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Simulation study of carbon and tungsten deposition on W/C twin test limiter in TEXTOR-94

K. Ohya [a,*], R. Kawakami [a], T. Tanabe [b], M. Wada [c], T. Ohgo [d], V. Philipps [e], A. Pospieszczyk [e], B. Schweer [e], A. Huber [e], M. Rubel [f], J. von Seggern [e], N. Noda [g]

[a] *Faculty of Engineering, University of Tokushima, Minami-Joshanjima 2 – 1Tokushima 770-8506, Japan*
[b] *Center of Integrated Research in Science and Engineering, Nagoya University, Nagoya 464-8603, Japan*
[c] *Department of Electronics, Doshisha University, Kyotanabe, Kyoto 610-0394, Japan*
[d] *Department of Physics, Fukuoka University of Education, Munakata, Fukuoka 811-4192, Japan*
[e] *Institut für Plasmaphysik, Forschungszentrum Jülich, Ass. Euratom-KFA, D-52425 Jülich, Germany*
[f] *Royal Institute of Technology, Alfven Laboratory, S-10044 Stockholm, Sweden*
[g] *National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*

Abstract

In order to investigate the impurity release and surface modification on a W/C twin test limiter, made of a half of W and the other half of C, exposed to the edge plasma of TEXTOR-94, simulation calculations of ion-surface interaction are conducted by a Monte Carlo code. According to the calculations, experimentally observed spatial distributions of WI and CII line intensities around the W side of the limiter can be explained by physical sputtering of W, reflection of bombarding C ions and physical sputtering of implanted C. The CII line emission, resulting from thermal C atoms, around the C side of the limiter is suppressed by deposition of W, and the reflection of C ions from W deposited on C causes the CII intensity to decay more slowly than that from C without the deposition. Bombardment with deuterium edge plasmas, containing impurity W, produces a thick W layer on the C side of the limiter, whereas C implanted in the W side is strongly sputtered due to impact of most constituent D ions. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Tungsten (W) and carbon (C) materials are candidates for parts of the ITER divertor. W and C atoms released from the materials due to impacts of deuterium (D) and impurity ions are ionized and transported away along the magnetic field lines in the scrape-off layer (SOL) plasma. This results in mutual contamination between W and C, C deposition on W and W deposition on C, which alters the interaction of the SOL plasma with both materials. Recently, a W/C twin test limiter, made of a half of tungsten and the other half of graphite (EK-98), has been exposed to the edge plasma of TEXTOR-94, and the release of D and impurities (W, C, O) from different surfaces (W and C) has been examined for identical plasma and observation conditions [1–3]. In the experiments, the mutual contamination has been clearly observed not only by spectroscopy but also by surface analysis.

In this study, the mutual contamination of the W/C twin test limiter and its impurity release are simulated by using a Monte Carlo code of plasma–surface interaction, erosion and deposition based on dynamic model (EDDY), which has been developed recently [4]. Calculated distributions of penetration of released particles into the plasma are compared with observed distributions of line spectra emissions of atoms or ions in front of the limiter surface. Emphasis is placed on the influence of the mutual contamination on emission processes of impurities W and C from W and C surfaces.

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[*] Corresponding author. Tel.: +81-886 56 7444; fax: +81-886 56 7444.
E-mail address: ohya@ee.tokushima-u.ac.jp (K. Ohya).

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2. Simulation model and experimental condition used for calculation

The W/C twin test limiter, which is 12 cm long in toroidal direction and 8 cm wide in poroidal direction with a spherical shape (radius of 7 cm), is inserted into the edge plasma of TEXTOR-94 at the position of the LCFS from the top of the vessel. The W or C side of the twin limiter is oriented to the ion drift side, discharge by discharge, which allows us to compare particle emissions from the W and C sides in the identical plasma condition. Radial distributions of spectral line intensities of light emissions from atoms or ions in front of the ion drift side of the limiter are measured by an image intensified CCD-camera coupled to a spectrometer; in this study, we observe CII (426.7 nm) and WI (429.5 nm). Details of the experiments are described elsewhere [3,5].

