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ABSTRACT

Data on chemical erosion of graphite in present fusion devices obtained by spectroscopy are presented and discussed in view of existing ion beam data. A distinction of data measured under erosion dominated, generally attached plasma conditions and under deposition dominated, mostly detached conditions is proposed. Under attached conditions published yields are between 1 and 5% with only a moderate temperature dependence. Under deposition conditions connected with cold plasma conditions chemical erosion depends more strongly on the target temperature and published yields are more uncertain. In general, yields evaluated by CD spectroscopy still suffer from significant uncertainties of the effective photon efficiency (D/XB) of the CD radical. A definitive conclusion on a flux dependence of the chemical erosion is not possible from the present database.

1. INTRODUCTION

Graphite wall materials are used in present day fusion devices in order to optimise the plasma core performance and to enable access to a large operational space. A serious concern of graphite is the chemical interaction with hydrogen which leads to significant erosion yields even under cold plasma conditions. Chemical erosion may be a lifetime limiting factor but, even more seriously, is also responsible for the formation of hydrogen rich carbon deposits which can lead to unacceptable amounts of tritium retention. Thus future devices like ITER foresee graphite only for the high heat flux areas in the lower divertor region. There graphite seems indispensable due to its ability to withstand transient heat fluxes in disruptions or ELMS. The detailed evaluation of the chemical erosion of graphite in connection with target lifetime and long term tritium retention is of high importance for fusion development.

A somewhat consistent database exist for the chemical erosion of graphite under ion beam and thermal hydrogen impact [1, 2, 3] but large uncertainties still exist how to estimate the chemical erosion under fusion conditions, although various tokamak experiments have been carried out over the last years. This contribution presents and discusses important parts of the present database of hydrocarbon chemical erosion of graphite under fusion conditions. It restricts to dedicated tokamak data based on spectroscopy but can not provide a review of the field. More information is available like mass spectroscopic measurements from tokamaks [4, 5] or erosion data from plasma simulators [6,7]. They are important but will not be considered here more in detail.

2. MEASURING CONDITIONS OF CHEMICAL EROSION IN FUSION DEVICES

The database of chemical erosion under fusion conditions suffers from the difficult access to diagnose the release of hydrocarbons. Spectroscopic approaches, which are discussed here, base on the emission light of the CD radical ($A^2\Delta-X^2\Sigma$) [8] resulting from the dissociation chain of CH_4 or higher hydrocarbons, and higher hydrocarbons are evaluated from C_2 band emission (Wellenlänge!). The light depends generally on the atomic data of the CD and all the hydrocarbon precursors in the dissociation chain towards the CD, which itself depends on plasma density and temperature. Possible losses of hydrocarbon precursors decrease the CD light if the species stick, but the light increases if

the precursors are reflected showing also the importance of surface processes for the CD light. All these processes determine finally the loss events per photon of the molecular CD or C₂-band (D/XB) which are needed to transfer light emission in particle sources. Figure 1 shows as an example the effective (D/XB) of CD depending on plasma parameters and sticking assumptions for a constant plasma background (column 1) and in front of a TEXTOR limiter with n_e, T_e defined at the LCFS and experimentally measured profiles, calculated with ERO-TEXTOR using the atomic data for methane [9,10]. As a further difficulty, spectroscopy integrates often over areas of different flux densities with different plasma parameters. CD light accounts also to a certain extent for the release of higher hydrocarbons, however with a lower efficiency (higher D/XB), for C₂H₄ e.g. about 0.7 - 0.5 of that of methane in the range 10 to 20eV according to [23]. In JET, however, higher D/XB for CD originating from C₂H₄ have been found. The scatter in chemical yield measurements published from different tokamaks originates largely from different assumptions on the effective D/XB values. An isotope effect in chemical erosion exists (see chapter 6) but in this contribution only data from plasma operation with a majority of deuterium are considered.

