repeating many times the same dose time and current of the Li metal dispenser (doser) and subsequently evaporating the Li and monitoring the Li signal with the mass spectrometer. The integrated areas under these multiple Li TPD curves correspond to the Li coverage and all of these were within 5% of each other. As it will be shown later, it was observed that  $D_2^+$  irradiation led to LiD formation; a second set of experiments using  $He^+$  was conducted to determine physical sputtering rates from pure Li films. The third and fourth sets of experiments were dedicated to sputtering of Li oxide (8 ML (monolayers) Li + 25 L (Langmuirs;  $10^{-6}$  Torr·s)  $O_2$ ) and Li–C–O (8 ML Li + 45 L CO) films with  $D_2^+$  ions in the energy range 1000–1600 eV/ $D_2^+$  at room temperature. The ion energy range was chosen such that the ion flux was high enough to cause measurable changes in Li film. The  $D_2^+$  ion flux was  $3 \cdot 10^{17} D^+ m^{-2} s^{-1}$ . In each case, Li was first evaporated on Ni at 300 K and then the chamber was backfilled with either  $O_2$  or CO to form Li–O and Li–C–O respectively. The formation of Li–O and Li–C–O layers was confirmed by monitoring the disappearance of the Li metallic peak and the concomitant formation of Li desorption peaks at higher temperatures in TPD measurements. The total disappearance of the Li metallic peak indicated that the entire Li layer had been uniformly converted to Li–O or Li–C–O layers. Note that the Li–O nomenclature refers to the oxidized film, which may be  $Li_2O$ . The retention and sputtering results are presented below.

### 3.1. $D_2^+$ irradiation of pure Li films

Li films were irradiated with  $D_2^+$  ions at 450, 600, 800, 1000 and 1200 eV for 1–60 min to elucidate the sputtering and retention mechanisms. After each ion irradiation, the samples were analyzed with AES and TPD and an identical film was subsequently formed. As seen in Fig. 1, where Li and  $D_2$  TPD signals for 450 eV  $D_2^+$  irradiations are compared, the Li metallic peak is transformed into LiD decomposition peak after about 5 min of irradiation. This is evidenced both by the shift of the Li TPD peak from the Li multilayer value of  $\sim 560$  K to a peak centered at  $\sim 630$  K, and by the simultaneous appearance of a  $\sim 630$  K peak in the  $D_2$  TPD signal [17]. Notably, LiD conversion occurs before an appreciable amount of Li is lost through sputtering. After 10 min of  $D_2^+$  irradiation, the LiD peak decreased due to Li sputtering. For longer sputtering periods where the film thickness was reduced to  $< 2$  ML, a second  $D_2$  TPD peak appeared at  $\sim 510$  K. Finally, after the longest sputtering time of 60 min, we saw that the  $D_2$  TPD peak was almost fully shifted to a third location at  $\sim 390$  K. Neither the  $\sim 510$  K nor the  $\sim 390$  K  $D_2$  peaks were associated with any peaks in the Li TPD signal. As the sputtering duration increased, we observed the formation of two high temperature Li peaks (between 700 and 900 K). AES analysis (not shown here due to space limitations) confirmed that these peaks were associated with Li oxide formation, as determined in a previous paper [17].

In order to determine the retention mechanisms behind the  $\sim 510$  K

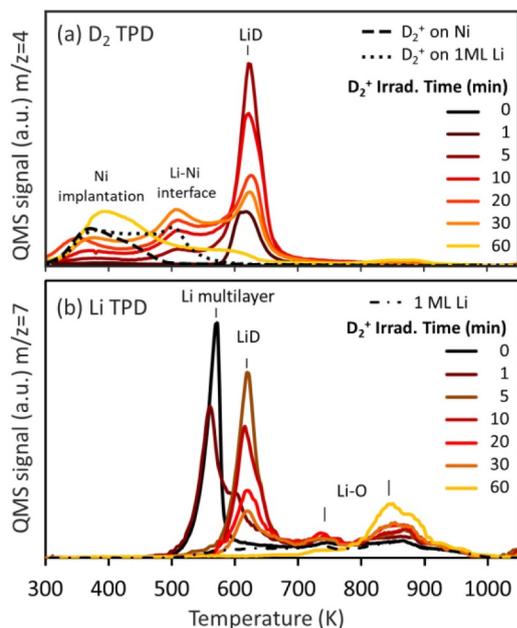


Fig. 1.  $D_2$  and Li TPD curves after 450 eV  $D_2^+$  incident on a 3 ML Li film. As  $D_2^+$  irradiation time was increased, Li was quickly converted to LiD before a substantial amount of Li was lost to sputtering.

