Damage to N-NBI Systems due to Positive Ion Back-Streaming

M. Wada[1, a)], T. Kenmotsu[2], K. Ikeda[3], M. Kisaki[4], H. Nakano[5] and K. Tsumori[6]

[1]*Graduate School of Science and Engineering, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan*
[2]*Faculty of Life and Medical Sciences, Doshisha University, Kyotanabe, Kyoto 610-0321, Japan*
[3]*National Institute for Fusion Science, Toki, Gifu 509-5202, Japan*

[a)]Corresponding author: mwada@mail.doshisha.ac.jp

Abstract. Sputtering yields of molybdenum (Mo) are computed for deuterium, oxygen and carbon as impurity ions from the residual gas of the vacuum system, as well as Mo and Cs using Yamamura formula. The incident ion energy ranges from 10 keV to 1 MeV, the back-streaming ion beam energy from the extraction voltage up to ITER full acceleration potential. The sputtering yield of Cs against Mo reached ten atoms per ion and was the largest among the investigated ion species. The effect due to retention of deuterons in Mo was studied for the case of grazing angle incidence of D^+ at D^- ion extraction energy to confirm the small effect onto the sputtering yield; the result obtained for 10 keV D^+ for 10% retention of D atoms in Mo increased the sputtering yield only by 2%. The back-streaming D^+ ions at 1 MeV energy should make a layer of high concentration deuterium atoms at 6 μm depth from the Mo surface. Possible failure mode associated with the particle implantation is discussed.

INTRODUCTION

The negative ion based neutral beam injection (N-NBI) system at the Large Helical Device (LHD) operated at the National Institute of Fusion Science has recently improved the performance for the deuterium operation [1]. The ratio of extracted electron current to the accelerated current reduced by 26% and the accelerated current increased to 120% by tuning the gap spacing between the plasma electrode and the extraction electrode. A higher consumption rate of Cs has been discussed for the deuterium operation as compared to hydrogen operation for the source before the extractor design improvement [2] and the possible reasons for larger consumption rate of Cs due to changing the feeding gas from hydrogen to deuterium have been discussed from the view point of Cs removal out of the plasma grid (PG) surface [3]. Deuterium operation may enlarge the Cs removal rate compared with hydrogen due to deuterons larger momentum transfer when they strike the surface. Meanwhile, deuterium ions can erode the ion source back-plate surface as they are back-accelerated toward the ion source. The erosion rates of the back-plates due to back-streaming positive ions were studied for ITER [4] as well as DEMO operation conditions [5]. A layer of molybdenum (Mo) as schematically shown Fig. 1 will protect the ion source back-plate confronting to the extraction grids from intense radiation of back-streaming ions.

A long-term operation of ITER is expected and the N-NBI system should have enough life for high power density operation. One should expect even longer life time of the NBI system for DEMO because DEMO should prove the reliability as the commercial energy source. The long-term operation reliability is a challenge in another field applying the electrostatic particle acceleration technology: space propulsion. Numerical lifetime evaluation tools are developed [6], as the test requires a long operation time exceeding several years. In these grid lifetime evaluation study, proper sputtering yield data have to be compiled. Carbon made grids, as exposed to Xe plasmas and beams of Xe^+ ions accelerated as the propellant, retain Xe near the surface and this Xe retention in the C grids was found to cause enhanced sputtering yields with the reduction in sputtering threshold energy [7]. The pair of Xe projectiles and C targets can cause severe sputtering enhancement, while in the case of N-NBI or the pair of D projectiles and Mo target