In the EDDY simulation, only the ion drift side of the W/C twin test limiter is modeled by a rectangular prism with a base of 6 cm × 8 cm, forming an inclination angle of 12° against the magnetic field lines. Simultaneous incidences of impurity C, O and W ions, as well as fuel D ions, are taken into account for the plasma–surface interaction. The velocity distribution of the bombarding ions is assumed to be Maxwellian with an ion temperature $T_{\mathrm{i,lim}}$ at the limiter. The average charge states of C and O ions are determined to be +4 and +5, respectively [6], whereas the C and O concentrations in the bombarding ion flux are taken to be 2% and 1%, respectively [7]. When bombardment of W ions is taken into account, their charge state and concentration are assumed to be +5 and 1%, respectively. After sheath acceleration in front of the surface, the ions bombard a fixed point, e.g., the center of the surface; the sheath potential is $-2.48\ T_{\mathrm{e,lim}}$ [8], where $T_{\mathrm{e,lim}}$ is the electron temperature at the limiter and $T_{\mathrm{e,lim}} = T_{\mathrm{i,lim}}$ is assumed. In the edge plasma, radial profiles of electron density and temperature measured by a He atomic beam [9] are fitted to linear and exponential functions as input parameters for the EDDY code; at the limiter, $n_{\mathrm{e,lim}} = 5.2 \times 10^{12}$ cm^{-3} and $T_{\mathrm{e,lim}} = 128$ eV.

Four ion species (D, C, O and W) are chosen randomly according to the composition of the incident ion flux. The EDDY code treats the slowing down of the incident ions in the solid and the associated formation of recoil atom cascades by the binary collision approximation. It takes into account dynamic alterations of the local composition which arise from the deposition of implanted ions and the collisional transport of solid atoms, in the same manner as the TRIDYN code [10]. This causes physical sputtering of implanted ions due to further bombardment with incident ions, in addition to the physical sputtering of the limiter materials (W or C). The reflected projectiles and sputtered particles as neutrals go straight into the edge plasma until they are ionized due to impact of plasma electrons, whose process is simulated using the Monte Carlo method. The motion of the ionized particles is followed by analyzing the kinetic equation for the Lorentz force perpendicular to the magnetic field lines and collisional friction force parallel to the field lines in the plasma. The charge state of the ionized particles is changed through successive ionization during gyromotion, which is also treated using the Monte Carlo method. The detailed description of the EDDY code has been given in Ref. [4].

3. Results and discussion

In Fig. 1, calculated radial distributions of the number of ionization events of neutral W and C^+ ions, released from the W side of the limiter and for C, ionized in the plasma, are shown, along with observed intensity distributions of WI and CII line emissions. On the condition of the fixed radial distributions of the edge electron density and temperature, the shape of the calculated distributions is determined by the energy of released particles and their species. The energy distribution of physically-sputtered atoms have a large low-energy peak of a few eV which are accompanied with a long high-energy tail, furthermore, the heavy atoms such as W are much more ionized than low-Z atoms such as C. As a result, the number of neutral W atoms strongly decreases at the edge plasma near the limiter surface.

Although no significant C layer was found on the W side experimentally [2,3], except for the limiter edge where the local electron temperature is low, the CII line emission is observed in front of the W side of the limiter (Fig. 1). The emission of C atoms from the W side will

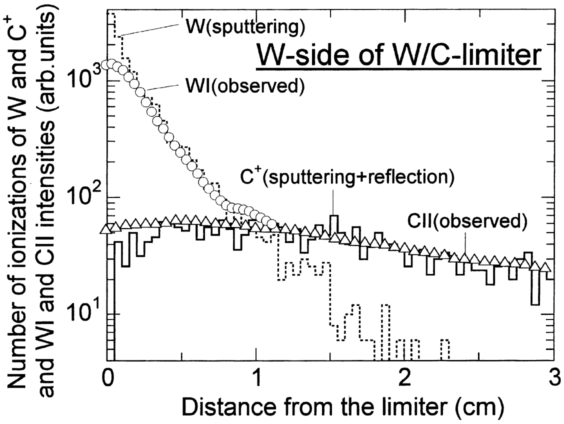

Fig. 1. Calculated radial distributions of the number of ionization events of neutral W atoms (physically sputtered), and C^+ ions (reflected and physically sputtered, and ionized) from W bombarded by D^+ (97%), C^{4+} (2%) and O^{5+} (1%) ions, along with observed distributions of WI and CII line emissions (symbols) in front of the W side of the W/C twin test limiter.

be due to the reflection of bombarding impurity C^{4+} ions and the physical sputtering of the impurity C implanted in W. Although the number of C^+ ions steeply decreases in the vicinity of the limiter (<0.3 cm from the limiter) since all of the released atoms are neutral, both the calculated distributions of ionization events of neutral W and C^+ ions are in good agreement with the observed intensity distributions of WI and CII line emissions. In the vicinity of the limiter, however, widely distributed light emissions on the limiter surface inclined against the line of sight of the CCD-camera cause the observed WI intensity distribution to change slowly and the CII intensity distribution not to disappear at the limiter.

