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Section 4. Erosion and deposition, hydrogen and deuterium inventory

Erosion of high-*Z* metals with typical impurity ions

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Abstract

This paper reviews the erosion properties of high-*Z* plasma facing materials due to the bombardment with typical impurity ions. The different impurity species present in today's fusion experiments are compared in terms of their importance for erosion of high-*Z* metals, showing that C is the main source of erosion. As example results are presented here from controlled ion beam experiments on the temperature dependent erosion and deposition processes occurring during bombardment of W by keV C-ions. It is shown that radiation enhanced sublimation (RES) and diffusion are responsible for the observed temperature dependence. A new code was developed to simulate the influence of thermally activated processes on the complex temperature dependence of protective C layer growth on W during simultaneous bombardment by keV C and eV hydrogen isotopes. To model RES, diffusion and chemical erosion of C the Monte Carlo program TRIDYN was coupled with a newly developed diffusion code DIFFUSEDC and a chemical erosion module YCEHM. This combination was validated by comparing calculated W erosion yields in D plasma with C as main impurity to spectroscopically measured values from ASDEX Upgrade as well as ion beam experiments using CH_3^+.

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Keywords: Plasma-wall interactions; Diffusion; Chemical erosion; Temperature dependence; Weight loss; TRIDYN code

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1. Introduction

In modern fusion devices the plasma contains various intrinsic impurities where C and O are the most common species. O originates from the residual gas but is efficiently removed from the plasma by gettering and has a typical concentration of 0.1% in the plasma [1]. C originates mainly from sputtering of the first wall with typical concentrations in the order of few percent in the edge plasma [1] which is favorable for radiative cooling of the edge and divertor plasmas. As carbon-based components are increasingly eliminated from present and future machines the necessity of introducing additional impurities into the divertor plasma arises in order to assure sufficient radiation cooling. Inert gases like Ne or Ar are the proposed species to be introduced into the divertor for radiative cooling [2].

The bombardment of the first wall with O and inert gases like Ne or Ar does not lead to layer deposition but to physical sputtering of the first wall. These processes are well studied and understood [3]. This is not the case for the complex erosion and deposition processes occurring during the simultaneous bombardment of the hot first wall with hydrogen isotopes and non-recycling impurities such as C. To investigate the transition from W erosion to C layer deposition under plasma conditions, controlled ion beam experiments were performed. In these experiments the temperature dependence of protective C-layer growth on W during C-ion bombardment was monitored by measuring the samples weight change in situ as a function of fluence. In addition the involved temperature dependent processes C such as diffusion [4] and radiation enhanced sublimation (RES) [5] were studied in separate experiments. To investigate RES, C self-sputtering experiments were performed where the temperature dependence of the C

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erosion was monitored again by in situ measurement of the sample's weight change as a function of fluence and sample temperature.

To model the simultaneous carbon bombardment and diffusion the Monte Carlo code TRIDYN [6] was coupled to the newly developed diffusion code DIFFUSEDC [4]. With this code package and the experimental information about C diffusion and RES it is possible to simulate the temperature dependent erosion and deposition processes occurring during bombardment of W by C without any free parameters and compare them to experimental results. To model the simultaneous bombardment of W with C and D hydrogen isotopes from a plasma a chemical erosion Module YCHEM was added to the TRIDYN+DIFFUSEDC code package. The new code was tested and verified by comparing simulations of CH_3^+ bombardment of W with experimental results [17].

This combination of TRIDYN+DIFFUSEDC+YCHEM and chemical erosion allows to simulate the bombardment of W by C and D from a fusion plasma. Taking into account the Maxwellian energy distribution and the acceleration of the incident C^{4+} and D^+ in the sheath potential the W sputtering yield due to a D plasma with C impurity was calculated. The results for the W sputtering yield are compared to spectroscopic measurements of the W sputtering yield reported for the ASDEX Upgrade W divertor experiment [7].

2. Experiment

The experiments described here were all performed at the Garching high current ion source [8]. For the weight change measurements polished W and C samples were irradiated by 2.4 keV ^{12}C ions at normal angle of incidence and fluences up to 10^{18} cm^{-2} in the temperature range from 300 to 1073 K. To desorb the samples they were annealed at a temperature of 1000 K, but always at least 100 K above the intended measurement temperature for up to 16 h. The C ions are produced from an arc ignited in a CO_2 and H atmosphere and are then separated from other species in a 60° sector magnet. The final beam energy of 2.4 keV at the target results from an extraction voltage of 4 kV minus a deceleration voltage of 1.6 kV at the target. The positive target bias is required for the electron beam heater and also suppresses any secondary electrons that could interfere with the current measurement.

