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ABSTRACT
The lifetime of the Beryllium first wall in ITER will depend on erosion and redeposition processes. The physical sputtering yields for Beryllium (both deuterium on Beryllium (Be) and Be on Be) are of crucial importance since they drive the erosion process. Literature values of experimental sputtering yields show an order of magnitude variation so predictive modelling of ITER wall lifetimes has large uncertainty. We have reviewed the old Beryllium yield experiments on JET and used current Beryllium atomic data to produce revised Beryllium sputtering yields. These experimental measurements have been compared with a simple physical sputtering model based on TRIM.SP Beryllium yield data. Fair agreement is seen forBeryllium yields from a clean Beryllium limiter. However the yield on a Beryllium divertor tile (with C/Be co-deposits) shows poor agreement at low electron temperatures indicating that the effect of the higher sputtering threshold for Beryllium carbide is important.

1. INTRODUCTION
The lifetime of the ITER Beryllium first wall depends on the balance of erosion and deposition processes. Physical sputtering dominates the Beryllium erosion yield and several measurements exist in the literature. However, Beryllium erosion yield measurements performed in the accelerator at IPP Garching [1] and in the PISCES plasma simulator [2] differ by an order of magnitude. On the JET tokamak, even higher yields, up to ~30%, were measured in 1989 from the Beryllium belt limiter during pure limiter operation [3]. Such large variations in the Beryllium sputtering yield makes the expected ITER first wall erosion rates extremely uncertain. In order to help to understand these differences and determine what yields should be used for ITER modelling to increase the confidence in predictive modelling, we have reanalysed the 1989 JET data with current Beryllium atomic physics data (dataset sxb96#be_pju#be1.dat) from the ADAS database [4].

In 1991 the JET tokamak was able to run single null divertor discharges with the strike points on either Beryllium tiles at the bottom of the vacuum vessel, or on carbon tiles at the top. Berylliumsputtering yield data from these Beryllium tiles [5] during lower X-point operation has also been revised using current ADAS data.

More recently, heavy Beryllium evaporations have been used to simulate a Beryllium first wall in JET in order to track Beryllium migration [6]. These experiments provided the opportunity to make a measurement of the Beryllium sputtering yield from the first wall for comparison with the above measurements.

Sputtering modelling was not very advanced at the time of these first Beryllium yield measurements. In particular, angle of incidence effects were uncertain and were typically included by an enhancement of the self-sputtering yield [7, 8]. Recent TRIM.SP calculations of Berylliumphysical sputtering yields [9] include angle of incidence data, and this has been used as input to a simple physical sputtering model to test against the experimental observations.

2. EXPERIMENTAL AND RESULTS

The use of photon efficiencies (or SXB values) is a standard method to convert experimental measurements of photon fluxes into particle fluxes for the atom or ion being observed. The sputtering yield of a Deuterium plasma on a Beryllium surface is then just the ratio of fluxes; Beryllium yield = Beryllium particle flux / Deuterium particle flux.

2.1 BERYLLIUM LIMITER YIELD DURING LIMITER DISCHARGES

The data from the discharges in [3] was reanalyzed. The discharges were a series of reproducible ohmic 3MA limiter plasmas with different plasma electron densities. These plasmas were nominally balanced on the upper and lower Beryllium belt limiters. Two extra discharges, #20943, #20946 have been added to the dataset since they were discharges with a large ramp in electron density, and the edge electron temperature, Te(a), from Langmuir probe measurements has been published [8, 10]. The two extra discharges are otherwise similar, though they do have a slightly different plasma elongation (1.5 vs. 1.4) and the upper/lower limiter balance is slightly different as indicated by magnetic measurements and the slightly different D-alpha variation with density, Fig.1. The roll over of the D-alpha signal at high density in Pulse No: 20943 indicates that the plasma is approaching detachment. Figure 2 shows spectrometer data from Pulse No: 20570 (line average density, nel_av ~ 1.9e19 m^{-3}) that illustrates that Be and D emission is dominant, with no significant oxygen or carbon lines observable.