and  $\sim 390$  K  $D_2$  peaks, two additional experiments were performed. First, the clean Ni substrate was irradiated by a total fluence of  $10^{15}$   $D^+$   $cm^{-2}$  of 1000 eV ions which were implanted into the Ni bulk. The resulting  $D_2$  TPD spectrum in Fig. 1(a) shows that the implanted D is released as  $D_2$  from the Ni at  $\sim 370$  K. Second, the same experiment was repeated on a 1 ML Li film on Ni that was prepared by heating the sample at 545 K to remove any Li in a multilayer film. Since the first monolayer of Li on Ni is assumed to not form LiD (due to the strong Li-Ni bonding), at monolayer Li coverage  $D_2^+$  is retained at the Li-Ni interface and in the Ni subsurface region as interstitial D atoms.  $D_2$  TPD in Fig. 1(a) shows two distinct peaks at  $\sim 370$  and  $\sim 500$  K, which were interpreted to be indicative of implantation into subsurface Ni and trapping at the Ni-Li interface, respectively.

Comparison of these two experiments with observations of  $D_2^+$  sputtering on thin Li films suggests a three-stage mechanism for D retention in thin Li films. First, D is retained in Li, converting it to LiD. Second, as the LiD is sputtered, D is still retained at the Li/Ni interface. Third, upon additional sputtering, D is retained in the bulk Ni. Since the Li to LiD transition occurs faster than relevant sputtering timescales, the sputtering yield of  $D_2^+$  into LiD was calculated. The sputtering yields for each incident ion energy are reported in Fig. 3. Note that in order to compare to literature values, where  $D^+$  sputtering is reported, our measured incident  $D_2^+$  ion energies and measured  $D_2^+$  sputtering rates were both divided by a factor of 2.

### 3.2. $He^+$ irradiation of pure Li films

In order to determine the physical sputtering rate of  $D_2^+$  into pure Li,  $He^+$  was chosen as an inert substitute for  $D_2^+$  due to its similar mass.  $He^+$  sputtering rates were calculated for incident ion energies of 450, 600, 800, 1000 and 1200 eV. The results are compared with  $D^+$  sputtering rates of LiD and with literature values in Fig. 3. First, it was found that no He was retained in the Li films (TPD shows no desorption at  $m/q = 4$ ). Second, the measured sputtering rates of  $He^+$  into Li are 2–3 times higher than the measured sputtering rates of  $D_2^+$  into LiD, indicating that the Li sputtering yield decreases significantly upon D retention. This behavior has been previously reported for bulk and liquid Li films [11,12,14] and was attributed to the preferential sputtering of D atoms over Li atoms [10–13]. Sputtering at low incident

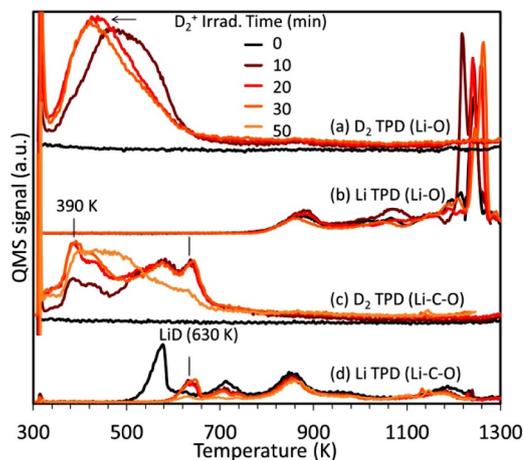


Fig. 2. TPD profiles of  $D_2$  (a, c) and Li (b, d) after exposure of Li-O and Li-C-O to 1200 eV  $D_2^+$ .

energies has been shown to be sensitive to bonding interactions [22], and we note that LiD bonds are stronger than Li-Li bonds (2.5 vs. 1 eV), but we believe that this should not be significant at these high energies. In summary, the presence of accumulated D decreases the sputtering yield of Li.

