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The Behaviour of the Apparent Chemical Sputtering Yield in the JET Tokamak

R D Monk, C H Amiss¹, H Y Guo, G F Matthews,
G M McCracken, M F Stamp.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,
¹College of William and Mary, Williamsburg, Virginia, USA.

ABSTRACT

In the JET Mark I and Mark II divertors the in-situ chemical sputtering yield of the carbon target plates has been studied under a wide range of conditions. To evaluate the chemical yield, the incident hydrogenic flux is directly evaluated from Langmuir probe measurements while the methane production rate is inferred from the CD/CH molecular band emission calibrated using methane injection experiments. It is found that the chemical sputtering yield reduces at high flux densities ($>2 \times 10^{22} \text{m}^{-2} \text{s}^{-1}$) and low impact energies ($<50 \text{eV}$). In the Mark II divertor both the absolute yield and the flux dependence depend upon the tile temperature with $Y_{\text{chem}} \propto \Gamma^{-0.4}$ at 450K and $Y_{\text{chem}} \propto \Gamma^{-0.7}$ at 360K. In the Mark I divertor the yield exhibits an even stronger flux dependence ($Y_{\text{chem}} \propto \Gamma^{-1.25}$) which is consistent with the relatively low tile temperature of 300K. However, the increased flux densities are associated with reduced impact energies which may also contribute to the yield reduction. The chemical yield is also shown to depend strongly on the isotope mass ($Y_{\text{chem}} \propto m_{\text{ion}}$) and is consistent with thermal reactions enhanced by radiation damage.

1. INTRODUCTION

In present day tokamak experiments carbon is the most common material from which plasma facing components are fabricated. It has the favourable properties of excellent thermomechanical characteristics, low atomic mass number and low neutron induced activation. However, the principle disadvantage of carbon is that erosion may occur via chemical interactions in addition to the normal physical sputtering processes. Given the high incident particle fluxes ($\leq 10^{24} \text{m}^{-2} \text{s}^{-1}$) expected at the carbon divertor target of a next-step tokamak such as ITER [1], the potential problems of excessive erosion and tritium codeposition have caused concern. It is therefore important to study the chemical erosion behaviour in existing tokamak experiments to validate sputtering models and allow extrapolation towards higher fluxes.

Over the years many well-controlled laboratory experiments have been carried out to characterise the chemical sputtering behaviour for fluxes in the range 10^{18} - $10^{20} \text{m}^{-2} \text{s}^{-1}$ and impact energies 10 - 10^4eV [2],[3]. While such conditions may be relevant for the vessel walls of fusion experiments, the fluxes are significantly lower than that characteristic of limiter and divertor surfaces. More recent investigations has utilised plasma simulators or in-situ tokamak measurements to study the chemical yield at higher fluxes of 10^{22} - $10^{23} \text{m}^{-2} \text{s}^{-1}$. In particular, measurements from ASDEX Upgrade tokamak [4],[5], TEXTOR [6] and the Berlin Plasma Generator PS-1 [7] have demonstrated the encouraging trend of reduced chemical yields at higher flux densities and lower impact energies.

In this paper, we report on measurements of the apparent chemical sputtering in the Joint European Torus (JET) Mark I and Mark II divertors using a combination of spectroscopic and Langmuir probe measurements. In section 2, we describe the experimental conditions, available

diagnostic measurements and the criteria used for selecting the data. The method used to evaluate the chemical yield is discussed in section 3 and results from methane injection experiments are used to calibrate the emission spectroscopy. In section 4, the dependence of the apparent chemical yield on hydrogenic isotope mass and surface temperature is presented. Finally, in section 5 we summarise the findings of this article.

2. EXPERIMENTAL METHOD

2.1 The JET Mark I and Mark II Divertors

In these experiments we investigate the behaviour of the chemical sputtering yield at the surface of the JET Mark I and Mark II divertor targets. These single-null divertor configurations both comprise rows of Carbon Fibre Composite (CFC) tiles which are mounted on a toroidally continuous support structure [8]. In moving from Mark I to Mark II, the width of the divertor entrance has been reduced in order to enhance the degree of divertor closure (i.e. the fraction of recycling neutrals ionised within the divertor region). A schematic poloidal cross-section of the Mark II divertor is shown in fig. 1 which shows a typical magnetic equilibria with the strike zones located on the horizontal target plates. One of the main purposes of increasing the divertor closure is to obtain easier access to detached regimes thereby reducing the power and particle fluxes arriving at the divertor target [9]. However, to effectively prolong the lifetime of the divertor target it is necessary that the sputtering yield decreases at high (ion and/or neutral) fluxes and low impact energies. Due to the chemical sputtering processes associated with carbon, it is not clear that the total (physical+chemical) yield will be sufficiently low in order to prevent excessive target erosion in a next-step tokamak. This unresolved issue is the primary motivation for the study presented in this paper.