3. PARAMETRIC DEPENDENCE OF CHEMICAL EROSION

Chemical erosion of carbon by hydrogen impact is a complex process, for which some of the atomistic mechanisms have been clarified recently [11] will not be discussed here. Measurements with ion beams or thermal atoms have show the dependencies of the formation rates on the target temperature, particle impact energies, fluxes, hydrogen isotope and surface condition of the carbon material. They are linked together in a rather complex manner. This leads also to synergistic effects such that the simultaneous impact of one component (e.g.thermal atoms) together with a high energy component (e.g. hydrogen or other ions) enlarge the erosion of the thermal component (“synergistic erosion”) [12].

Beam data show a strong temperature dependence at higher impact energies (>200eV) with a decreasing tendency with decreasing impact energy (flattening of temperature dependence). However, for thermal atom impact (0.2eV), (or cold, detached-like plasmas) the target temperature dependence is again strong indicating a transition of the parametric dependence of the erosion on target temperature between about 5-10eV ion impact energy which is of importance for the understanding of chemical erosion under cold plasma conditions. For this cold plasma condition the absolute erosion is in addition very sensitive to the “surface structure” of the graphite which is of no significant importance at higher hydrogen impact energy (or attached plasma condition).

4. EROSION AND DEPOSITION DOMINATED SURFACES

The important difference between erosion in beam experiments and under fusion conditions is that in ion beams the eroded carbon material is lost and erosion occurs on “fresh” material whereas in fusion nearly all the eroded carbon returns to the and is re-eroded again (carbon recycling). Under fusion conditions a reasonable ordering parameter is to separate the chemical erosion on erosion and deposition dominated areas. The outer divertor under attached conditions and the limiters are

mostly erosion dominated connected in general with higher plasma temperatures, typically 10-30 eV (divertor) or 25-70eV (limiter). The areas in the inner divertor (often detached) and the outer SOL regions in limiter machines are deposition dominated connected with lower plasma temperatures and also higher fraction of background carbon fluxes. On these areas the structure of the deposited carbon depends on the impact energy turning the deposited film from a so called hard film (density > 1.6, refractive index >2, hydrogen content at 400K = 0.4) to a more soft-like film (density < 1.6., refractive index <1.8, hydrogen content at 400K > 0.4). Under these conditions the chemical erosion is strongly temperature dependent and largely enhanced for soft, polymerlike carbon films compared with hard films. Figure 2. displays in the upper part chemical erosion data normalised to 570K by thermal hydrogen impact for different types of films [13,14] with the density as ordering parameter and in the lower part the relative erosion of hard and soft like films depending on temperature [15]. These data are important to understand chemical erosion under cold plasma temperature conditions.

4.1. FUSION CHEMICAL EROSION DATA TEMPERATURE DEPENDENCE

In TEXTOR detailed measurements have been done under limiter conditions ($T_e \sim 50\text{eV}$) with a stepwise heating of the limiter from the rearside up to about 1400K [16] showing (fig.3) a temperature enhancement from 400K to 700K is <1.3, much weaker as beam data show at comparable ion impact energies (200eV). Figure 3 compares these data with measurements in the outer divertor of ASDEX-U [17], JET [18] and JT-60U [19] and with ion beam data from [20]. The outer divertor of JET and ASDEX-U show no measurable increase with target temperature in the temperature range of 450-520 and 300-400K respectively where as JT60-U found an increase by a factor of 1.6 from 420K to 550K. The absolute yields will be discussed considered in chapter 4 and the CD band photon efficiencies used for the evaluation are listed in table 1. Interestingly, on the deposition dominated areas in the inner divertor of JET [21], a the normalised molecular CD and C₂ and carbon ion signals (CIII) increase almost by a factor of two during a moderate increase of the target temperature from 450 to 520 K, observed both in L mode and H-mode plasmas. (Fig 4). The almost identical increase of the CD and C₂ molecular light with ion signals (C⁺⁺ and C⁺) shows the dominance of the chemical erosion sources in the inner divertor. This sharp temperature dependence is in good agreement with erosion of soft carbon films measured in beam experiments as shown in fig 3 . Obviously the erosion due to lose energy hydrogen ion and atom impact is below the transition energy at which the temperature dependence changes as discussed in section 2. Large overall chemical yields of about 20% are estimated with large contributions of C₂-hydrocarbons in reasonable agreement with the yields shown in fig 2 for soft carbon layers.