To look up the ADAS photon efficiency (SXB) for the Be II 436nm line, the electron temperature at the location of the Beryllium ion is required. For these discharges, the edge electron temperature Te(a) is scaled as 80/(nel_av**1.3), which matches the Pulse No: 20943 data [10], and which gives Te(a)=16eV for the data at nel_av = 3.5e19 m^{-3}, 80eV for 1.0e19 m^{-3} and 260eV for 0.4e19 m^{-3}. This scaling is not strictly applicable at very low densities, so the maximum Te(a) was clamped to 100eV.

The spectroscopic calibrations for the 1989 data could not be re-established, but the SXB values used for Be II and D-alpha were identified. We therefore calculate a revised beryllium sputter yield by scaling to the current photon efficiency data from the ADAS database. The D-alpha photon efficiency was unchanged, at a value of 20. There is some uncertainty here since this assumes the Deuterium molecules at the JET limiter behave the same as on TEXTOR [11], effectively doubling the ADAS Deuterium atom SXB (10-11 for our edge conditions). The current ADAS Be II (436nm) photon efficiencies are larger than the preliminary values used in 1989 so the revised experimental Beryllium sputtering yields have increased, Fig.3.

As a consistency check, the yield was also estimated from the Be II /D-gamma spectroscopic intensities. The visible spectrometer has similar sensitivity for these two wavelengths so the yield can be calculated without an absolute diagnostic calibration. ADAS data gives an intensity ratio of ~30 for the D-alpha/D-gamma photon efficiency ratio for an electron density of ~3e12 cm^{-3} and Te~20-50eV; combining this with SXB(D-alpha) = 20 and taking SXB(Be II) from ADAS, an effective Be sputter yield of 11% is derived for Te(a) ~ 20eV , nel_av ~ 3.0e19 m^{-3}. This point is also plotted in fig.3, and is consistent with the other data.

Figure 3 demonstrates that while the yield data do not lay on a single curve (probably because the relative upper-lower limiter loading was different), the effective Beryllium sputtering yield varies from 8% to 45% and decreases with increasing electron density.

2.2 BERYLLIUM OUTER DIVERTOR YIELD IN X-POINT PLASMAS

In 1991 the JET tokamak had carbon tiles in the upper divertor and lower belt limiter, and Beryllium tiles on the lower divertor and upper belt limiter. The plasmas considered here were 3MA X-point ohmic discharges on the Beryllium divertor tiles [5]. The mixture of first wall materials and varied plasma operation in 1991 meant that the Be divertor tiles contained C/Be codeposits. For these pulses, the effective carbon sputtering yield in the Be divertor derived from the C II (658nm) and D-alpha spectral lines is 1-2%. However, the plasma line-average Z-effective varies from 1.0 to 1.8 for the same discharges, so the carbon concentration in the plasma core must be very low.

The data from the discharges in [5] were likewise re-analysed by scaling with the current Be photon efficiency data from the ADAS database. The revised Be yield data can be seen in Fig.4, showing a variation from 0.6% to 20% for Te(a) = 20-80eV in these X-point discharges.

2.3 BERYLLIUM WALL YIELD DURING X-POINT PLASMAS

A main chamber Beryllium yield measurement would ideally be performed with a pure Beryllium wall. We can get close to this situation by looking at data taken after the heavy (0.2 grams) Beryllium evaporation that was performed for Beryllium transport studies [6]. The Be-coating will be non-uniform since the coating thickness deposited depends on the evaporator head temperature and the line-of-sight distance from the evaporator head and any shadowed areas will receive no coating.

JET Pulse No's: 68114 and 68116 represent nominally identical 2.5 MA X-point discharges, with a line average electron density of 2.8e19 m^{-3} and 1.4MW of neutral beam heating from 7-15s (Pulse No: 68114 had 2.7MW of NBI from 11-15s). Pulse No: 68116 is the first plasma discharge following the strong Beryllium evaporation.