The attainable target current is in the order of 10^{-5} A with a spot size of approximately 0.5 cm^2 yielding a flux in the order of 10^{14} $cm^{-2}\,s^{-1}$. During source operation the pressure in the target chamber is in the order of 10^{-5} Pa.

The weight change is measured in situ as a function of applied fluence using a Mettler ME21 microbalance with a weight uncertainty of ±2 μg. The sample temperature was determined with an infrared pyrometer which was calibrated at 1073 K with an optical pyrometer. The emissivity used for the measurement with the optical pyrometer was taken from [9]. It was then assumed that the infrared emissivity would not change in the temperature range from 1000 to 1073 K where the measurements at elevated temperatures were performed.

3. Experimental results

3.1. C self-sputtering

To investigate the enhanced, temperature dependent erosion of C by C due to RES C self-sputtering experiments were performed bombarding C with 2.4 keV ^{12}C ions in the temperature range from 300 to 1073 K. The results of the weight change measurements are depicted in Fig. 1. The weight of the samples increases linearly since the C-sputtering yield is smaller than unity and does not change throughout the irradiation. However it exhibits a strong temperature dependence due to RES. From the slope of the weight change the temperature dependent C self-sputtering yield can be deduced. Already at a temperature of 1000 K the sputtering yield is more than a factor of 2 higher than at room temperature. The values obtained thereby correspond well to literature data from [10] as can be seen in Fig. 4.

3.2. C on W

To investigate the temperature dependence of the protective C layer growth W samples were bombarded

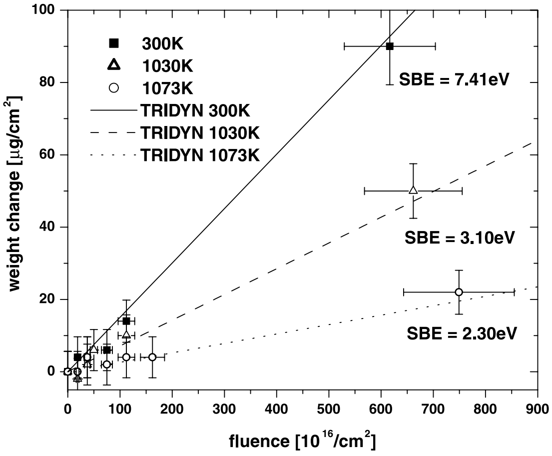

Fig. 1. Weight change of C during irradiation with 2.4 keV ^{12}C ions in the temperature range from 300 to 1073 K. Also shown are pure TRIDYN simulations together with the SBEs used.

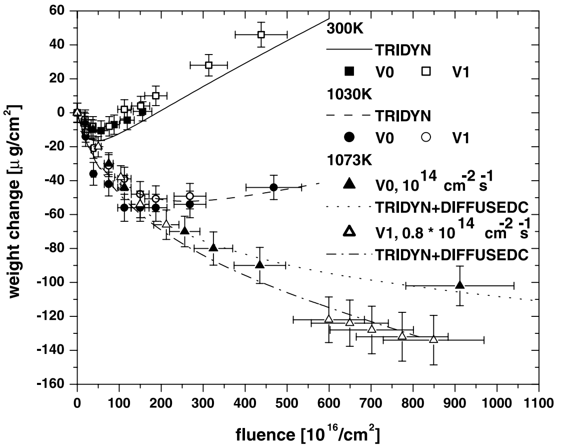

Fig. 2. Weight change of W during irradiation with 2.4 keV ^{12}C ions in the temperature range from 300 to 1100 K. Also shown are the results of TRIDYN+DIFFUSEDC calculations which reproduce the experimental data well within the experimental error bars.

with C with 2.4 keV ^{12}C ions in the temperature range from 300 K to 1073 K. The results are shown in Fig. 2 and show a similar trend at all temperatures: initially the samples weight decreases, passes through a transition point and then starts to increase again. This general behavior can be understood as follows: At the start of the bombardment pure W is eroded by the incident C. At the same time C is implanted below the surface. The strong W erosion leads to the observed weight loss during the initial erosion phase. With the ongoing bombardment the implanted C eventually reaches the surface leading to a reduction of the C reflection. This together with the fact that the C self-sputtering yield is smaller than the unity in the temperature range investigated (see also Fig. 1) leads to the formation of a C layer that shields the underlying W from further erosion and is responsible for the weight increase in this deposition phase.