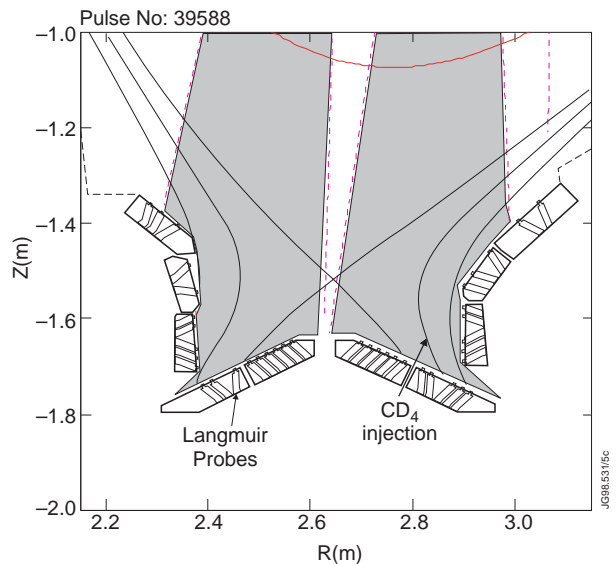


Fig.1: Cross-section of the JET Mark II pumped divertor geometry showing a typical horizontal target magnetic equilibrium (the magnetic flux surfaces are separated by 1cm at the outer midplane). The inner and outer viewing areas of the survey spectrometer are indicated by the shaded regions. Also shown is the methane injection location and the fixed Langmuir probe positions.

2.2 Relevant Diagnostic Systems

In the JET Mark I and Mark II divertors, several spectroscopic diagnostics are available for monitoring the hydrogenic and impurity behaviour from which the chemical sputtering yield is inferred. One of the systems employs a visible survey spectrometer which is absolutely calibrated to measure the integrated photon flux from each divertor strike zone and routinely moni-

tors the Balmer series lines D_α (656.1nm), D_β (486nm), D_γ (433.93nm), CD molecular band (430.7nm) and CIII (465nm). The viewing regions of the survey spectrometer are shown in fig. 1 and encompass the whole interaction region for the inner ($2.3\text{m} < R < 2.6\text{m}$) and outer ($2.62\text{m} < R < 2.9\text{m}$) divertor strike zones. Photon fluxes from each of the strike zones are integrated over the collection area and assumed to be toroidally symmetric in order to evaluate the total fluxes. Since the inner divertor detaches at a relatively low main plasma density compared to the outer [9], the measurements and analysis presented in this paper are for the outer divertor only. This allows the widest range of divertor plasma parameters and minimises the problems of interpreting spectroscopic measurements when volume recombination processes are dominant.

In addition to the spectroscopic diagnostics described above, there are three poloidal arrays of 40 fixed Langmuir probes which routinely measure spatial profiles of the ion saturation current (j_{sat}^+) and electron temperature (T_e). From these measurements the incident ion flux to the surface ($j_{\text{sat}}^+ \sin \theta$) and impact energy ($5kT_e$ [10]) are evaluated. In quoting the impact energy, we have typically averaged over three Langmuir probes spanning the strike zone region. The location of the Langmuir probes in relation to the survey spectrometer views are shown in fig. 1 overlaid with the magnetic equilibria from a typical horizontal target discharge. By integrating the probe measurements, one can determine the total ion flux to each strike zone and directly compare with the integrated survey spectrometer measurements.