Figure 5 shows the ratios of the intensities of D-beta 486nm, C III 465nm and Be II 527nm lines on a horizontal line-of-sight looking at a main chamber wall tile. Pulse No: 68116 has a 5% higher D-beta intensity from 7-11s even though the line integral electron density is 1% lower. This is presumably due to small changes in wall conditioning and particle confinement in the two discharges. From 11-15s the two discharges have different NBI power, and this has a small effect on the D-beta and C III signals. The carbon and Beryllium ratios show that the heavy Beryllium evaporation has reduced the carbon source by a factor of two, and increased the Beryllium source by a factor of about six. This data implies that the main chamber wall is effectively ~55% Beryllium and ~45% carbon in #68116, and ~9% Beryllium and ~91% carbon in Pulse No: 68114. Note that this is a local spectroscopic determination of the wall composition, and may not be representative of other main chamber locations.

Using a photon efficiency for Be II 527nm of 25 (assuming Be II emission is at Te ~ ionisation potential ~ 20eV), 20 for D-alpha, and an ADAS value of 8 for the ratio of the D-beta to D-alpha photon efficiency; the effective Beryllium wall yield is 0.65%. Scaling to a 100% Beryllium wall, the yield would have been 1.2%. Uncertainties in the edge density and temperature are the main source of error in this measurement, but are estimated to have less than 50% effect.

4. MODELLING AND DISCUSSION

It is important to note that tokamak Beryllium yield measurements are 'effective' sputtering yields – they include the effects of other plasma impurities and self-sputtering by Beryllium.

For D sputtering of Be, where the Be returns to the surface it was sputtered from, the effective sputter yield, Y_{eff}, is given by $Y_{eff} = Y_{d\text{-}be}/(1-Y_{be\text{-}be})$ where $Y_{d\text{-}be}$ is the sputter yield of D on Be, and $Y_{be\text{-}be}$ is the Be self-sputter yield. If a fraction , x, of the Be ions return to the surface with full energy, and ignoring the (1-x) atom/ions that return with reduced energy or are lost to distant surfaces, then $Y_{eff} = Y_{d\text{-}be}/(1-x*Y_{be\text{-}be})$. Consequently if $x*Y_{be\text{-}be}$ approaches one, the effective yield will approach infinity.

Figure 6 shows the TRIM Beryllium physical sputtering yields [9] as a function of impact energy and impact angle (zero degrees is normal incidence). It is clear that for impact angles of greater than about 45 degrees, where the self-sputtering yield is greater than one, the effective yield could run away.

In tokamak plasmas, the magnetic field lines at the plasma wetted surfaces are typically within a few of degrees of grazing incidence. The electrostatic sheath, the ion gyro motion and the surface roughness all have an effect on the ion impact angle, generally leading to an average impact angle of ~40-60 degrees but with a significant angular spread. For our simple model we take the TRIM data for an angle of incidence of 45 degrees and study the effect of different x values. This is a somewhat arbitrary choice since the Y_{eff} equation clearly shows that larger values of $Y_{be\text{-}be}$ at larger angles can be offset by reducing x.

Figure 7 illustrates effective yield curves for x=0.8, 0.3 and 0.0, as indicative of limiter, x-point or wall yields. The ion impact energy is assumed to be 2Ti + 3zTe where the second term is due to acceleration in the sheath and Ti=Te and z=3. Effects that vary with plasma edge density and temperature are excluded (such as impurity screening). The modelled effective yields are in rough agreement with experiment for high electron temperatures, though at low temperatures the experimental yields are significantly lower, especially for the X-point yield measurements. The two different trends in the experimental limiter yield data is a concern, with no clear explanation. These plasmas contact slightly different parts of the belt limiters since the plasma elongations are slightly different. The relative power and particle loadings on the two belt limiters may also be different – magnetic measurements indicate small differences in LCFS position. Discharge #20943 had the advantage of Langmuir probe measurements of Te(a) whereas the other data was scaled from line average density data. The density scaling may not be applicable at low density where there is some evidence that the edge ion temperature increases strongly and Te(a) remains low [10]. The main effect on the data would be to reduce SXB (Be II), and hence the experimental sputtering yields. The drop in the impact energy due to a lower sheath potential would be offset by the increase in ion energy.