In Fig. 1, a strong temperature dependence of the position of the transition point and the slope of the weight gain in the deposition phase can be observed. Above 1000 K according to [4] noticeable C diffusion takes place in W and as seen from Fig. 1, the C self-sputter yield increases due to RES. These two processes are, as simulations show later, responsible for the observed temperature dependence of the erosion/deposition balance. The diffusion thereby is responsible for the shift of the transition point to higher fluences because this C transport from the surface yields a lower C concentration at the surface at a given fluence. This leads to higher C reflection and thus to a slower accumulation of C on the sample which shifts the transition point to higher fluences. Therefore the duration of the initial erosion phase depends on the ratio of C flux into the bulk to the incident flux of C ions. This flux dependence can also be observed in the two 1073 K measurements in Fig. 2: in measurement V1 the incident flux was smaller by a factor of 0.8 compared to V0 which leads to larger extend of the erosion phase.

The slow increase of the sample's weight in the deposition phase at temperatures above 300 K is due to RES. In this phase the W is shielded by the C-layer so the dominant process that governs the weight change is C self-sputtering which is increased due to RES.

4. Modeling

To model the weight change of W during C irradiation the involved temperature dependent processes, i.e. C diffusion and RES, had to be included in the computer simulation. To account for the simultaneous diffusion and implantation the Monte Carlo program TRIDYN [6] was coupled with the diffusion code DIFFUSEDC [4]. The coupling works as follows: The bombardment of a sample with a fluence Φ during a total irradiation time t is simulated in discrete steps of length $\mathrm{d}\Phi$. Each step thereby consists of TRIDYN calculation during which the fluence $\mathrm{d}\Phi$ is applied. The resulting depth profile then serves as initial condition in the following DIFFUSEDC calculation during which the time evolution of the profile during a time step $\mathrm{d}t$ at a temperature T is calculated. The depth profile resulting from this calculation then in turn serves as initial condition for the TRIDYN calculation of the next fluence step $\mathrm{d}\Phi$. This cycle is repeated N times until the entire fluence Φ has been applied. In order to fulfill the demand of simultaneous diffusion and implantation, $\mathrm{d}t$ and $\mathrm{d}\Phi$ have to be chosen appropriately. The time steps $\mathrm{d}t$ have to be chosen such that the typical length of diffusion is smaller than the typical length of implantation, corresponding to the mean projected range of C in W. In the simulations 'smaller' was considered to be less than 10% of R. This correlation is shown in Eq. (1).

$$\begin{aligned}&\sqrt{\mathrm{D(C)}_{\max}\,\mathrm{d}t} \ll R,\\&\mathrm{D(C)}_{\max} = \text{maximum value for D},\\&R = \text{mean projected range of C in W},\end{aligned} \tag{1}$$

$\mathrm{D(C)}_{\max}$ at 1073 K is of the order of 10^{-19} m^2/s and the mean projected range of 2.4 keV C^{12} in W is of the order of 10 nm. With these values Eq. (1) gives $\mathrm{d}t = 100$ s. Once $\mathrm{d}t$ is set, $\mathrm{d}\Phi$ can be calculated from the total implantation time t and total fluence Φ known from the experiment using Eq. (2).

$$\mathrm{d}\Phi = \frac{\Phi}{t/\mathrm{d}t}. \tag{2}$$

A test of the dependence of the simulation result on dt showed that a value of 100 s is a good compromise between accuracy and computational time.

To take the enhanced erosion due to RES of C into account the surface binding energy (SBE) of C, which governs sputtering, was reduced. The SBEs to be used to give the correct sputtering yield were deduced from pure TRIDYN simulations of the C self-sputtering experiments. In these calculations the SBE of C was iteratively reduced until the calculated weight change would match the experimental values.