5. CHEMICAL EROSION YIELDS

5.1 ATTACHED CONDITIONS

Various data have been published for attached conditions on erosion dominated areas in the outer divertor or on limiters, although at different target temperatures. The temperature dependence under these conditions is not strong (see 4.1) and a comparison even at different temperatures is reasonable.

The data, measuring conditions and D/XB values are listed in table 1.

In TEXTOR limiter data are obtained with a relative simple observation geometry allowing local measurements, with flux densities from power fluxes and n_e, T_e data. A fixed D/XB (CD) of 100 (Hg: S/XB 1000) is used up to fluxes of about 10^{23} H/m²s but with increasing D/XB values up to about 250 for higher fluxes obtained by methane injection under identical conditions (not done for data at lower fluxes so far). As seen in fig 5 yields are about 3-5 % up to 10^{23} /m²s, decreasing down to 1% with higher fluxes using the relatively matched D/XB data [16]. The contribution of the hydrocarbons to the C⁺⁺ light is about 40% of the total light. Few measurements have been done on C₂ hydrocarbons with the conclusion that C₂ hydrocarbons contribute to about 50% of the methane for attached conditions (same C-release as methane). In JET [18] the yields evaluated are integrated over the whole outer or inner divertor and fluxes are from I_{sat} and H_{α} which matches well (with S/XB (H_{α}) = 20). CD light is calibrated by methane injection but based on the important assumption that the D/XB of the intrinsic sources is similar to the injected although the location of the source does not match. With D/XB varying between 70 and 130 yields of about 5%, very similar as in TEXTOR (with similar D/XB) are deduced. Similar yields are deduced in the inner but the flux determination is more difficult due to regular detachment. Higher hydrocarbons (C2-band) is about 50% of methane in the outer divertor (same C-release) and about the same in the inner (twice C-release), resulting in overall yields of 10 and 20% in the outer and inner respectively. In ASDEX-U published yields in [17] for the outer divertor are based on fixed D/XB of 50 and fluxes from probes and H_{α} , which agrees also well. The data are for lower temperatures $T < 470\text{K}$ with values of about 3% at lower fluxes (10^{22} /m²s) decreasing with fluxes down to 1% (8×10^{22} /m²s, D-plasmas). In DIII-D [22,23] yields for the outer divertor region for attached conditions are with a D/XB of 50 and H-flux from spectroscopy. Yields are 1-2.5% for virgin targets at similar low temperatures as ASDEX-U. Surprisingly the yields decrease by almost a factor of ten in the course of long term plasma operation (20000 shots) which has been attributed to consecutive boronization (30 boronizations in ten years operation, which is, however, not seen in devices like (TEXTOR) or (ASDEX, JT-60) applying also boronization with a comparable amount of boron deposition. This needs further clarification. In JT-60U [19] data for L-mode plasmas for the outer divertor at different target temperatures uses D/XB values are from (24) ranging between 90 and 100 and fluxes from probes and spectroscopy. D-yields between 3.6 (550K) and 2.2% (450K), showing a comparable strong temperature dependence when compared with JET, ASDEX and TEXTOR for attached conditions (fig 3).

4.2. DETACHED CONDITIONS

Larger uncertainties exists for detached plasma conditions, the reason for this is twofold: at first, D/XB values are more uncertain and next the target temperature is more important for the yields and data can only be compared for matched temperatures. DIII claim a drastically reduced chemical source under detached conditions, 0.01%, [22] at a cold target (<450K) and with a D/XB of 5 resulting from model calculations. In contrast, the D/XB evaluated in JET by gas injection in the

private flux region increases for detached conditions and a D/XB values >100 are used. This together with higher target temperature (450-550K) results in a much larger deduced chemical source, with yields of 5 and 7% for methane and C₂ hydrocarbons respectively.