### 3.3. $D_2^+$ irradiation of Li-O and Li-C-O films

$H_2O$  and CO are the main gas-phase contaminants in fusion experiments leading to the formation of Li oxide and Li-C-O compounds. The next sets of experiments were dedicated to the irradiation of Li oxide (8 ML Li + 25 L  $O_2$ ) and Li-C-O (8 ML Li + 45 L CO) with  $D_2^+$  ions. TPD profiles of  $D_2$  and Li after irradiation of Li-O and Li-C-O films by 1200 eV  $D_2^+$  at 300 K are plotted in Fig. 2. As expected, the thermal stability of Li in Li-O is larger than that of pure Li. Heating the sample to high temperatures during TPD from the Li-O films revealed Li peaks at 1200 K. As seen in Fig. 2(b), compared to the Li peak at 0 min, the Li peak at 10 min shifted to a lower temperature by 25 K while the Li peak at 30 min shifted to a higher temperature by 25 K. These shifts are not due to experimental artefacts, and we do not currently understand the reason for these shifts. One hypothesis is that they are related to film composition and morphology changes during irradiation. D is mainly implanted in Ni and  $D_2$  desorbed at 400–500 K. This peak shifted to lower temperatures for higher  $D_2^+$  fluences indicating that after the Li-O layer and the Ni implantation region is saturated, D starts recombining at the surface and desorb. There was also a small amount of D retained to  $\sim 900$  K, which coincides with a Li peak from the Li-O.

Li TPD peaks at 700–850 K coincided with CO TPD desorption peaks that were obtained simultaneously (CO TPD plots are not shown here). Most of the D was desorbed as  $D_2$  in multiple peaks from 390–630 K, which are attributed to arise from implanted D in Ni, D trapped at the Li-Ni interface, and LiD [16,17]. The  $D_2$  peak desorbing from LiD decreases with  $D_2^+$  fluence due to the sputtering of the Li film. In both cases (Li-O and Li-C-O films), D retention saturated with increased incident  $D_2^+$  fluence, as was determined by a plot of the integrated  $D_2$  TPD area with increasing  $D_2^+$  exposure (not shown).

### 3.4. Li sputtering results

The Li sputtering yield results from pure Li and Li compound (Li-O and Li-C-O) films with  $D_2^+$ / $He^+$  irradiation are plotted in Fig. 3 and are compared with simulated and measured values from the literature [4,10,23]. Sputtering of Li-O with  $D_2^+$  had the highest Li sputtering rate due to  $D_2^+$  and it peaked at higher ion energies than for pure Li and Li-C-O (1600 eV/ $D_2^+$ ). While Li sputtering rate values of LiD and Li

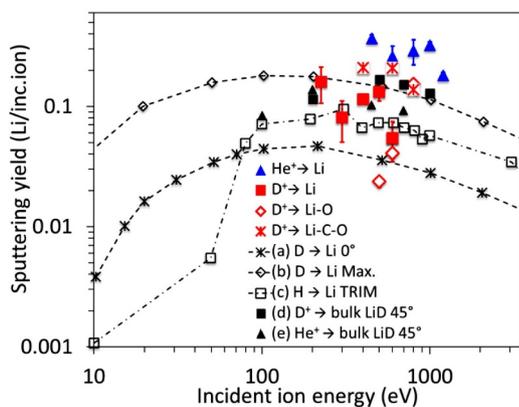


Fig. 3. Measured sputtering yields of Li and their dependence on incident ion energy are compared with simulated and measured values from the literature (a, b) [10] (c) [4] (d, e) [23].

compare well with the literature, the sputtering rate values of  $\text{He}^+$  on Li are 2–3 times higher indicating that hydride or hydroxide formation reduces physical sputtering of Li. Molecular dynamics simulations of sputtering of the Li–C–O compounds showed a chemical sputtering reduction of more than a factor of four due to the presence of oxygen [24]. We also point out that when comparing the data of our measurements in this work with data on bulk Li, backscattering from the Ni substrate of the incident ions may increase the sputtering yield of these thin films [25].