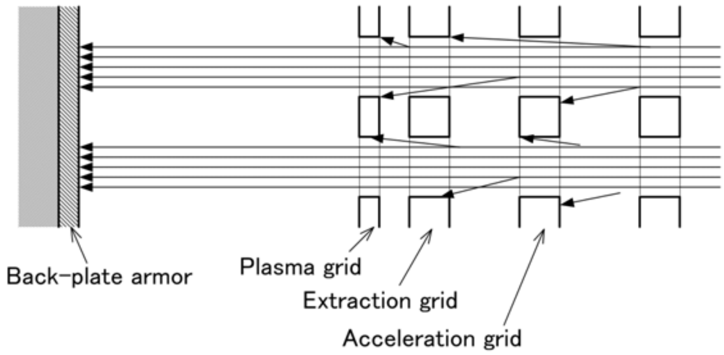

FIGURE 1. Two modes of ion source erosion due to back-streaming positive ions: to the back-plate and grids.

grid materials, the enhancement in sputtering yield is expected to be small. However, deuterium atom retained in Mo can scatter out Mo atom near the surface receiving momentum from the incident deuteron coming into the surface at a shallow angle. Thus, these two processes, sputtering of the Mo armor protecting the end-plate, and the enhancement of the erosion of extraction electrodes retaining deuterium as shown in Fig. 1 are discussed in this report.

SPUTTERING YIELD CURVES FOR MOLYBUDENUM

Sputtering yield curves against Mo are computed for atomic and molecular deuterium ions, oxygen and carbon ions as residual gas impurities, ions of Cs leaked out from the ion source and Mo ions as the electrode material. They are calculated using the Yamamura formula [8] in the energy range from a typical extraction potential up to ITER N-NBI full energy: 1 MeV.

Deuterium atoms and molecules

Deuterium atoms and molecules should be pumped out from the ion source plasma grid to the downstream. High energy D^- beam can ionize these atoms and molecules to positive ions. The sputtering yields of Mo due to D^+, D_2^+ and D_3^+ injections at normal incidence are shown in Fig. 2. The maximum sputtering yield for a D^+ ion is less than

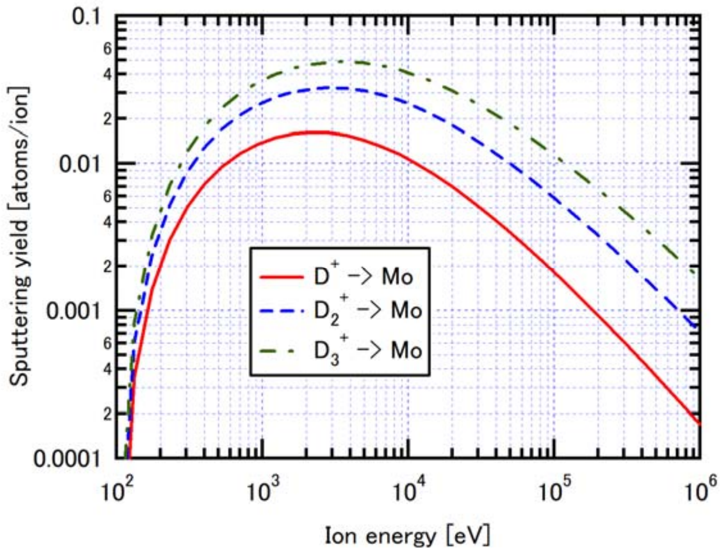

FIGURE 2. Sputtering yields of Mo for D^+, D_2^+ and D_3^+ normal incidence.

0.02 even at the maximum yield at about 20 keV. The sputtering yield is about 8 X 10^{-3} at the LHD N-NBI 180 keV acceleration energy, while it is less than 2 X 10^{-4} at 1 MeV ITER full acceleration energy. At high acceleration energy, deuterons and deuterium molecular ions are implanted deeper into Mo, and do not cause large amount of prompt emission of Mo by forming collision cascades in the subsurface region.