The emission of C atoms from a graphite surface is also due to chemical erosion by impacts of D and O ions, producing volatile compounds such as CD_4 and CO with thermal energy; which are easily dissociated in the plasma. Due to the emission of the thermal C atoms, the observed intensity distribution of CII line emission in front of a whole C test limiter decays more steeply than the calculated distribution of the number of ionization events of sputtered and subsequently ionized C atoms, as shown in Fig. 2(a). For the C limiter, the measured $T_{\mathrm{e,lim}}$ and $n_{\mathrm{e,lim}}$ at the position of the limiter surface are somewhat lower for the W/C twin limiter; $T_{\mathrm{e,lim}} = 52$ eV and $n_{\mathrm{e,lim}} = 3.0 \times 10^{12}$ cm^{-3}. In the figure, in addition to the physical sputtering of implanted C and bulk C, the dissociated thermal C atoms due to the chemical erosion are simply simulated by low-energy emission of implanted C atoms with the Maxwellian velocity distributions at a temperature of 0.1 eV. The reflection of bombarding C ions from the C surface much less contributes to the total calculated distribution. However, surface contamination by metal impurities such as W largely suppresses the chemical erosion [11], and hence the contribution of thermal C atoms to the observed CII line emission, as shown in Fig. 2(b). Assuming the W^{5+} ion flux to be 1% in the bombarding ion flux and the total ion fluences to be 1×10^{19} cm^{-2}, furthermore, calculated distribution for physically-sputtered and ionized C atoms is in good agreement with observed distribution of CII line emission; D, C and O concentrations in the bombarding ion flux are 96%, 2% and 1%. With increasing maximum concentration of W in C, the reflection of bombarding C ions is enhanced as shown in Fig. 3, therefore, the calculated distribution of the number of ionization events of released and subsequently ionized C atoms decays more slowly than that without W deposition on C.

As also shown in Fig. 3, since the reflection coefficient for W ions, as well as the sputtering yield of deposited W, increases with increasing W concentration in the W/C layer formed on C, the observed distribution of WI line emission from the C side is influenced by both the reflection and physical sputterings. Fig. 4 demonstrates the observed WI line emission from the C side deposited by W, along with the calculated distributions of the number of ionization events of neutral W released due to the reflection of bombarding W ions and the physical sputtering of deposited W by impact of W^{5+} ions. The calculated distribution for physically-sputtered W atoms, which is analogous to the distribution for W atoms from the W side (Fig. 1), decays more steeply than the observed WI emission, whereas the decay of reflected W atoms is close to the observation. This may indicate an important contribution of the reflection of impurity W ions to the release of W atoms from the C side deposited by W.