5. FLUX DEPENDENCE

Figure 5 shows a compilation of published data on chemical erosion depending on flux density together new data points from TEXTOR evaluated for lower flux densities with fixed D/XB of 100 (conditions are listed in table 1). In a flux range $10^{22} - 10^{23}$ a clear flux dependence $\#/m^2s$, is deduced in ASDEX [17], $Y \sim \Gamma^{-0.7}$ (fixed D/XB) and somewhat weaker in JT-60 [19], $Y \sim \Gamma^{-0.2-0.3}$, (D/XB 90-100). Such an effect is not seen in TEXTOR (16) (D/XB=100)), and JET [18] (D/XB, 70-130) For higher fluxes exceeding $10^{23} /m^2 s$ and under conditions of large n_e and T_e ($>10^{13} /m^3$ and $T_e > 100eV$) a clear decrease of the yield is seen in TEXTOR (with D/XB values relatively calibrated). A clear statement on the flux dependence from fusion based data is thus still not possible presently.

6. ISOTOPE EFFECT

Isotope effects between H and D are seen in JET [17], ASDEX [18], JT-60 [19] and TEXTOR in beam experiments and are thus clearly proven. Enhancements factors are between 1.3 and 2 but possible dependencies of the isotope effect on hidden parameters (like flux or target temperature) have not been identified so far.

CONCLUSIONS

An erosion dominated areas the temperature dependence is weak and published yields based on CD spectroscopy show a certain consistency with values between 1 and 5% using photon efficiencies for the CD band between 50 and 200. On redeposition dominated areas the plasma is colder and surface temperature enters more strongly. Evaluated yields show large inconsistencies with low ($< 0.1\%$ DIII) and large yields ($>5\%$ JET) which is largely due to different D/XB values, 5 and ~ 50 respectively and differences in the target temperature.

Measurements on a possible flux dependence in an intermediate flux range ($10^{22} - 10^{23} \#/m^2s$) are not consistent presently with a flux dependence $Y \sim \Gamma^{-n}$ with n ranging from 0.7 (ASDEX-U), 0.3 (JT-60U) and zero (TEXTOR, JET). As a conclusion, quantitative erosion data on yields and a possible flux dependence need very careful in situ calibrations for CD spectroscopy that matches the plasma conditions, viewing geometry and hydrocarbon source location as much as possible which has not been done for the present measurements (with few exceptions). D/XB values depend on the experimental geometry and are machine specific and not transferable easily to other conditions without accurate modelling based on the atomic and surface data of all the species in the hydrocarbon chain and using measured plasma conditions. New experiments are planned on several devices based on in situ calibrations and further work on the atomic database (like in [9]) and model validation in dedicated experiments is needed.

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| Attached conditions | Target temperature (K) | N_e ($\times 10^{19}/m^3$) | T_e (eV) | D/XB (CD) | Yield % (Methane) |
|----------------------------|------------------------|--------------------------------|------------|--|---|
| TEXTOR Limiter | 300 – 1500 | 0.1 – 1 | 30-100 | 100 (increasing for fluxes $>10^{23}/m^2s \rightarrow 250$) | 3 – 5 decreasing to 1% for fluxes ($>10^{23}/m^2s$) |
| ASDEX Outer divertor | 370 – 470 | 1–5 | 5–15 | 50 | 3 – 1 decreasing with flux ($10^{22}-10^{23} \#m^2s$) |
| JET Outer divertor | 400 – 550 | 1 – 7 | 20 – 8 | 70–130 | 5 no flux dependence |
| Jt-60U Outer divertor | 420 – 550 | 2 – 20 | 10 – 20 | 90 – 100 | 3.6 – 2.5 small decrease with flux ($10^{22}-10^{23} \#m^2s$) |
| DIII-D Outer divertor | <450 | 0.5 – 1 | 25 – 40 | 50 | 1 – 2.5 |
| Detached conditions | | | | | |
| JET Inner divertor | 400 – 550 | 0.02 – 2 | 1 – 6 | >100 | 5 |
| DIII-D Outer divertor | <400 | | | 5 | 00.01 |