To model the simultaneous bombardment of W by C and hydrogen isotopes an additional module YCHEM is inserted into the TRIDYN+DIFFUSEDC cycle described above. In the application of a fluence step dΦ YCHEM is applied after the TRIDYN run and simulates the chemical erosion of C by modifying the implantation profile calculated by TRIDYN according to fixed chemical sputtering yield Y_{Chem}, taken from experimental data. This modified depth profile then serves as input for DIFFUSEDC. To modify the depth profile due to the additional chemical erosion, YCHEM uses the same model as used in TRIDYN to simulate surface recession and layer deposition: TRIDYN samples the target into n_{L} layers of thickness Δx_i ($i = 1, \ldots, n_{\mathrm{L}}$). The ith layer thereby contains concentrations $q_{i,j}$ ($j = 1, \ldots, n_{\mathrm{C}}$) of the n_{C} components in the system. As is known from experiment [11] chemical erosion takes place along the entire path of the incident projectile and is peaked at its average range. Therefore YCHEM distributes the chemical erosion in a gaussian $G(x_i)$, peaked at the average range. This yields the following chemical erosion $Y_{\mathrm{Chem},i}$ of layer i with thickness Δx at depth x_i.

$$\begin{aligned} &Y_{\mathrm{Chem},i} = G(x_i)\Delta x Y_{\mathrm{Chem}} q_{i,c}, \\ &q_{i,c} = \text{C-concentration in layer}\, i. \end{aligned} \tag{3}$$

The chemical erosion modifies the areal density $v_{i,\mathrm{C}}$ of C in layer i according to Eq. (4).

$$\begin{aligned} &v_{i,\mathrm{C}} = q_{i,\mathrm{C}} N_i \Delta x_i - \mathrm{d}\Phi Y_{\mathrm{Chem},i} \xi_{\mathrm{H}}, \\ &N_i = \text{numberdensity in layer}\, i, \\ &\xi_{\mathrm{H}} = \text{hydrogen fraction in}\, \mathrm{d}\Phi. \end{aligned} \tag{4}$$

The areal densities of the other components remain the same and the new concentrations $q_{i,j}$ can be calculated from Eq. (5),

$$q_{i,j} = \frac{v_{i,j}}{\sum_{k=1}^{n_{\mathrm{C}}} v_{k,i}}, \tag{5}$$

and the new layer thickness Δx_i from Eq. (6)

$$\begin{aligned} &\Delta x_i = \sum_{j=1}^{n_{\mathrm{C}}} \frac{v_{i,j}}{N_{0,j}}, \\ &N_{0,j} = \text{numberdensity of pure component}\, j. \end{aligned} \tag{6}$$

Finally this new depth profile is resampled with constant step width Δx and is then passed to DIFFUSEDC.

To compare the computer simulations to the experimental results the weigh change as a function of the applied fluence has to be deduced from the calculated partial sputter yields and reflection coefficients according to equation Eq. (7) which gives the weight change per fluence step dΦ.

$$\begin{aligned} &\mathrm{d}W = \sum_{j=1}^{n_{\mathrm{C}}} M_j\left(\xi_j\left(1 - R_j\right) - S_j\right)\mathrm{d}\Phi L, \\ &M_j = \text{mass of component}\, j, \\ &\xi_j = \text{fraction of component}\, j\, \text{in beam}, \\ &R_j = \text{reflection coefficient of component}\, j, \\ &S_j = \text{partial sputter yield of component}\, j, \\ &L = \text{Lohschmidt number}. \end{aligned} \tag{7}$$

The input parameters for the modules of this simulation code were all taken from experiments as follows: TRIDYN requires n_{C}^2 SBEs, one for each combination of components. Since the hydrogen isotopes are not allowed to accumulate layers on the samples the only SBEs of interest are those of C and W. The SBE of W on W is deduced from its heat of sublimation and a value of 8.68 eV [12] was used for all calculations. For W on C the SBE was calculated from the SBE of the pure components by applying Eq. (8) [13] using 8.68 eV for $\mathrm{SBE_W}$ and 7.4 eV for $\mathrm{SBE_C}$ which is deduced from the heat of sublimation of C. This yields a value of 8 eV for $\mathrm{SBE_{W\ on\ C}}$ which was used for all calculations.

$$\mathrm{SBE}_{X\,\mathrm{on}\,Y} \approx \tfrac{1}{2}(\mathrm{SBE}_X + \mathrm{SBE}_Y). \tag{8}$$

As mentioned above the SBE of C on C was reduced to account for the enhanced erosion due to RES. To determine the SBE for each temperature the C self-sputtering experiments were simulated using TRIDYN and reducing the SBE of C on C to fit the experimental data (see Fig. 1). The SBE of C on W was again calculated from Eq. (8) by using the temperature dependent values for $\mathrm{SBE_C}$ and the constant value of 8.68 eV for $\mathrm{SBE_W}$.