2.3 Plasma Conditions

To minimise the possible influence of variable tokamak conditions, the experiments analysed for this paper are those in which the main plasma density is gradually increased by deuterium gas fuelling. An example of such a discharge in deuterium with 2MW of additional heating and the strike points on the horizontal target plates is shown in fig. 2. With increasing main plasma density the onset of detachment is seen from the “roll-over” and decrease of the ion flux at 19s followed by the density limit disruption at 20.6s. Such experiments have the advantage of producing a range of incident hydrogenic divertor fluxes (and simultaneously impact energies) within each discharge and allows the onset of plasma detachment to be easily identified. At present, this study includes only ohmic and L-mode discharges to avoid the transient features associated with Edge

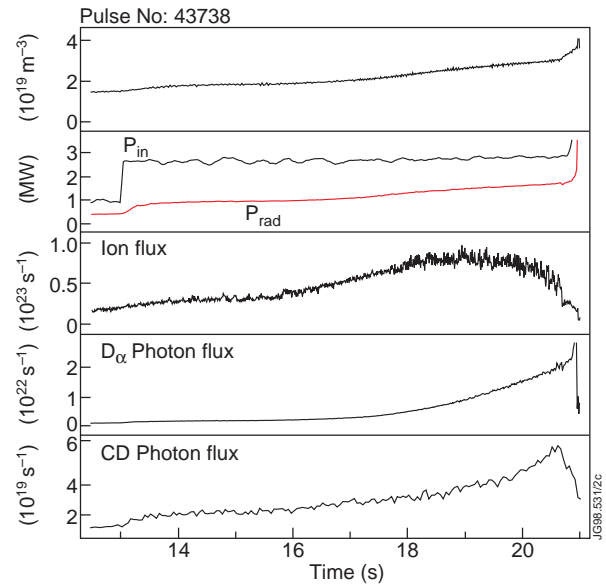


Fig.2: Evolution of the plasma parameters for a typical L-mode discharge with 2MW of neutral beam additional heating. The main plasma density is continually increased by deuterium gas fuelling (up to a maximum rate of $1.4 \times 10^{22} \text{els}^{-1}$) until the density limit occurs. In parallel with the plasma density, the ion and photon fluxes at the outer divertor are observed to increase.

Localised Modes (ELMs) which are associated with the H-mode regime. The discharges were carried out in deuterium and hydrogen at 2MA, 2.5T ($q_{95}=3.9-4.4$) with additional heating powers in the range of 2-6MW and the strike points located on either the horizontal or vertical divertor target plates.

3. EVALUATION OF THE CHEMICAL SPUTTERING YIELD

To evaluate the chemical yield (Y_{chem}) the incident hydrogenic flux to the divertor target is compared with the resulting hydrocarbon (methane) production rate. As described above, these quantities are provided by a combination of spectroscopic and Langmuir probe measurements. Assuming that deuterium is the dominant species, the yield is calculated as follows

$$Y_{chem} = \frac{\Gamma_{CD_4}}{\Gamma_D} = \frac{D/XB(CD_4)}{S/XB(D_\alpha)} \cdot \frac{I(CD)}{I(D_\alpha)} \equiv \frac{D/XB(CD_4) \cdot I(CD)}{j_{sat}^+ \sin \theta} \quad (1)$$

where $D/XB(CD_4)$ is the number of CD_4 dissociations per CD band photon, $S/XB(D_\alpha)$ is the number of ionisations per D_α photon, $I(CD)$ is the intensity of the CD band emission, $I(D_\alpha)$ is the D_α photon flux, j_{sat}^+ is the ion saturation current measured by the Langmuir probes and θ is the perpendicular field line angle to the divertor target plate. Following this approach the average chemical sputtering yield across the outer strike zone may be evaluated using the incident hydrogenic flux derived from the D_α spectroscopy or the Langmuir probes. It is evident that the accuracy of these calculations relies heavily upon the determination of the photon efficiencies (S/XB and D/XB) that are used to evaluate particle fluxes from the spectroscopic measurements. In the following two sub-sections, the assumptions and method by which these quantities are derived is discussed in more detail.

3.1 Evaluation of the Incident Hydrogenic Flux

Evaluation of the incident hydrogenic flux commonly employs measurements of the Balmer series lines (D_α , D_β or D_γ) with a suitable value for the number of ionisations per photon (the so-called S/XB) which depends on the local electron temperature and density [11]. In practice, the functional behaviour of the S/XB with temperature and density coupled with the conservation of divertor electron pressure implies that the assumption of a constant S/XB is applicable under most conditions. However, this assumption becomes invalid as the electron temperature decreases below 10eV since the S/XB becomes more strongly dependent on the local electron temperature and density [11]. An additional consideration is that most of the particles are recycled from the divertor target as molecules rather than atoms due to the low probability of backscattering. The production of excited atoms from electron impact on D_2 molecules leads to the emission of additional D_α photons and may increase the effective S/XB factor [12]. However, this effect may not be significant if the molecules dissociate close to the divertor target and therefore make a small contribution to the line integrated D_α emission. Finally, with the onset of plasma detachment and volume recombination, the simple interpretation of spectroscopic pho-

ton fluxes as particle fluxes becomes difficult. The additional D_α photons due to recombination can lead to an overestimate of the incident flux from which an artificially low chemical yield is inferred. In the case of the JET results, direct measurements of the incident ion flux are routinely measured by the divertor Langmuir probe array and may be used to benchmark the spectroscopic results.