Table 1:

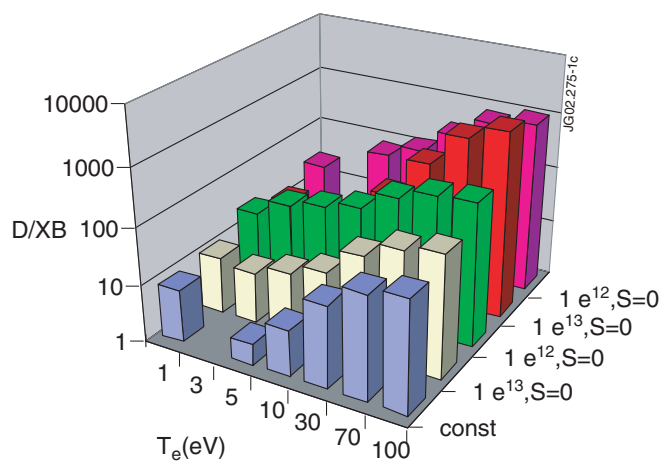


Figure 1: Effective D/XB values for methane depending on T_e , N_e and sticking probability (S). Column 1 is for constant plasma conditions the other data for TEXTOR edge plasma conditions with the given n_e , T_e at the LCFS.

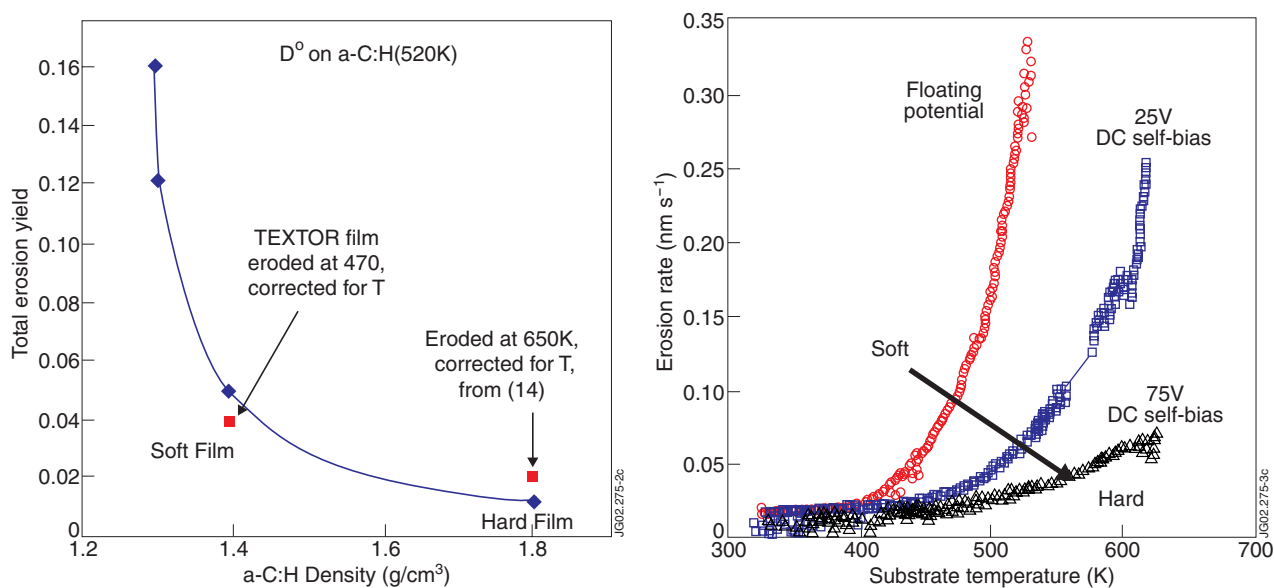


Figure 2: Chemical erosion for thermal hydrogen atom impact for different types of carbon films, data from are from (13) and (14)