The above sputtering results can be extrapolated to predict approximate surface lifetimes for Li-coated PFCs in LTX and future machines. LTX is a low aspect ratio tokamak that has shown significant increase in plasma performance for Li layers on the order of 50 nm [4,7]. Typical relevant parameters are edge electron temperatures of 200 eV and edge ion temperatures of 60 eV, but it is noted that the wall sheath potential accelerates the ion impact energy on the wall up to 1 keV [4]. Assuming uniform sputtering with an edge fluence of  $1 \cdot 10^{21} \text{ m}^{-2}$  per shot and taking a measured sputtering yield of 0.1 ions/atom, we predict that the deposited Li film should be fully sputtered in approximately 50 shots, which is about as long as a typical run day. In practice, slightly longer lifetimes have been observed. The discrepancy could be a result of significant backscattering from Ni in measurements for the thinnest Li films used in this experiment, the nonuniformity of Li coatings in the tokamak, or the unconsidered redeposition of sputtered Li back onto the walls in LTX experiments. Furthermore, the sputtering yield decreases at higher edge incident ion energies, which increases the lifetime of Li films due to sputtering. The persistence of low-recycling wall conditions in LTX after an appropriate sputtering time suggests that these other effects must be considered.

#### 4. Conclusions

Temperature programmed desorption was used to study Li sputtering yields in pure Li, LiD, Li–O, and Li–C–O films at 300 K upon bombardment by energetic  $\text{He}^+$  and  $\text{D}_2^+$  ions. Pure Li films were observed to become LiD films upon  $\text{D}_2^+$  irradiation before significant sputtering occurred.  $\text{He}^+$  sputtering of pure Li yielded 2–3 times higher sputtering yields compared to  $\text{D}_2^+$  irradiation. This result indicates that the formation of LiD reduces the sputtering yield, in agreement with previous measurements on bulk and liquid Li.

The Li sputtering yield upon  $\text{D}_2^+$  irradiation of Li–O film was lower than the Li–C–O sputtering yield and peaked at higher energy (1600 eV/  $\text{D}_2^+$ ). Based on the current studies, Li oxide formation in a fusion experiment may be advantageous due to the enhanced thermal stability of Li–O, lower sputtering yield of Li–O, and similar hydrogen retention properties of Li–O when compared with pure Li. However, the role of LiOD formation and its dissociation to  $\text{Li}_2\text{O}$  and  $\text{H}_2\text{O}$  in a

fusion experiment should be further studied.

We make several additional conclusions from these experiments. Upon oxidation, the temperature for complete Li desorption (removal) was increased by 350 K, while CO exposures on a pure Li layer, which formed a Li–C–O compound surface increased this stability by 300 K. In addition, D retention saturates when irradiating Li and Li compound films with increasing incident  $\text{D}_2^+$  fluences. TPD analysis showed that as the Li film was sputtered, and the thickness was reduced to a monolayer level, D was retained at the Li–Ni interface and in the Ni substrate.

#### Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Science/Fusion Energy Sciences under Award Number DE-SC0012890 and USDOE Contract DE-AC02-09CH11466. YY acknowledges partial support by a fellowship from the Program in Plasma Science and Technology (PPST) at Princeton University.