Taking into account the problems of evaluating absolute fluxes from the spectroscopic Balmer series lines it was important to establish criteria by which the data is correctly selected. It was also desirable to identify the data points for which the divertor is detached since the interpretation is much more uncertain under these conditions. An example of the typical procedure used in this analysis is shown in fig. 3 for a deuterium discharge with the strike points on the vertical target. At the initial low density phase of the discharge, the ratio between the ion flux and D_α flux is ~ 20 in accordance with expectations from atomic physics models [11]. Applying the assumption of $S/XB=20$ subsequently produces good agreement between the absolutely calibrated D_α photon flux and the probe ion flux until 17.2s at which point the D_α flux diverges. The divergence of the D_α derived flux defines the limit of applicability for these flux measurements and is coincident with the divertor T_e falling below 10eV. To identify the onset of plasma detachment we have applied two criteria. Firstly, from the simple “two-point” model of the attached divertor plasma, one expects that the incident ion flux should increase quadratically with the upstream separatrix density [13]. Assuming that the core line averaged density is proportional to the upstream separatrix density (i.e. $\Gamma_{div} \propto n_e^2 \propto n_{sep}^2$), one can compare the evolution of the two-point model scaling to experiment as shown in fig. 3. The divergence of the experimental ion flux from this scaling (at ~ 18.4 s in this example) is used to identify the onset of plasma detachment [9]. The second criteria is based upon identifying detachment from the onset of volume recombination measured from the ratio of the D_γ to D_α photon fluxes [14]. One can see from fig. 3 that this ratio increases steadily from 17.5s and while in this example it does not provide such a distinct detachment threshold, it nevertheless reinforces the choice made on the basis of the ion flux scaling criteria.

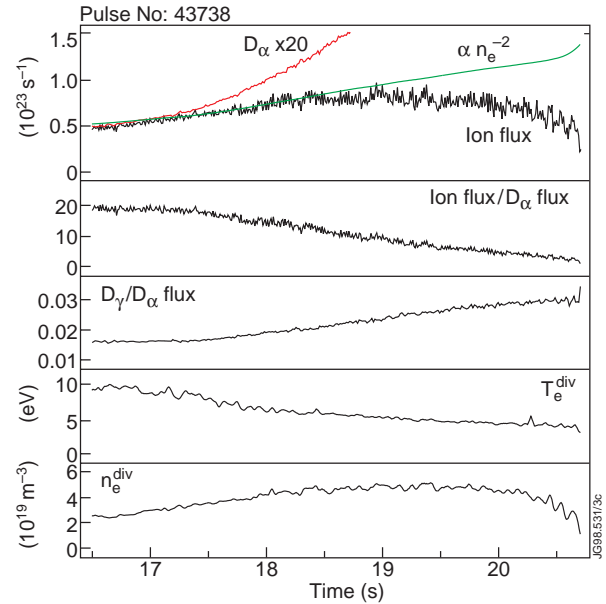


Fig.3: Comparison of the ion flux directly measured by the Langmuir probes with the D_α inferred flux and the n_e^2 scaling for a vertical target discharge. The vertical lines in the first panel at 17.2s and 18.4s represent respectively the limit of the D_α flux measurement and the onset of detachment. The behaviour of the D_γ/D_α ratio, divertor T_e and n_e are also shown for reference.

3.2 Evaluation of the Methane Production Rate

In principle, the in-situ methane production rate can be derived from the CH or CD molecular band emission [15]. The visible spectroscopy diagnostic (described in section 1) is used to integrate across the molecular band around 430.7nm to measure the total CH and CD emission. To infer the number of CH₄/CD₄ dissociation events from these measurements the photon efficiency (or so-called D/XB) has to be known accurately. Due to the complexity of the methane dissociation process [16] there is considerable uncertainty in this parameter. Assumptions used previously for the D/XB include values of 80-100 [15] and 50 [4]. However, recent modelling has indicated the D/XB may have a strong dependence on the electron temperature [17].