Impurity ions

The back-ground pressure of ITER and DEMO beamlines should be extremely small because of huge pumping capacity of the system. However, ions of the residual gas can cause erosion of the back-plate and the accelerator grids for long term operation of the NBI system. Sputtering yields of Mo for O^+, C^+ and CO_2^+ at normal incidence are computed, as they are formed from the back-ground gas of H_2O, CO and CO_2. Both C^+ and O^+ ion sputtering yields show peaks from 10 to 20 keV, while they decrease below unity above 200 keV energy. The sputtering yields for these monoatomic ions are about three orders of magnitude higher than D^+ ions. Sputtering yields of molecular ions lead to severe damage to the extraction/acceleration electrodes and the end-plate. The energy per atom is reduced by forming a molecular ion, while low energy multiple heavy particles strike the surface inducing collision cascades at a shallow depth from the surface. The sputtering by a CO_2^+ ion impact shows the peak in the yield curve exceeding 4 Mo atoms per a CO_2^+ ion at about 30 keV energy. The yield exceeds unity even at full ITER acceleration energy, 1 MeV.

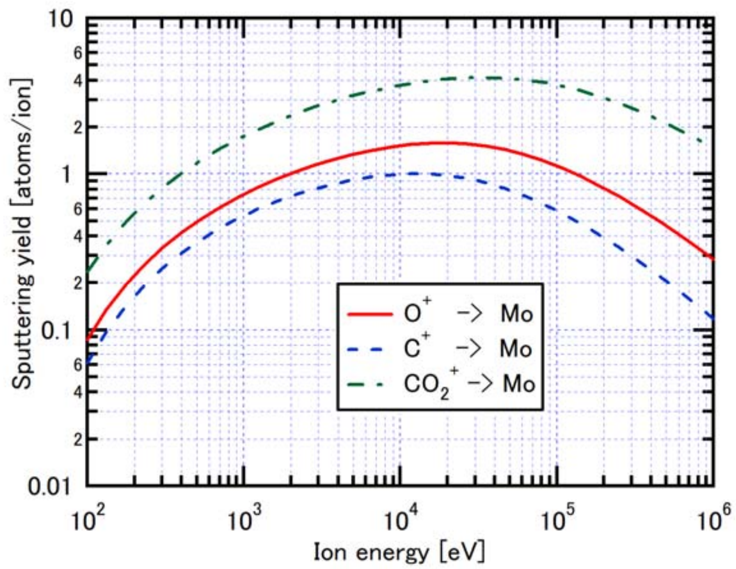

FIGURE 3. Sputtering yields of Mo due to O^+, C^+ and CO_2^+ ions

Mo and Cs

The serious impact on back-plate sputtering due to back-streaming Cs has been discussed in Ref [5]. A Cs ion initiates a collision cascade near the surface of Mo because of its large Z number and transfers momentum to Mo efficiently due to the mass similar to the Mo mass. The resulting sputtering yield shown in Fig. 4 is indeed the highest among the combination of ion-target studied in this report. It exceeds 10 in the peak energy range from 100 keV to 1 MeV. The yield is also large in the energy range of the beam extraction potential; it is larger than 5 Mo atoms per Cs^+ ion at 10 keV. This means that if Cs touches down the extraction grid and ionized by coextracted electrons, they may cause a severe damage on the back side of the plasma grid.

Release of Cs from the ground and acceleration grid may accompany arcing, when the electrode material can be also liberated and ionized. The yield of self-sputtering, or Mo sputtering by Mo^+ ion impact is calculated and shown in Fig. 4. It is a little higher at low energy and a little lower at higher energy as compared to the sputtering yield of Cs^+. The sputtering yield is as large as nearly 10 throughout the energy range of beam acceleration for N-NBI.

