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Modelling of the Chemical Erosion of a Carbon Limiter in the Scrape-Off-Layer of TEXTOR-94

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1. Introduction

Low-Z carbon based materials are still the primary choice for high heat flux components in present and future fusion devices. Their thermomechanical properties are excellent, they do not suffer even under extreme power loads in off-normal events like disruptions. Moreover, released carbon impurities can be tolerated by the plasma up to comparably high levels. However, these materials exhibit large erosion rates, which may lead to unacceptable small lifetimes under steady state operation conditions. Additionally, the large erosion fluxes can lead to the built-up of thick tritium containing carbon deposits which results in an unacceptable retention of the tritium fuel in future devices.

In the following ERO-TEXTOR [1] simulation calculations of the chemical erosion at a carbon limiter exposed to the Scrape-Off-Layer of TEXTOR-94 are presented. The results of modelling will be compared with experimental data. For the calculations it is assumed that the only product of chemical erosion is methane (CD_4). The dissociation of the eroded CD_4-molecules moving through the plasma is determined using the database according to Ehrhardt and Langer [2]. The interaction of the eroded particles with the background plasma includes friction forces, thermal forces and diffusion. If eroded particles return to the limiter surface they can erode new material and if they are not redeposited they will again move through the plasma as neutrals. The reflection coefficient of carbon atoms and carbon ions is calculated using TRIM data. Due to the lack of reflection data the reflection probability of CD_4-molecules and hydrocarbon radicals is determined by an input parameter of the code (in the following the reflection coefficient for neutral radicals and CD_4-molecules is abbreviated with $R_{neutral}$ whereas for charged radicals the term R_{ion} is used). It is further assumed that radicals are reflected from the surface as CD_4-molecules.

2. The photon efficiency D/XB for CD from CD_4

CD-light spectroscopy above the sample is applied in order to determine experimentally the erosion by CD_4-formation. For this, the D/XB-value is used which relates the amount of chemically eroded CD_4-molecules to the number of emitted CD-band photons. In practice, one measures the number of CD-photons and multiplies this quantity with the known D/XB-value resulting in the number of chemically eroded CD_4-molecules. The D/XB-value itself must be derived independently by e. g. puffing a defined amount of CD_4-molecules into the plasma and then measuring the CD-light.

The aim of these ERO-TEXTOR calculations is to investigate the influence of the plasma parameters (electron density n_e and electron temperature T_e) and of the reflection coefficient R of returning hydrocarbons on the D/XB-value. Therefore calculations were carried out for a

spherically shaped graphite limiter as it is used in TEXTOR-94 (radius 70mm, toroidal length 110mm and poloidal length 80mm) positioned with the tip at the last closed flux surface (lcfs). For the radial profiles of n_e and T_e an exponential decay in the direction to the limiter is assumed with decay lengths of 20 mm and 25 mm respectively which are typical values in TEXTOR-94. The flux Γ_{D^+} is assumed to erode carbon (by forming CD_4) by chemical sputtering with a yield of 1.5%. The influence of n_e and R on the CD-light distribution in the vicinity of the limiter is shown in fig.1. An increase of the electron density by a factor 10 results in a decrease of the ionization lengths. The CD-distribution is much more concentrated in the vicinity of the limiter surface. Here, the "standard reflection model" with R_{ion}=0.5 and $R_{neutral}$=1 is used. Also included in fig. 1 is the case where all returning hydrocarbons stick on the surface, i. e. $R_{ion}=R_{neutral}=0$. This leads to a narrow spatial distribution of the CD-light adjacent the limiter surface. The reason for this behaviour is the different energy of reflected hydrocarbons compared to chemically sputtered ones. The latter start with thermal energies of a few eV, whereas the reflected have the energy of the incoming particles, which is in the range of 100 eV (energy gain in the sheath potential $\approx 3T_e$). Only the reflected hydrocarbons with their higher starting energies are able to give rise to noticeable CD-light emission far away from the limiter. The slower chemically sputtered CD_4-molecules achieve the CD-state at shorter distances from the limiter.