DIFFUSEDC requires the diffusion coefficient for C a wide concentration range for C in W. The experimental determination of the diffusion coefficient of carbon in W is described in detail in [4]. Due to the large C concentration arising during ion implantation the concentration dependence of the diffusion coefficient could not be neglected. In order to determine the diffusion coefficient as a function of concentration D(C), diffusion couples consisting of ~100 nm thin W layers on C substrates were heated at temperatures from 1000 to 1073 K. Below 1000 K the diffusion was found to be too small to be measured quantitatively. After each heating step the depth profile of C atoms diffused into the W

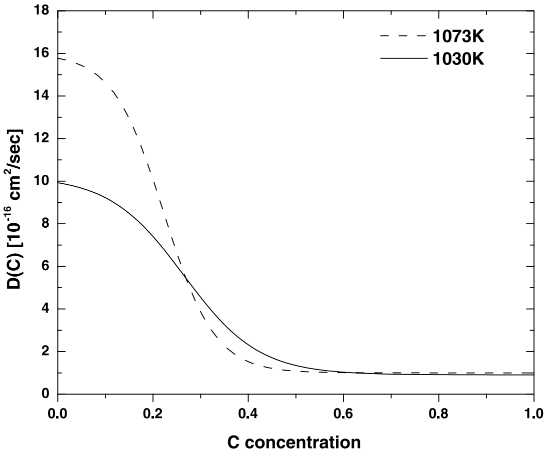

Fig. 3. Concentration dependent diffusion coefficients [4] used in the simulation of bombardment at 1030 and 1073 K.

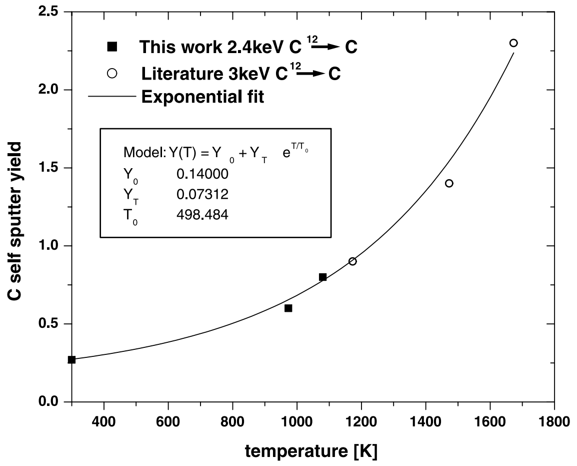

Fig. 4. Comparison of measured C self-sputtering yields with literature data taken from [10]. Also shown are the results of an exponential fit to the data (see text).

layer was measured by Rutherford backscattering spectroscopy. From these depth profiles, D(C) was extracted either directly by applying 'Boltzmann–Matano' Analysis [4] or by simulating the diffusion profile and iteratively adjusting D(C) to fit the measured profiles. Both methods give similar results and show strong diffusion for small C concentrations (10^{-19} $\mathrm{cm^{-2}\,s^{-1}}$ at 1073 K) and a drop by about one order of magnitude for concentrations above 40% C (Fig. 3) The chemical erosion yields required for YCHEM were taken from [14]. Therewith all input parameters are determined from experimental values and there remain no free parameters for the simulations.

5. Simulations results

5.1. C self-sputtering

The results of C self-sputtering experiments were simulated using TRIDYN calculations. Thereby the SBE of C on C was reduced as to reproduce the measured weight change in the calculation. The results of these simulations together with the SBEs used are shown in Fig. 1. In the simulations of the C bombardment of W at elevated temperatures the SBE of C on C at the corresponding temperature is required. Therefore from the temperature dependent sputter yield data shown in Fig. 4 an interpolation formula for the SBE of C on C as a function of temperature T was deduced. Since the currently accepted model for RES [5] predicts an exponential increase of the sputter yield with temperature, an exponential dependence of the SBE on T was assumed Eq. (9) was used to fit the data from Fig. 4.

$$\mathrm{SBE}(T) = ((0.14 + 0.073\,\mathrm{e}^{T/500})/2.17)^{-1}. \tag{9}$$

5.2. C on W

To simulate the experimental results on the temperature dependence of the protective C layer growth during bombardment of W by C from Fig. 3 the coupling TRIDYN+DIFFUSEDC was used. The input parameters for TRIDYN Φ, dΦ and the SBEs are given in Table 1. Not included in this table are the SBE of W on W (8.68 eV) and W on C (8.0 eV) which remain the same for all calculations. The concentration dependent diffusion coefficients used are shown in Fig. 3. The results of these simulations without free parameters are shown in

Table 1
Input parameters for the TRIDYN and TRIDYN+DIFFUSEDC simulations of the bombardment of W with C at 300, 1030 and 1073 K