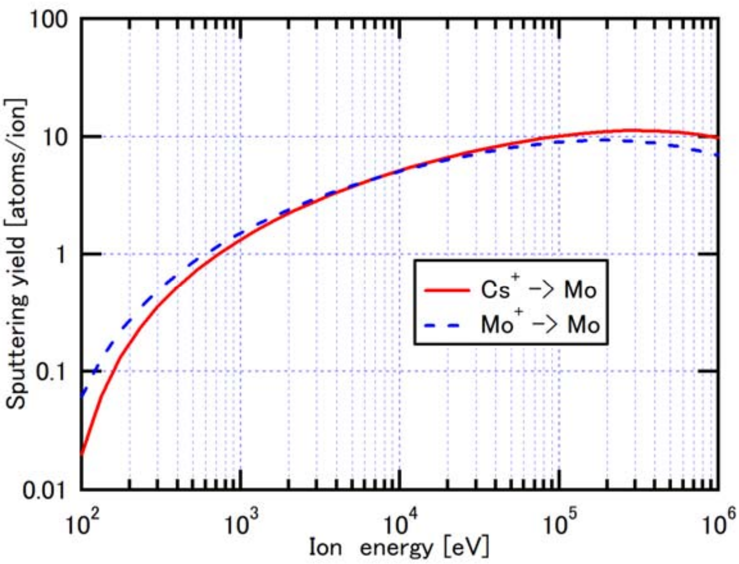

FIGURE 4. Sputtering yield curve of Mo for Cs^+ and Mo^+ ions at normal incidence.

EFFECT DUE TO DEUTERIUM RETENTION

Implanted deuterium atoms occupy sites near Mo nucleus and can be scattering centers for incoming deuterons. If the concentration of deuterium atoms near the surface is high, it should enhance the momentum transfer from the incident deuteron to excite a collision cascade. The resulting sputtering yield is higher even though the final effect onto the sputtering yield should be small because of large mass difference between a deuteron and a Mo atom. To confirm this, ACAT (Atomic Collision in Amorphous Target) program was run with 10% deuterium retention in Mo. The incident D^+ energy was set at 10 keV as a typical extraction energy and the sputtering yield for an incidence D^+ ion was investigated by changing the projectile incident angle. The result shown in Fig. 5 does not show the difference between the sputtering yield for pure Mo, Y_{pure}, and the sputtering yield for Mo retaining 10% atomic concentration of deuterium, Y_{10}. The ratio of increment in sputtering yield, R_{Ys}:

$$R_{Ys} = \frac{Y_{10} - Y_{pure}}{Y_{pure}} \times 100 \quad [\%] \tag{1}$$

due to D retention is plotted in Fig. 5 to elucidate the retention effect. The graph now indicates that the D retention increases the sputtering yield for all angles.

The increment in sputtering yield caused by D retention appears larger at the center region in Fig. 5. However, this seemingly large yield was caused by a systematic error in the present ACAT calculation. The ACAT program was used without increasing the number of cells containing target atoms and simulated only a small region about the distance of the deuterium range, or the penetration length in Mo. However, the incident deuterium ion and the scattered deuterium atom can go out of the simulation volume easily after the small number of nuclear scattering. In the normal incidence, sputtering events can only happen after a series of multiple collisions and the effect due to missing the particles from the volume appears emphatically. On the other hand, few collision processes occupy the large part of the sputtering yield for a shallow angle incidence, or an angle approaching to 90-degree from the surface normal in

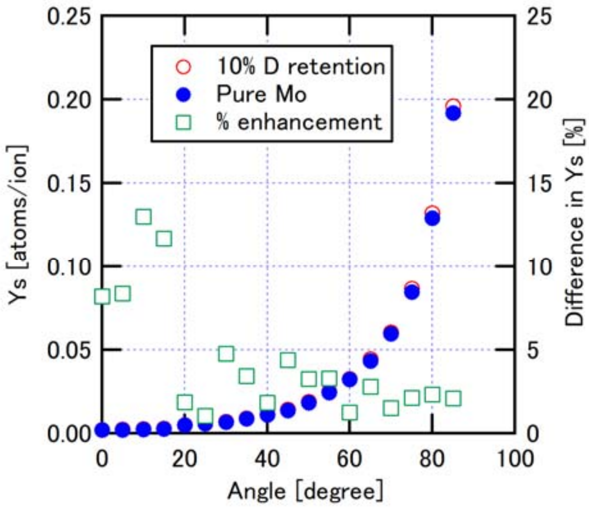

FIGURE 5. Sputtering yield for pure Mo (closed circle), that for Mo retaining 10% D (open circle) and the difference between the two in percent (open square).