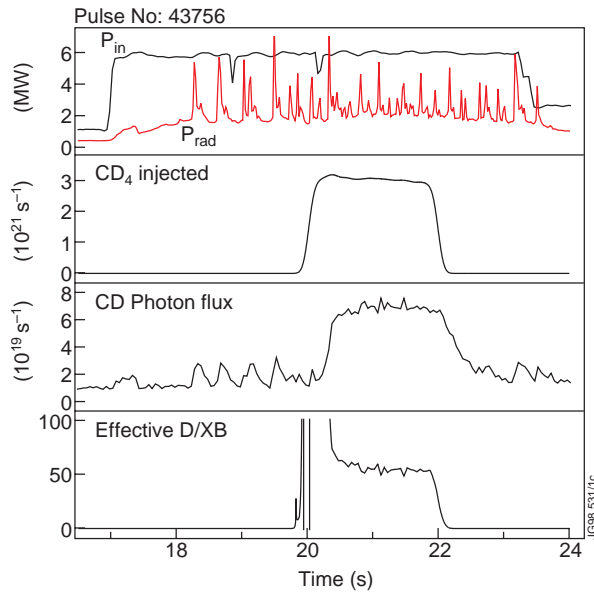


Fig.4: Example of an ELMy H-mode deuterium discharge in which CD₄ is injected in the outer divertor from 20-22s. The increase in the CD band emission is used to determine the effective D/XB shown in the lower panel.

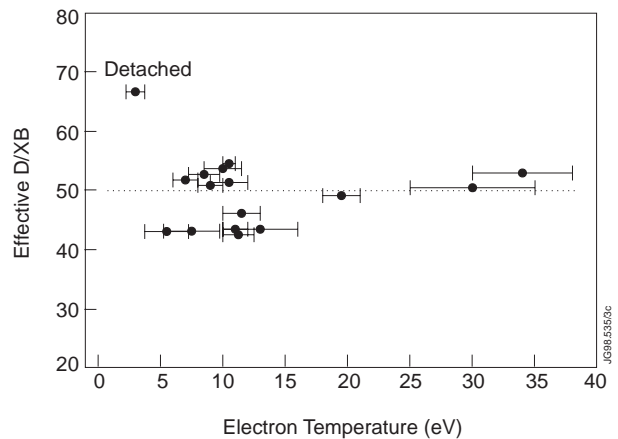


Fig.5: Dependence of the effective D/XB derived from CD₄ injection experiments on the separatrix electron temperature. The assumption of D/XB=50 provides good agreement with the data under a wide range of conditions.

Given the uncertainty in the D/XB factor, we have applied a calibration procedure similar to that carried out in TEXTOR [6]. In these experiments, a known quantity of deuterated methane is injected through gas nozzles located in the horizontal target of the outer divertor (shown in fig. 1) which are distributed around the torus to provide toroidal symmetry. From the resulting increase in the CD molecular band emission above the background level it is possible to determine the effective D/XB. Depending on whether the divertor strike zones are located on the horizontal or vertical target plates, the methane is injected into the scrape-off layer or private flux region respectively. However, no significant differences in the inferred D/XB was found between the two strike zone positions for a given range of divertor plasma parameters. This may be attributed to the fact that, in either case, the viewing area of the spectrometer measuring the CD band emission is sufficiently large to encompass the whole strike zone region. An example of one of these experiments is shown in fig. 4 where methane is injected into an ELMy H-mode

discharge at 20s with a molecular rate of $3 \times 10^{21} \text{ s}^{-1}$. During the period of CD_4 injection, one observes that the CD photon flux increases significantly and reaches a new steady-state value. These experiments have been carried out in deuterium over a wide range of conditions from ohmic discharges to ELMy H-modes with up to 12MW of additional heating. In fig. 5, the effective D/XB is plotted for all the experiments as a function of the separatrix electron temperature. One observes that it is remarkably constant with $\text{D/XB} \cong 50$ over a wide range of plasma parameters. There is no evidence of a strong temperature dependence predicted by Naujoks [17]. However, it should be noted that the divertor electron density has not been maintained at a constant value during these experiments and varies in the range of $1\text{-}6 \times 10^{19} \text{ m}^{-3}$. In one case, the D/XB is significantly higher than 50 but the divertor is detached and would normally be outside the range of interest for this study. These results may be compared with the TEXTOR limiter experiments where the D/XB was a factor of two higher than our values (~ 110 at 10eV) and increased to 200 at 90eV [6].