T (K)	Φ (10^{16} $\mathrm{cm^{-2}}$)	dΦ (10^{16} $\mathrm{cm^{-2}}$)	$\mathrm{SBE_{C\ on\ C}}$ (eV)	$\mathrm{SBE_{C\ on\ W}}$ (eV)
300 K V0, V1	600	600	7.41	8.00
1030 K V0, V1	1110	0.925	2.95	5.82
1073 K V0	1110	0.925	2.3	5.5
1073 K V1	1040	0.825	2.3	5.5

Fig. 2 and one can see that they reproduce the experimental results well within the error bars. In particular the fluence dependence is well reproduced in the two simulations performed at 1073 K which only differ in the incident C-flux respectively in the step width $d\Phi$. From these simulation results, one can conclude that the model of diffusion and RES being responsible for the observed temperature dependence of the protective C layer growth is correct.

5.3. CH_3 on W

To test the combination of TRIDYN+DIFFUSEDC+YCHEM the bombardment of W with 3.0 keV CH_3 at 300 and 1000 K was simulated. The resulting particle energies are 2.4 keV for C and 200 eV for H. The experimental weight change data was taken from [17].

In the TRIDYN part H was added as an additional incident species with fraction $\xi_H = 75\%$ in the beam. For the simulation at 1000 K the same SBE and D(C) were used for TRIDYN and DIFFUSEDC as for the 1030 K calculation of the bombardment of W with C only. The chemical sputter yield Y_{Chem} was taken form literature data and was 10%. In Fig. 5 the results of the calculation are compared to experimental data for irradiation of W with CH_3 at 1000 K [17] and with pure C at 1030 K. The simulations reproduce the experimental values well within the error bars. One can clearly see, that the additional chemical erosion of the applied C inhibits layer growth and continuous W erosion takes place. The W is only eroded by the incident C, the H energy is below the sputtering threshold [8].

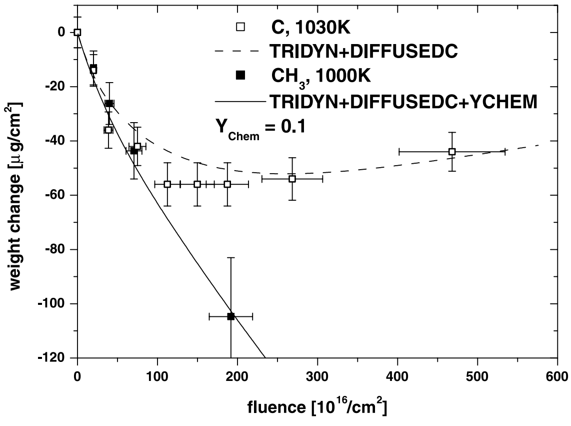

Fig. 5. Comparison between experimental and simulated data of the bombardment of W with 2.4 keV C at 1030 K and 3.0 keV CH_3 at 1000 K.

For the simulation at 300 K the diffusion of C can be neglected such that the DIFFUSEDC step could be omitted in the simulation and only TRIDYN+YCHEM were used. The same SBEs for C and W were used in TRIDYN as for the simulation of the bombardment of W with C only at 300 K and the chemical sputter yield was 4%. In Fig. 6 the result of this simulation is compared to the experimental data for W irradiated with pure C and CH_3 respectively. One can see that despite of the small chemical erosion at 300 K, the slope of the weight gain in the deposition phase is lower than for bombardment with pure C.

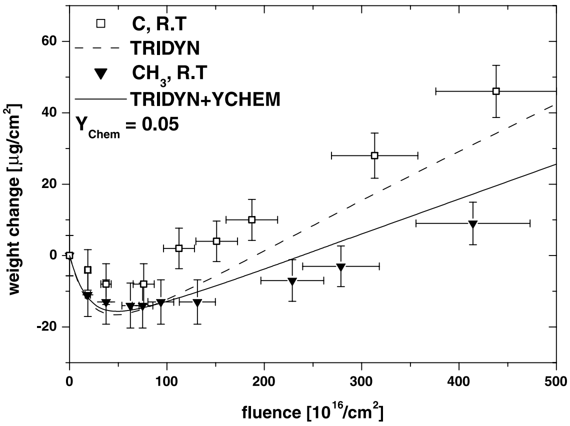

Fig. 6. Comparison between experimental and simulated data of the bombardment of W with 2.4 keV C and 3.0 keV CH_3 at 300 K.