#### References

- [1] M.G. Bell, H.W. Kugel, R. Kaita, L.E. Zakharov, H. Schneider, B.P. LeBlanc, D. Mansfield, R.E. Bell, R. Maingi, S. Ding, S.M. Kaye, S.F. Paul, S.P. Gerhardt, J.M. Canik, J.C. Hosea, G. Taylor, Plasma response to lithium-coated plasma-facing components in the National Spherical Torus Experiment, *Plasma Phys. Control. Fusion* 51 (2009) 124054, <https://doi.org/10.1088/0741-3335/51/12/124054>.
- [2] R. Majeski, R. Doerner, T. Gray, R. Kaita, R. Maingi, D. Mansfield, J. Spaleta, V. Soukhanovskii, J. Timberlake, L. Zakharov, Enhanced energy confinement and performance in a low-recycling tokamak, *Phys. Rev. Lett.* 97 (2006) 1–4, <https://doi.org/10.1103/PhysRevLett.97.075002>.
- [3] J.C. Schmitt, R.E. Bell, D.P. Boyle, B. Esposti, R. Kaita, T. Kozub, B.P. LeBlanc, M. Lucia, R. Maingi, R. Majeski, E. Merino, S. Punjabi-Vinoth, G. Tchilingirian, A. Capece, B. Koel, J. Roszell, T.M. Biewer, T.K. Gray, S. Kubota, P. Beiersdorfer, K. Widmann, K. Tritz, High performance discharges in the Lithium Tokamak experiment with liquid lithium walls, *Phys. Plasmas* (2015) 22, <https://doi.org/10.1063/1.4921153>.
- [4] R. Majeski, R.E. Bell, D.P. Boyle, R. Kaita, T. Kozub, B.P. LeBlanc, M. Lucia, R. Maingi, E. Merino, Y. Raites, J.C. Schmitt, J.P. Allain, F. Bedoya, J. Bialek, T.M. Biewer, J.M. Canik, L. Buzi, B.E. Koel, M.L. Patino, A.M. Capece, C. Hansen, T. Jarboe, S. Kubota, W.A. Peebles, K. Tritz, Compatibility of lithium plasma-facing surfaces with high edge temperatures in the Lithium Tokamak Experiment, *Phys. Plasmas* 24 (2017) 1–13, <https://doi.org/10.1063/1.4977916>.
- [5] J.P. Allain, D.G. Whyte, J.N. Brooks, Lithium erosion experiments and modelling under quiescent plasma conditions in DIII-D, *Nucl. Fusion* (2004), <https://doi.org/10.1088/0029-5515/44/5/009>.
- [6] P.S. Krstić, J.P. Allain, C.N. Taylor, J. Dadrás, S. Maeda, K. Morokuma, J. Jakowski, A. Allouche, C.H. Skinner, Deuterium uptake in magnetic-fusion devices with lithium-conditioned carbon walls, *Phys. Rev. Lett.* (2013) 110, <https://doi.org/10.1103/PhysRevLett.110.105001>.
- [7] M. Lucia, R. Kaita, R. Majeski, F. Bedoya, J.P. Allain, T. Abrams, R.E. Bell, D.P. Boyle, M.A. Jaworski, J.C. Schmitt, Dependence of LTX plasma performance on surface conditions as determined by in situ analysis of plasma facing components, *J. Nucl. Mater.* 463 (2015) 907–910, <https://doi.org/10.1016/j.jnucmat.2014.11.006>.
- [8] C.H. Skinner, R. Sullenberger, B.E. Koel, M.A. Jaworski, H.W. Kugel, Plasma facing surface composition during NSTX Li experiments, *J. Nucl. Mater.* (2013) 438, <https://doi.org/10.1016/j.jnucmat.2013.01.136>.
- [9] M.V. Alenina, V.P. Kolotov, Y.M. Platov, Investigations of lithium carbide as tritium breeding material for blanket of the fusion reactor, *Probl. At. Sci. Technol.* 87 (2013) 120–123.
- [10] J. László, W. Eckstein, Sputtering and reflection from lithium, gallium and indium, *J. Nucl. Mater.* 184 (1991) 22–29, [https://doi.org/10.1016/0022-3115\(91\)90528-F](https://doi.org/10.1016/0022-3115(91)90528-F).
- [11] J.P. Allain, D.N. Ruzic, M.R. Hendricks, Measurements and modeling of D, He and Li sputtering of liquid lithium, *J. Nucl. Mater.* 290–293 (2001) 180–184, [https://doi.org/10.1016/S0022-3115\(00\)00504-3](https://doi.org/10.1016/S0022-3115(00)00504-3).
- [12] J.P. Allain, D.N. Ruzic, Measurements and modelling of solid phase lithium sputtering, *Nucl. Fusion* (2002), <https://doi.org/10.1088/0029-5515/42/2/312>.
- [13] M. Chen, T. Abrams, M.A. Jaworski, E.A. Carter, Rock-salt structure lithium deuteride formation in liquid lithium with high-concentrations of deuterium: a first-principles molecular dynamics study, *Nucl. Fusion* 56 (2016) 016020, <https://doi.org/10.1088/0029-5515/56/1/016020>.
- [14] T. Abrams, M.A. Jaworski, M. Chen, E.A. Carter, R. Kaita, D.P. Stotler, G. De Temmerman, T.W. Morgan, M.A. Van Den Berg, H.J. Van Der Meiden, Suppressed gross erosion of high-temperature lithium via rapid deuterium implantation, *Nucl. Fusion* (2016), <https://doi.org/10.1088/0029-5515/56/1/016022>.
- [15] T. Abrams, M.A. Jaworski, R. Kaita, D.P. Stotler, G. De Temmerman, T.W. Morgan, M.A. Van Den Berg, H.J. Van Der Meiden, Erosion of lithium coatings on TZM molybdenum and graphite during high-flux plasma bombardment, *Fusion Eng. Des.*