Fig. 5. At a large incident angle from the normal, the difference in sputtering yields converged to about 2%. Thus, the effect due to deuterium retention in Mo will not substantially enlarge the sputtering yield and the yield of pure Mo can be safely used to estimate the life time of ion source/accelerator components.

DISCUSSION

The effect due to D retention in Mo was confirmed small as expected from the sputtering theory. The deuterons back-accelerated from the region downstream of the accelerator grids strike the surface with implantation energy range and will penetrate deep into the accelerator/extraction grids and the ion source back-plate. This deuterium implantation into Mo deposits energy in a thin subsurface layer causing local heating. The temperature distribution is subsequently homogenized quickly because the thermal conductivity of Mo is larger than 1 W/cm/K up to 1000 K temperature [9]. However, there still is a concern on the behavior of implanted D in Mo.

The stopping power data for deuterium in Mo is found in Ref [10] in the energy range from 50 keV to 1 MeV, and by numerically fitting the data, the slowing down of deuterium in Mo can be computed. The result is shown in Fig. 6 for the case of 1 MeV deuteron injection to Mo. As shown in the figure, the precipice after the Bragg peak is quite sharp. The width of the stopped D atom density distribution has less than one micrometer thickness. Meanwhile, Tanabe *et al* reported the diffusion coefficient of deuterium in Mo, D_{Mo}, can be expressed as,

$$D_{Mo} = 3.2 \text{ X } 10^{-6} \times \exp\left(-54.6 \text{ kJ mol}^{-1}/RT \right) \qquad [\text{m}^2/\text{s}] \qquad (2)$$

where R is the gas constant and T is the absolute temperature [11]. This equation gives the value of D_{Mo} less than 10^{-9} cm^2/s at 500 C^o and predicts slow diffusion of deuterium atoms in Mo. Thus, depending upon the particle flux and the energy distribution, back-streaming ions can form a thin layer of high concentration D atoms. Bubbles are known to be formed in Al by hydrogen ion implantation [12], and the mechanical stress induced by the modified layer may cause fracture of the Mo surface.

The above argument should be confirmed through an experiment based on the D^+ ion beam injection corresponding to the current density and the distribution of the back-streaming ions. The operation temperature of the ion source wall has to be also specified. The precise data on deuteron stopping in Mo should be obtained and compiled, as not only the Bragg peak but also the deuterium trapping spatial distribution are heavily dependent upon the stopping power/struggling data in the low energy range. The stopping power was determined semi-empirically in this study. Yamamura formula also utilizes semi-empirical relations for determining the necessary parameters. Sputtering yields,

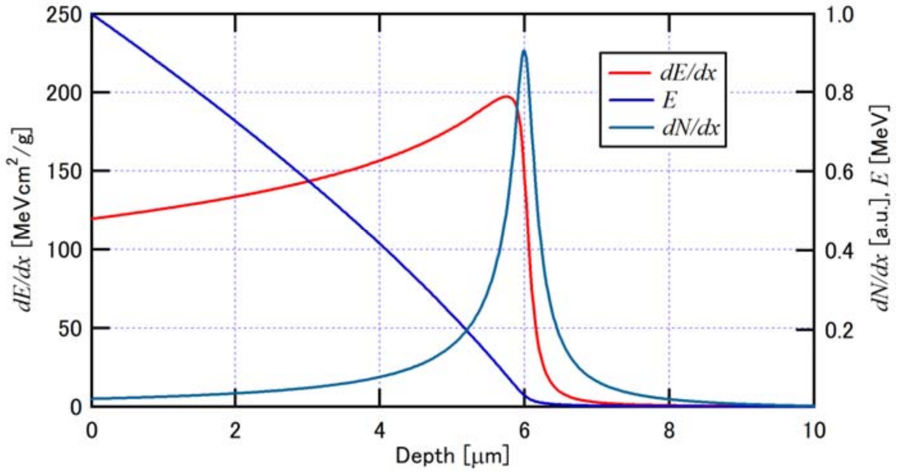

FIGURE 6. Stopping power dE/dx, deuteron energy E and deuteron distribution dN/dx for 1 MeV deuteron incidence onto a Mo target.