5.4. W-sputter yields from ASDEX

After the validation of the TRIDYN+DIFFUSEDC+YCHEM code against the CH_3 measurements, experimental results from fusion experiments were modeled. The aim was to calculate the W sputtering yields as a function of the electron temperature in the plasma for a surface temperature of 300 K. Again due to the low surface temperature diffusion was neglected and only TRIDYN+YCHEM were used. The same SBEs for C and W were used in TRIDYN as for the simulation of the bombardment of W with pure C at 300 K. In contrast to ion beam experiments the energy of the ions from the plasma is not sharp but follows a Maxwellian distribution with its center shifted to higher energies due to the acceleration in the sheath potential. According to [15] the sheath potential U_{STH} as a function of the electron temperature T_e (eV) is approximately given by $U_{STH} \approx 3T_e/e_0$. With this approximation for the sheath potential and an average charge state of Q the mean energy of the incident ions is given by,

$$E_{AV} = QU_{STH} + T_e, \tag{10}$$

assuming that the ion temperature is equal to 0.5 of the electron temperature. The chemical erosion yield used

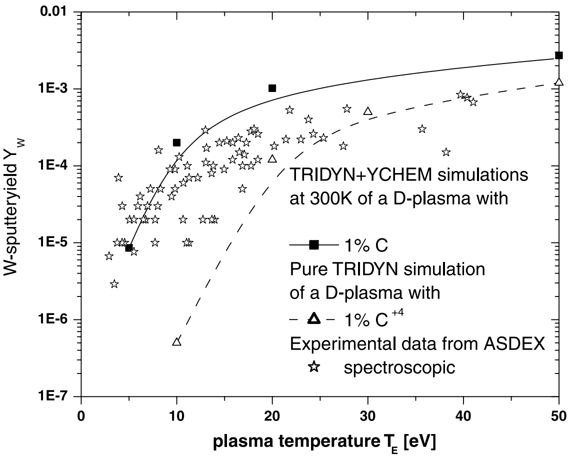

Fig. 7. Comparison of experimental W sputter yields for ASDEX Upgrade and calculated yields as a function of plasma temperature.

for YCHEM was that for D with an energy according to Eq. (10) and a surface temperature of 300 K. Based on this input data the W sputter yield from a D plasma with 1% C impurity was calculated assuming C^{4+} ions. The result is depicted in Fig. 7 together with the results of a pure TRIDYN calculation without additional chemical erosion. The new model fits the experimental data well whereas the pure TRIDYN calculation underestimates the W erosion. Without including the chemical erosion a protective C layer builds up in the pure TRIDYN calculation, shielding the W form sputtering and resulting in a steep decrease of the sputtering yield already at 20 eV. D^+ ions alone cannot erode W at temperatures below 30 eV. D^+ ions alone cannot erode W at temperatures below 30 eV.

5.5. Parameter scan of W erosion as function of T_e and C concentration

Using the validated code package, the steady state erosion for different plasma temperatures and carbon concentrations can be obtained. By performing analogous calculations as for the modeling of the W-sputter yield data from ASDEX, the equilibrium weight change d*W* at 300 K surface temperature of a W sample was calculated. A negative d*W* thereby indicates net erosion and a positive d*W* net deposition. The result is depicted in Fig. 8 showing that the erosion increases with C-concentration until at 4% a maximum of the erosion of W occurs. No W erosion occurs for zero C-content from the pure D-plasma in the temperature range considered here. At higher C concentrations C accumulates in the surface layer resulting in less erosion. The thick black line indicates the erosion/deposition boundary.