- 89 (12) (2014) 2857–2863, <https://doi.org/10.1016/j.fusengdes.2014.06.005>.
- [16] A.M. Capece, J.P. Roszell, C.H. Skinner, B.E. Koel, Effects of temperature and surface contamination on D retention in ultrathin Li films on TZM, *J. Nucl. Mater.* 463 (2015) 1177–1180, <https://doi.org/10.1016/j.jnucmat.2014.10.048>.
- [17] L. Buzi, Y. Yang, F.J. Domínguez-Gutiérrez, A.O. Nelson, M. Hofman, P.S. Krstić, R. Kaita, B.E. Koel, Hydrogen retention in lithium and lithium oxide films, *J. Nucl. Mater.* 502 (2018) 161–168, <https://doi.org/10.1016/j.jnucmat.2018.02.010>.
- [18] K. Wang, P. Ross, Reversible Li deposition on Ni in ultrahigh-vacuum, *J. Electrochem. Soc.* 142 (1995) L95–L97, <https://doi.org/10.1149/1.2044257>.
- [19] J. Engbæk, G. Nielsen, J.H. Nielsen, I. Chorkendorff, Growth and decomposition of lithium and lithium hydride on nickel, *Surf. Sci.* 600 (2006) 1468–1474, <https://doi.org/10.1016/j.susc.2006.01.040>.
- [20] H. Tawara, Y. Itikawa, H. Nishimura, M. Yoshino, Cross sections and related data for electron collisions with hydrogen molecules and molecular ions, *J. Phys. Chem. Ref. Data* 19 (1990) 617–636, <https://doi.org/10.1063/1.555856>.
- [21] V. Saltas, C.A. Papageorgopoulos, Adsorption of Li on Ni(110) surfaces at low and room temperature, *Surf. Sci.* 461 (2000) 219–230, [https://doi.org/10.1016/S0039-6028\(00\)00588-4](https://doi.org/10.1016/S0039-6028(00)00588-4).
- [22] F.J. Domínguez-Gutiérrez, P.S. Krstić, Chemical sputtering of boronized and oxidized carbon surfaces irradiated by low-energy deuterium atoms, *J. Appl. Phys.* 121 (2017) 215302, <https://doi.org/10.1063/1.4984756>.
- [23] J.P. Allain, J.N. Brooks, D.A. Alman, L.E. Gonzalez, Model development and analysis of temperature-dependent lithium sputtering and sputtered Li + transport for tokamak plasma-facing applications, *J. Nucl. Mater.* 337–339 (2005) 94–98, <https://doi.org/10.1016/j.jnucmat.2004.10.144>.
- [24] F.J. Domínguez-Gutiérrez, P.S. Krstić, Sputtering of lithiated and oxidated carbon surfaces by low-energy deuterium irradiation, *J. Nucl. Mater.* 492 (2017) 56–61, <https://doi.org/10.1016/j.jnucmat.2017.05.014>.
- [25] R. Simovic, J. Vukanic, The albedo problem of low-energy light ions treated analytically in the DP0 flux approximation, *J. Phys. D Appl. Phys.* (1997) 2331–2337, <https://doi.org/10.1088/0022-3727/30/16/011>.