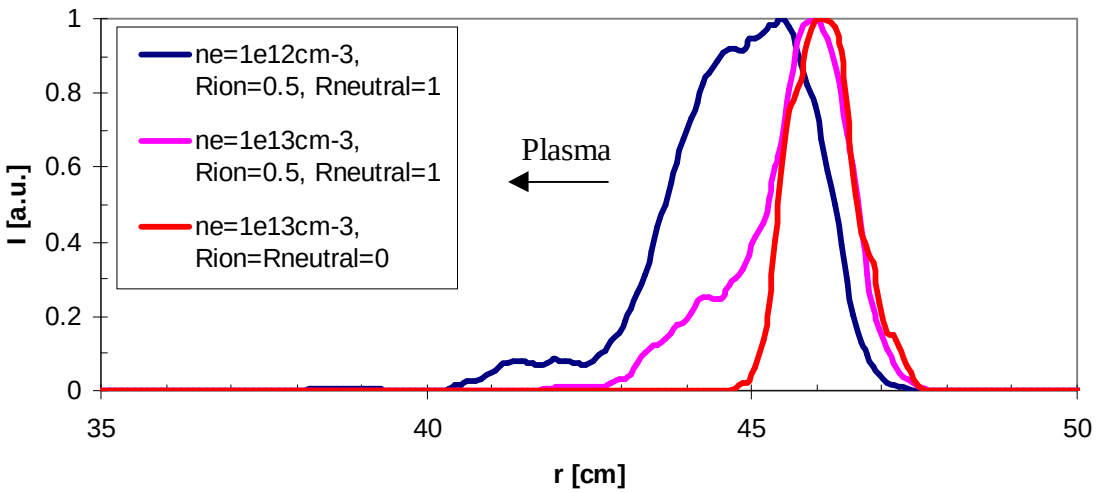

Fig. 1 *Simulated (normed) profiles of CD-emission in radial direction in dependence on the electron density n_e and on the reflection model for returning hydrocarbons. The electron temperature T_e at the lcfs (r=46cm which is also the position of the limiter tip) is choosen to be 30eV.*

To obtain the D/XB-values out of the simulation calculations the total sum of chemically eroded CD_4-molecules has to be related to the total amount of emitted CD-photons above the limiter. The dependence of D/XB on T_e and n_e using the "standard reflection model" for hydrocarbons is shown in fig. 2a. Except for very low temperatures the D/XB-value increases with increasing T_e at a fixed n_e. This results from an increase of the dissociation rates for the CD_4-chain with increasing T_e. At small temperatures below a few eV an additional effect has to be considered: Here the rate coefficient of CD excitation decreases strongly with smaller T_e [3]. This increases the D/XB-value. The effect is more pronounced at higher electron densities at the lcfs (fig.2a, n_e=1e13cm^{-3}). Then, CD is created close to the limiter at locations where the temperatures are decayed. Additionally, fig. 2a shows that D/XB increases with decreasing n_e

for the "standard reflection model". This is because of decreasing dissociation and accordingly increasing radial penetration into the plasma. CD is then formed at locations with higher electron temperatures (T_e increases exponentially with increasing distance from the surface) and therefore reduced lifetimes and hence reduced photon emission.

The experimentally determined D/XB-values in fig. 2a [4] increase with increasing T_e like the calculated ones, but the dependence is weaker. The simulated values and the measured data are in the same order of magnitude. The remaining differences between simulation and experiment can be due to slightly different plasma parameters (n_e, T_e, decay lengths). In addition, the experimental data were obtained by a gas puffing experiment whereas the simulation assumed chemical sputtering as CD_4-source.

To investigate the influence of the reflection probability for hydrocarbons on D/XB, fig.2b shows the results for $R_{ion}=R_{neutral}=0$. As in the "standard reflection" case (fig. 2a) a similar increase with T_e is obtained. The n_e-dependence, however, is for temperatures greater than ≈40eV opposite – D/XB increases with n_e at the lcfs. The reason for this behaviour is the absence of reflected hydrocarbons. Only chemically sputtered can contribute to CD-emission near the limiter surface. This effect is more pronounced if T_e at the lcfs is high enough. Under these conditions the amount of emission decreases with increasing n_e (at the lcfs) due to a higher probability of redeposition before the CD-state can be reached. Compared to the "standard reflection model" the D/XB-values are higher due to the absence of reflected hydrocarbons which of course leads to a decrease of CD-emission. The experimentally obtained values are smaller than the simulated ones. The assumption of the "standard reflection model" with $R_{ion}=0.5$ and $R_{neutral}=1$ gives a better accordance to the measurements and therefore this model will be used in the following (chapter 3) presented simulations.