4. EXPERIMENTAL RESULTS

4.1 Isotope Dependence

In order to determine the role of the isotope mass on the chemical sputtering yield, several experiments were repeated in both deuterium and hydrogen with the Mark II divertor target. Based on partial pressure measurements of the recycling gas in the divertor, the respective isotope ratios of $\text{D}/(\text{H}+\text{D}+\text{T})$ and $\text{H}/(\text{H}+\text{D}+\text{T})$ were ≥ 0.95 in all cases. In fig. 6 the average chemical sputtering yield of the outer strike zone is plotted as a function of the peak incident ion flux density for both isotopes in vertical and horizontal divertor configurations (at an approximately constant target tile temperature of $\sim 450\text{K}$). The effect of the isotope mass is clearly seen at low fluxes ($Y_{\text{chem}} \propto m_{\text{ion}}$) although this trend weakens towards higher fluxes (and correspondingly lower impact energies $< 50\text{eV}$). Comparable results are obtained using the incident hydrogenic flux derived from the D_α photon flux. Similar isotope dependencies have been reported from ASDEX Upgrade [5].

While the chemical sputtering yield has been derived from the integral ion flux, the results shown in fig. 6 are plotted versus the peak ion flux density measured by Langmuir probes close to the separatrix. Initial analysis of the chemical yield behaviour showed that the vertical target discharges have a lower chemical yield than the equivalent horizontal target discharge for a given integral ion flux. Inspection of the divertor ion flux profiles revealed that

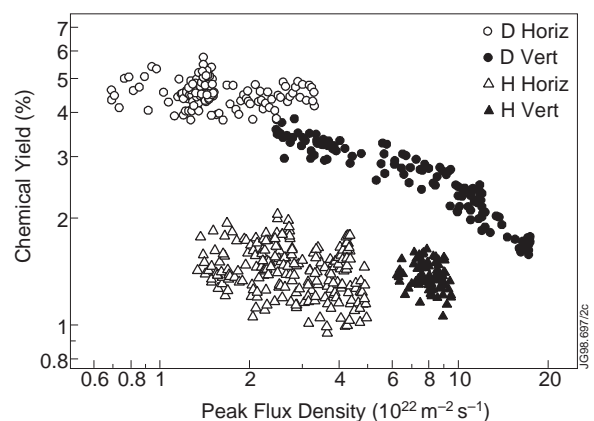


Fig.6: Effect of the isotope mass on the average chemical sputtering yield in the Mark II divertor for a tile temperature of $\sim 450\text{K}$. The deuterium (D) and hydrogen (H) data points are divided according to horizontal (Horiz) and vertical (Vert) divertor configurations.

the vertical target discharges exhibit more peaked profiles and, for a fixed value of the integral ion flux, have higher peak ion flux densities than the horizontal target discharges. By plotting the yield versus the peak flux density instead of the integral flux (as shown in fig. 6) there is a clear separation between the horizontal and vertical target plate discharges. It is evident that the peak flux density is a more meaningful parameter for evaluating flux dependencies and also allows direct comparison with results from other studies.

At the high flux densities achieved with the vertical target discharges, a weak flux dependence of the yield is evident ($Y_{\text{chem}} \propto \Gamma^{-0.4}$). Such a flux dependence is not seen for the horizontal target and hydrogen discharges and the reasons for this is unclear. It is also sufficiently weak that it may be accounted for by uncertainties in the D/XB evaluation. However, it should be stressed that the impact energy was not kept constant while the flux increased so that the reduction in yield may also be attributed to reduced impact energy and this is discussed further in the following section. The existence of an isotope dependence of the chemical sputtering yield indicates that the thermal chemical erosion process is enhanced by radiation damage via kinetic energy transfer which provide open bonds for hydrogen attachment [18]. Since this enhancement of the thermal chemical yield is associated with a threshold energy of $\sim 15\text{eV}$ [18], one may attribute the weaker isotope effect seen at high flux density in fig. 6 to lower impact energies and consequently reduced radiation damage.