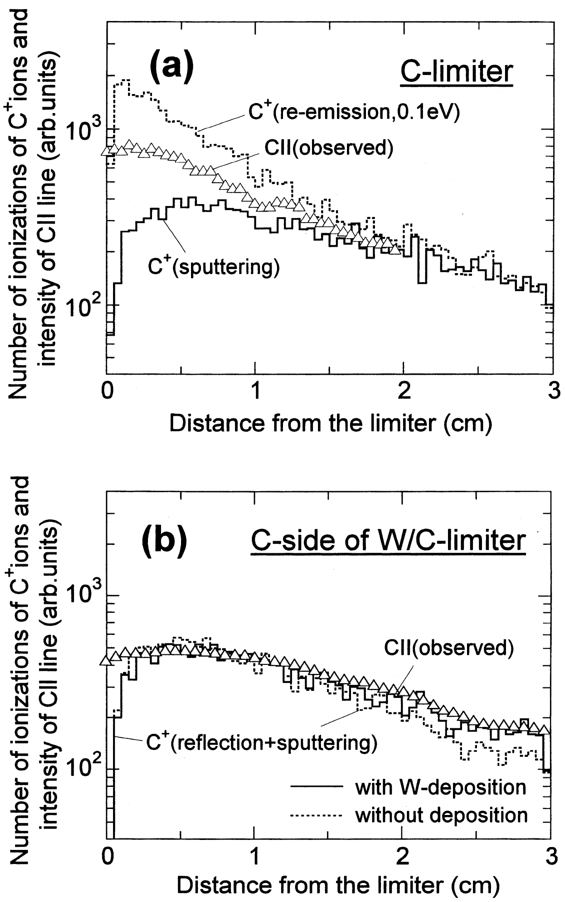

Fig. 2. Calculated radial distributions of the number of ionization events of C^+ ions, emitted from (a) C and (b) W-deposited C and ionized in edge plasmas, along with observed distributions of CII line emissions (symbols) in front of (a) a whole C test limiter and (b) the C side of the W/C twin test limiter.

Fig. 5 shows calculated depth profiles of W and C implanted in the C side for different total ion fluences. In the calculation, the maximum concentration of W implanted in C is limited to be 1 in the W/C ratio assuming production of tungsten carbide. The depth profiles of W give a thick W/C layer, whose thickness increases with

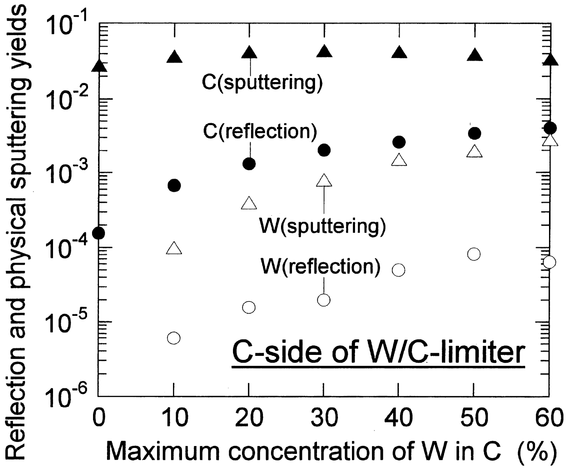

Fig. 3. Calculated reflection and physical sputtering yields of C and W from W-deposited C by impacts of D^+ (96%), C^{4+} (2%), O^{5+} (1%) and W^{5+} (1%) ions, as a function of maximum W concentration in C. The reflection (sputtering) yield is calculated as the ratio of the number of reflected (sputtered) particles to the total number of bombarding ions.

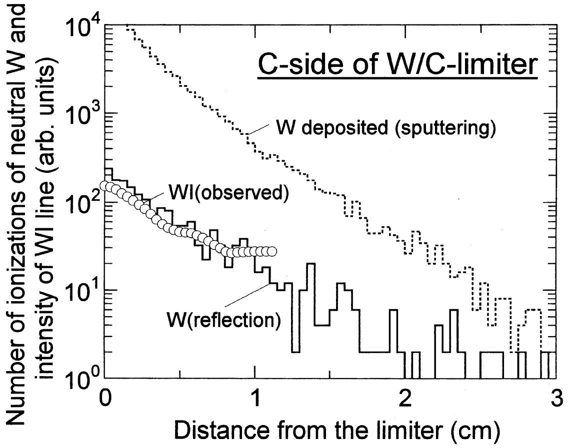

Fig. 4. Calculated radial distributions of the number of ionization events of reflected and physically sputtered W atoms from W-deposited C by impact of W^{5+} ions, along with observed distribution of WI line emission in front of the C side of the W/C twin test limiter.

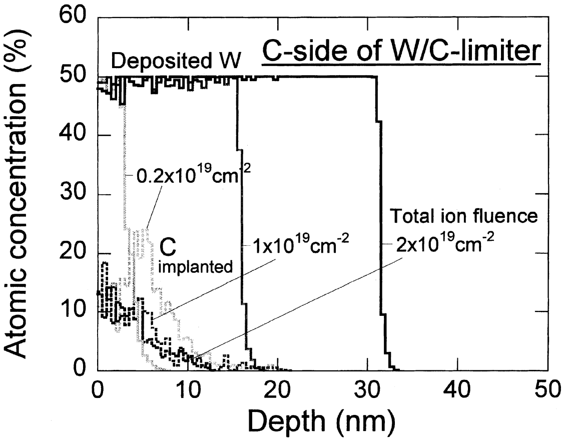

Fig. 5. Calculated depth profiles of impurities W and C implanted in the C side of the W/C twin test limiter at different total fluences of bombarding ions; D^+ (96%), C^{4+} (2%), O^{5+} (1%) and W^{5+} (1%).