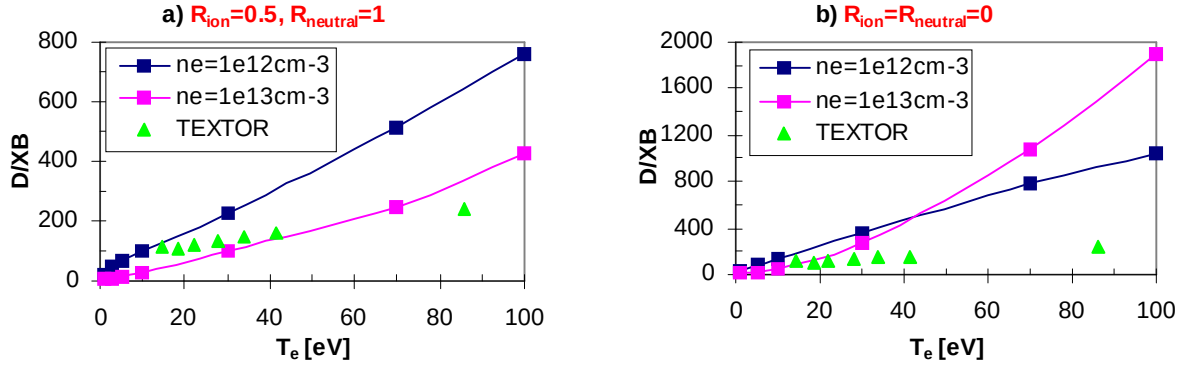

Fig. 2 *Experimental (TEXTOR) and simulated D/XB-values in dependence on the electron temperature T_e and the electron density n_e (T_e and n_e given at the lcfs).* ***a)*** *Simulation assuming the "standard reflection model" for hydrocarbons with $R_{ion}=0.5$ and $R_{neutral}=1$ and* ***b)*** *using the "sticking model" with $R_{ion}=R_{neutral}=0$.*

3. Chemical erosion yield in dependence on the surface temperature

The influence of the surface temperature has been investigated experimentally by means of a heated carbon limiter (geometry as described above) exposed to the SOL plasma of TEXTOR-94 under ohmic conditions. As an example fig.3 shows a comparison of the measured with the simulated CD- and CII-light profiles in radial direction for a shot where the limiter was kept at r=47cm (i.e. 1cm behind the last closed flux surface) with a surface temperature of 950K. The measured CD-profile corresponds very with the modelled profile after normalization (fig. 3a). For the CII-profile the contributions of chemical and physical sputtering have to be taken into

account whereas the amount of CII-emission due to reflected background carbon particles can be neglected. Good agreement of the (normalized) simulated CII-profile with the measured profile is achieved if a chemical erosion yield of 4.5% is assumed, fig. 3b. This value corresponds well with the experimentally obtained erosion yield under the given conditions [4]. Therefore, the comparison of the simulated with the experimental CII-profile provides an indirect method to determine the chemical erosion yield. Simulations of shots with various surface temperatures of the limiter show a similary good agreement with the measurements (not presented here).

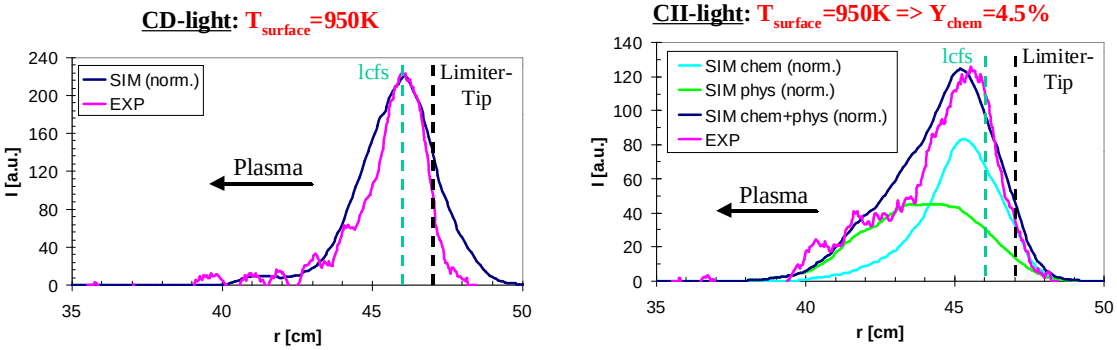

Fig. 3 *Comparison of simulated (SIM) and experimental (EXP) CD- and CII-light profiles in radial direction for an ohmic shot with a limiter surface temperature of 950K. The simulated CII-profile has a contribution due to chemical sputtering (ch) with Y_{chem}=4.5% and physical sputtering (ph) with Y_{phys} according to Abramov [1]. The simulated profiles have been normalized to the experimental profiles.*

4. Summary

The chemical erosion and the transport of eroded particles through the plasma can be modelled by means of the ERO-TEXTOR code. The calculated D/XB-values range in the same order of magnitude as the measured values but increase stronger with increasing T_e. The "standard reflection model" for hydrocarbons (R_{ion}=0.5, $R_{neutral}$=1) yields better agreement of simulation and experiment than the "sticking model" (R_{ion}=$R_{neutral}$=0).

The shape of the modelled radial profiles of the CD- and CII-emission corresponds well with the experimental profiles. From a comparison of the simulated and measured CII-profiles it is possible to determine the chemical erosion yield. These results are also in good agreement with the experimentally observed yields.

5. References

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