4.2 Tile Temperature Dependence

Dedicated experiments have been carried out to assess the effect of the divertor and wall temperature on the impurity production processes. These experiments were motivated by the observation that impurity yields in the divertor region of the Mark II divertor (in terms of $\text{CIII}/\text{D}\alpha$) were approximately a factor of two higher than for the Mark I divertor [19]. Due to changes in the cooling properties of the divertor mechanical structure, the typical bulk tile temperature in the Mark I divertor was $\sim 300\text{K}$ compared to $\sim 450\text{K}$ in Mark II. It was suspected that the increased impurity production was due to the elevated tile temperature as observed by laboratory ion beam experiments [20]. To address this issue, experiments were carried out in the Mark II divertor at different wall and divertor temperatures. During these discharges, the bulk temperature of the tile was monitored with thermocouples mounted several centimetres from the plasma facing surface. While infra-red surface temperature measurements were not available for these experiments, evaluation of discharges with similar divertor energy deposition ($\sim 7.5\text{MJ}$) show that the surface temperature near the strike point increases by $\sim 60\text{K}$. It is therefore important to note that the quoted bulk tile temperature is an underestimate but that the surface temperature evolution should be similar since the discharges were carried out with identical input power.

One can clearly see from fig. 7a that, at high flux densities, the chemical sputtering yield is reduced at the lower tile temperature. Furthermore, the flux dependency is stronger at low surface temperature with $Y_{\text{chem}} \propto \Gamma^{-0.4}$ at $\sim 450\text{K}$ and $Y_{\text{chem}} \propto \Gamma^{-0.7}$ at $\sim 360\text{K}$. It would appear that at low flux density ($< 5 \times 10^{22} \text{m}^{-2} \text{s}^{-1}$) the chemical yield does not depend on the tile temperature.

This effect cannot be explained and requires further investigation. It is interesting to note that in the lower temperature range the flux dependence is identical to that reported from ASDEX Upgrade which operates in the range of 290-350K [4]. The variation of the flux dependence with tile temperature indicates that the time consuming chemical processes associated with chemical sputtering (such as the rearrangement of bonds during the hydrogenation process) may be playing a role. This would imply that any such flux dependence would be negligible at the relatively high divertor surface temperature ($\sim 1500\text{K}$) of a next-step experiment such as ITER [1]. However, in this study it has not been possible to unambiguously separate the effect of flux density and impact energy on the reduction of the chemical yield. This point is illustrated in fig. 7b in which the results from the surface temperature study are plotted versus impact energy as derived from the electron temperature measured by the Langmuir probes.

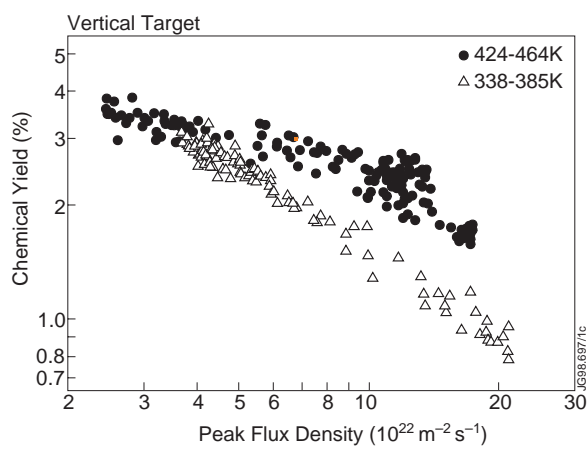


Fig.7a: Effect of the bulk tile temperature on the average chemical yield versus peak flux density for vertical target deuterium discharges in the Mark II divertor. The increased flux dependence at lower temperature is evident.

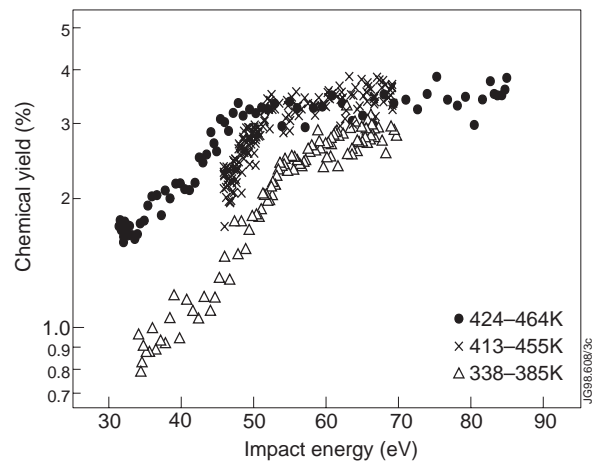


Fig.7b: Effect of the bulk tile temperature on the average chemical yield versus impact energy for vertical target deuterium discharges in the Mark II divertor. This highlights that the apparent flux dependence of the yield may also be attributed to reduced impact energy.