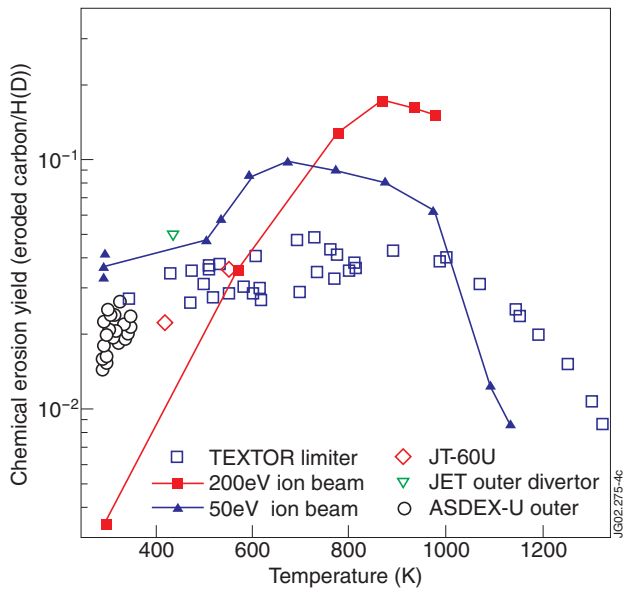


Figure 3: Temperature dependence of chemical erosion measured in different fusion devices together with ion beam data. For data evaluation see also table 1.

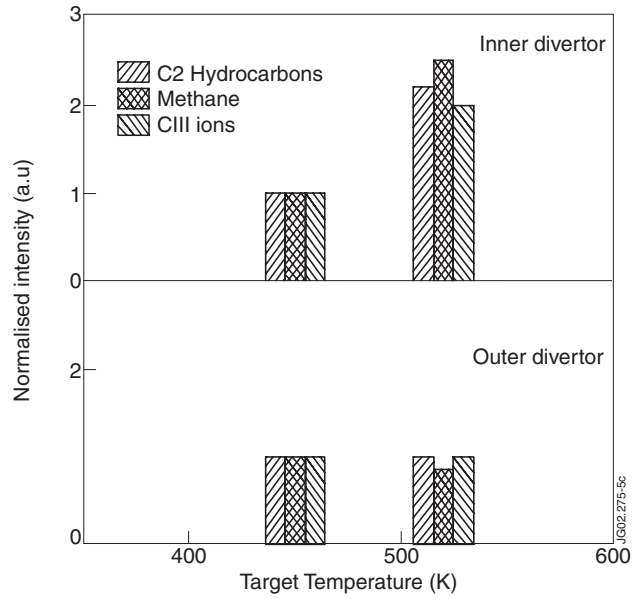


Figure 4: Temperature dependence of the normalised C2, CD and CIII light emission for the inner and outer divertor of JET depending on target tile temperature.

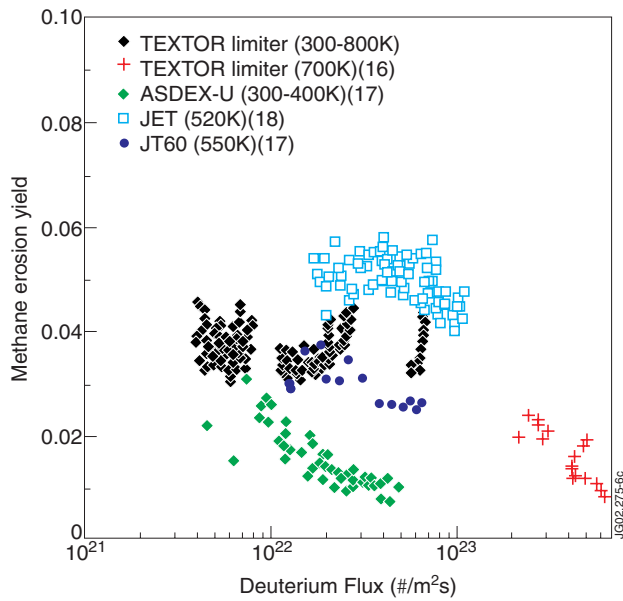


Figure 5: Chemical erosion yields evaluated in different devices depending on ion flux density