increasing ion fluence, on the C side, whereas the profile of implanted C is unchanged against the ion fluence after the formation of thick W/C layer. The formation of the thick W deposition on the C side may be due to the high threshold energy for sputtering of deposited W and the 'prompt redeposition' of sputtered W [12]: sputtered W atoms are ionized in the plasma and gyrate in the magnetic field and hence a large part of them, e.g., 80%, are redeposited on the surface. Although the thick W/C layer was also observed experimentally [3], the observed W depth profile broadens much deeper than the calculated one inside the solid, probably due to thermal processes, such as thermal and radiation induced diffusions [13] and non-uniform deposition/erosion which causes surface topographies [14], which the present EDDY code does not take into account.

At most positions of the surface of the W side, no deposition of C was observed by means of an ion surface analysis technique after a series of the discharges [3]. This means that C atoms implanted in the W side due to impact of C are sputtered mainly due to the impact of most constituent D ions. Therefore, calculated implantation profiles of C in W, assuming constant C concentration of bombarding ion flux to be 2%, are approximately unchanged against the ion fluence or exposure time. When approaching the plasma edge, however, the C concentration in the plasma increases due to strong C source at the radial position of 46 cm, i.e., the ALT-II graphite main limiter. Assuming the C/D flux ratio estimated in [6], which depends on the edge plasma density and temperature, the thick C containing layer are calculated near the edge of the limiter (>5.7 cm from the top of the limiter), as shown in Fig. 6. This can reproduce the recently observed C deposition on the edge of a whole W limiter [15], i.e., a very sharp increase of the amount of deposited C within about 3–4 mm on the edge. Nevertheless, the limiter surface is preheated to about 750 K and during the plasma exposure it is strongly heated up due to high-fluence bombardment with the edge plasmas. As a result, surface-temperature-dependent processes, such as chemical erosion or radiation enhanced sublimation, may change the deposition profile of C, due to the surface temperature distribution.

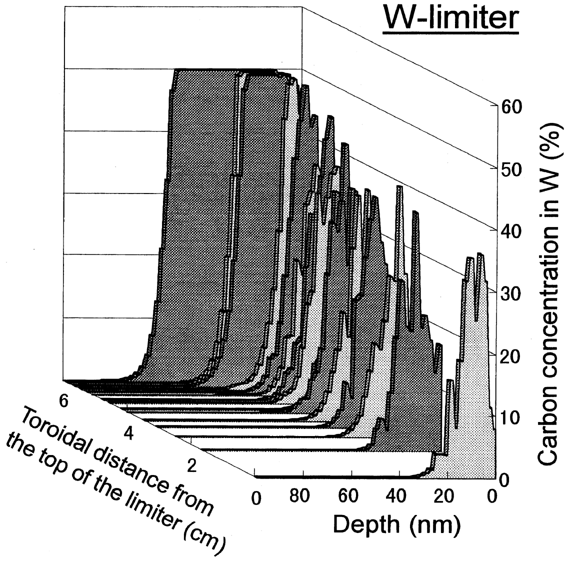

Fig. 6. Calculated depth profiles of implanted C, as a function of the toroidal distance from the top of a whole W test limiter. The C/D flux ratio estimated in [6], which depends on the edge plasma density and temperature, is assumed at each position of the limiter surface.

4. Conclusions

Experimentally observed spatial distribution of WI and CII line intensities around the W side of the W/C twin test limiter can be explained within the present EDDY calculations by physical sputtering of W, reflection of C ions contained by the edge plasmas and physical sputtering of implanted C near the surface. The low-energy re-emission, such as chemical sputtering, from the C side of the limiter is suppressed by deposition of W, and the projectile reflection, which much less contributes to the release of C from the whole C test limiter, play an important role in the release of C from the W-deposited C side of the W/C twin test limiter. The calculated radial distribution of the number of ionization events of sputtered and reflected, and ionized C atoms, assuming the surface W concentration in the W/C ratio of ~1, reproduces the observed CII distribution. The release of W from the C side is influenced also by reflection of bombarding W ions, in addition to sputtering of deposited W.

Bombardment with W containing deuterium plasma ions produces thick W layer on C, whereas C atoms implanted in W are sputtered mainly due to impacts of most constituent D ions and as a result, no thick C layer is produced on W. The large C ion flux and low-plasma temperature at the edge of a W test limiter results in thick C deposition, which can reproduce the experimental observation.

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