particle reflection coefficients, energy reflection coefficients and implantation profiles are to be confirmed with experimental data at the energy range larger than 100 keV to make more accurate estimations

CONCLUSION

Sputtering yield data necessary to estimate the life of N-NBI ion source/accelerator systems are computed and summarized in the energy range of D^- extraction and acceleration. Back-streaming ions of heavy elements including Cs and the electrode material may erode the extraction/acceleration electrodes. Molecular positive ions can also cause severe damage to electrodes. The effect due to deuterium retention upon the Mo sputtering yield appears small and can be neglected to estimate the lifetimes of ion source and accelerator components. The deuterium implantation, however, may cause some problem creating fracture of thin material layer as it may form a thin deuterium accumulated region at a shallow depth from the surface. Precise information on beam optics and energy distribution function of back-streaming positive ions and accurate deuterium stopping power data in the concerned energy range are necessary to properly evaluate the lifetime of N-NBI systems for ITER and DEMO.

ACKNOWLEDGEMENTS

This work has been supported in part by Japan Society for Promotion of Science KAKENHI No. 17H03512.

REFERENCES

1. K. Ikeda, K. Tsumori, K. Nagaoka, H. Nakano, M. Kisaki, Y. Fujiwara, S. Kamio, Y. Haba, S. Masaki, M. Osakabe, Rev. Sci. Instrum. **90**, 113322 (2019).
2. K. Ikeda, K. Tsumori, M. Kisaki, H. Nakano, K. Nagaoka, M. Osakabe, S. Kamio, Y. Fujiwara, Y. Haba, and Y.Takeiri, AIP Conference Proceedings, **2011**, 060002 (2018).
3. M. Wada, AIP Conference Proceedings, **2052**, 020005 (2018).
4. R.S. Hemsworth, D. Boilson, P. Blatchford, M. Dalla Palma, G. Chitarin, H.P.L de Esch, F. Geli, M. Dremel, J. Graceffa, D. Marcuzzi, G. Serianni, D. Shah, M. Singh, M. Urbani and P Zaccaria, New J. Phys. **19**, 025005 (2017).
5. R.S. Hemsworth and D. Boilson, AIP Conference Proceedings, **1869**, 060001 (2017).

6. I. Funaki, M. Nakano, Y. Kajimura, T. Miyasaka, Y. Nakayama, T, Hyakutake, M. Wada, T. Kenmotsu, T. Muramoto, H. Kuninaka, I Shinohara, 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 2011, (2011).
7. T. Kenmotsu, M. Wada, T. Hyakutake, T. Muramoto, M. Nishida, Nucl. Instrum. Methods, **B 267**, 1717(2009).
8. Y. Yamamura, Y. Itikawa, N. Itoh, Report IPPJ-AM-26, Nagoya University (1993).
9. C.Y. Ho, R.W. Powell, P.E. Liley, “Thermal Conductivity of Selected Materials, Part 2,” National Bureau of Standards, NSRDS-NBS 16 (1968).
10. C.A. Williamson, J.P. Boujot, J. Picard, Report CEA-R3042, CEA (1966).
11. T. Tanabe, Y. Furuyama, N. Saitoh and S. Imoto, Trans. Jpn. Inst. Metals, **28** 706(1987).
12. K. Kamada, J. Nucl. Mater. **169**, 141 (1989).