Overall, the observation of an enhanced chemical yield with increased tile temperature is consistent with the relative behaviour of Mark I and Mark II divertors. The chemical yields for the two divertor configurations are compared in fig. 8 for deuterium discharges with both horizontal and vertical target configurations. Over the whole range of flux density, the yield is lower in the Mark I divertor by a factor of 2-3 compared to Mark II. In addition, the Mark I divertor exhibits a particularly strong flux dependence ($Y_{\text{chem}} \propto \Gamma^{-1.25}$) at high fluxes in contrast to the relatively weak flux dependence in

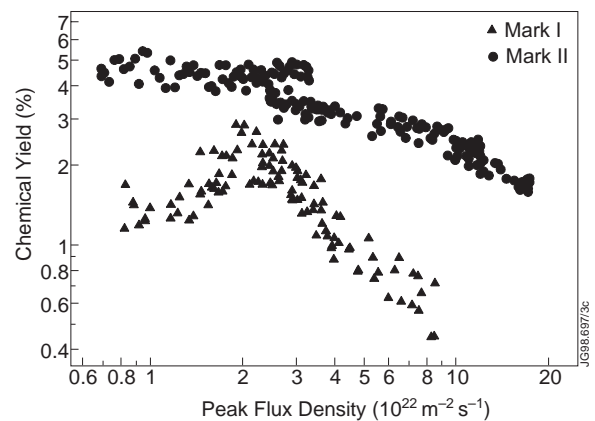


Fig.8: Comparison of chemical sputtering yields for deuterium discharges in the Mark I and Mark II with horizontal and vertical target configurations.

the Mark II divertor. It is interesting to observe that the chemical yield in the Mark I divertor appears to reach a maximum value at a value of $\sim 2 \times 10^{22} \text{ m}^{-2} \text{ s}^{-1}$ rather than the plateau that is observed at low fluxes in the Mark II divertor.

5. CONCLUSIONS

In the JET Mark I and Mark II divertors, the in-situ chemical sputtering yield of the carbon target plates has been studied under a wide range of conditions. To evaluate the chemical yield, the incident hydrogenic flux is directly evaluated from Langmuir probe measurements and D α spectroscopy while the methane production rate is inferred from CD/CH molecular band emission. One of the major uncertainties with this approach is the D/XB coefficient used for the conversion of the CD/CH molecular band emission into a methane production rate. To address this issue, the effective D/XB is evaluated from methane injection experiments for which it is found that D/XB=50 provides good agreement over a wide range of plasma parameters.

Using this approach it is found that the chemical sputtering yield depends upon the isotope mass ($Y_{\text{chem}} \propto m_{\text{ion}}$) but falls at high fluxes (and low impact energies). The observation of the isotope dependence is consistent with thermal reaction processes which are enhanced by radiation damage. At the high flux densities ($> 2 \times 10^{22} \text{ m}^{-2} \text{ s}^{-1}$) associated with vertical target discharges in the Mark II divertor it is observed that the chemical yield is reduced. It should, however be highlighted that it is not yet possible to unambiguously separate the effects of flux density and impact energy on the chemical yield. It is also observed that both the absolute chemical yield and its flux dependence vary according to the tile temperature with $Y_{\text{chem}} \propto \Gamma^{-0.4}$ at $\sim 450\text{K}$ and $Y_{\text{chem}} \propto \Gamma^{-0.7}$ at $\sim 360\text{K}$. These results indicate that time consuming chemical bond rearrangements (whose rate depend upon the tile temperature) are contributing to the apparent flux dependence of the yield. An important implication of these results is that such flux dependencies may be negligible at the high divertor tile temperatures that are expected in next-step tokamaks such as ITER.

Typical chemical yields evaluated for the Mark I divertor are found to be a factor of 2-3 lower than for Mark II and exhibit a particularly strong dependence ($Y_{\text{chem}} \propto \Gamma^{-1.25}$). These results are consistent with the tile temperature studies described above since the target tiles of the Mark I divertor are at the low temperature of $\sim 300\text{K}$ compared to Mark II at $\sim 450\text{K}$. While significant progress has been made, further work is necessary to improve the evaluation of the D/XB which remains the most critical aspect of the chemical yield evaluation. The role of heavier hydrocarbons, which are expected to be important at low impact energies, also requires investigation.

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