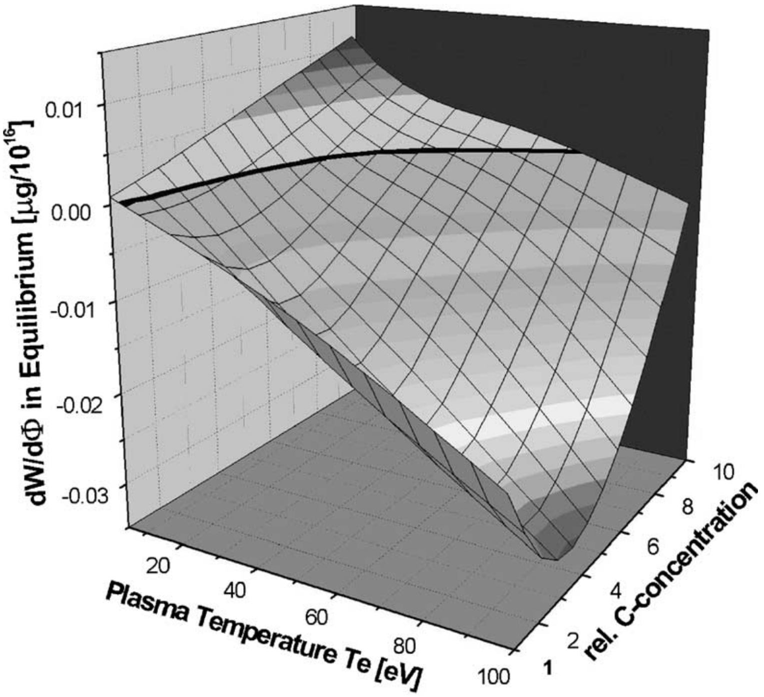

Fig. 8. Parameter scan of weight change as function of plasma temperature and C impurity concentration.

6. Discussion

In this work we found enhanced C self-sputtering at elevated temperatures both on solid graphite samples and on C layer deposited on W. A comparison of our data with literature values for self-sputtering [10] is shown in Fig. 4. One can see that our data agrees well with literature data showing an exponential increase with temperature as expected from current RES models [5]. However those models are based on the diffusion of lattice imperfection in crystalline graphite. It is therefore surprising that it is also applicable to deposited amorphous C layers. The question arises whether there are different processes not included in the current RES models that also lead to weakly bounded C atoms at the surface.

The measurements in [4] and the C self-sputtering experiments show that RES and C diffusion in W cannot be neglected above 1000 K. The influence of diffusion and RES are obvious in the clear flux dependence and the reduced weight increase in the deposition phase respectively at elevated temperatures. This together with the good agreement of the model calculations with the experimental data leads to the conclusion that the experimentally observed temperature dependence of the C layer growth on W is due to diffusion and RES. The dynamics of the weight change is thereby determined by the ratio of the incident flux to the C bulk diffusion. RES is responsible for the weaker increase of the samples weight in the deposition phase.

There have been earlier approaches trying to explain this temperature dependence in odel calculations. In [16] the weight change measurements were modeled by coupling TRIDYN to the diffusion code PIDAT. In this work RES and the concentration dependence of the diffusion coefficients were neglected so it was not possible to reproduce the weight change measurements. Also the time steps of 1000 s used were too coarse as that diffusion and implantation could have been considered to occur simultaneously. An analytical approach of the temperature dependence is given in [17]. There the experimental results are explained by enhanced C erosion due to RES only, completely neglecting diffusion. This approach leads to C self-sputtering yields way higher than experimental values.

The calculation of the W erosion under simulated plasma conditions using the TRIDYN+YCHEM code show a better resemblance of the experimental W sputter yield data at low electron temperatures compared to pure TRIDYN calculations. The deviations at higher electron temperatures are probably due to an overestimation of the chemical erosion yield which was chosen to be constant corresponding to the average D ion energy and a surface temperature of 300 K. Nevertheless the simulations show that continuous W erosion is only possible during the simultaneous bombardment with C and D since the D energy is below the sputtering threshold (200 eV for W) and C alone would deposit a protecting layer.

7. Conclusions

In this work we investigated the erosion of W by C and the simultaneous bombardment of W with C and D. For the irradiation of W with pure C it was found that C diffusion in W and enhanced C sputtering due RES hinder the protective C layer growth during irradiation of W by C. To simulate the experimentally observed temperature dependence of the W samples weight change TRIDYN was coupled to the newly developed diffusion code DIFFUSEDC. These calculations reproduced the experimental results without any free parameters and showed that for pure C bombardment and surface temperatures below 1073 K a shielding C layer builds up on the W surface, protecting it from further erosion.

In order to be able to simulate W erosion under plasma conditions chemical erosion was added to the coupling of TRIDYN+DIFFUSEDC and the new code was validated by simulating W bombardment by CH_3 and comparing it to experimental data. With this new TRIDYN+DIFFUSEDC+YCHEM code W erosion due to a D plasma with C impurities was calculated and compared to experimental results from ASDEX Upgrade. These calculations reproduced the experiments well and showed that in contrast to pure C bombardment the simultaneous bombardment of W with C and D leads to continuous erosion of the W.

For the use of high-Z materials as wall materials the erosion due to impurity ions must be considered [18]. The estimate of the erosion effect of non-recycling impurities, such as C or Be, is most difficult due to the delicate balance of erosion and deposition and details of the material mixing must be taken into account.

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