The X-point dataset clearly indicates a much lower sputter yield than the limiter data. The model suggests that this can be partially explained by reduced self-sputtering (cleaner plasmas) but agreement is still poor at low Te(a). These plasmas, and hence the X-point tiles also, contain noticeable carbon impurity. The low experimental yield at low Te(a) could be consistent with Beryllium carbide formation on the tiles, with its higher threshold energy for sputtering [1].

The experimental measurement of the wall Beryllium yield should be a test of Yd-be since impurity ions flowing out of the plasma will be mostly swept into the divertors and the main impacting species at the wall will be deuterium charge exchange (CX) neutrals. If the CX neutrals have a 30 degree average angle of incidence and an energy of 25eV then ref. [9] indicates a 1.1% sputtering yield, close to the experimental value. This should not necessarily be considered good agreement because the CX flux to the wall has an energy distribution that extends to several hundred eV.

5. SUMMARY

Beryllium sputtering yield measurements have been revised with the use of current Beryllium atomic data from the ADAS database, leading to yields up to 50% larger than previously reported [3]. Systematic errors are still significant (but estimated to be less than a factor of two) because of the approximations and assumptions made in the analysis. We do not measure the molecular Deuterium fluxes, but instead assume that they modify the D-alpha photon efficiency from 10-11 [ADAS] to a value of 20. Edge electron temperature and density are not available for all the spectroscopic data, so scalings with line average density are used.

This work shows that the trends in the Be sputtering yields have not changed though the effective Beryllium yield on Beryllium limiters has increased to 45% for very low density limiter plasmas with negligible carbon impurity. At high density, low Te(a) (~16eV), the Beryllium yield is ~8%. These values can be modelled from TRIM $Y_{d\text{-}be}$ and $Y_{be\text{-}be}$ data if the ion impact angle is assumed to be 45 degrees, and most of the sputtered Beryllium returns to the belt limiter.

In X-point discharges, the effective Beryllium yield from the outer strike point varies from 0.6 to 20%. The same modelling, but with only ~30% of the sputtered Beryllium returning to the strike point tiles can match the experimental data at high edge temperatures, but for low edge temperatures (20eV) the model predicts yields (13%) much larger than experiment (0.6%).

The effective yield of Beryllium from a Beryllium main chamber wall is also rather low, at 1%. This is the TRIM.SP value of $Y_{d\text{-}be}$ for 30 degree angle and 25eV energy whereas the impacting charge-exchange neutrals have energies up to many hundred eV.

The sputtering model is very simple, and should not be expected to be an excellent fit to all the data. However the model does indicate the sensitivity of the effective yield to the angle of incidence variation of the Beryllium self-sputter yield, and how this may be mitigated by reducing the Beryllium fraction that returns to the sputtering surface.

The particularly low experimental yields at low Te(a), when carbon is present on the Berylliumsurfaces, are not well modelled and this indicates that the TRIM yield data used in the model is inaccurate at low energies for a carbon contaminated Beryllium surface.

This work suggests that ITER erosion-deposition modelling should use TRIM.SP data for Beryllium sputtering yield data, but that surface contamination of the Beryllium first wall may significantly reduce the yield.

Next year JET will begin operation with a new Beryllium wall and Beryllium divertor [12], and upgraded diagnostics. This will allow detailed study of Beryllium sputtering and migration and provide further data for ITER modelling.

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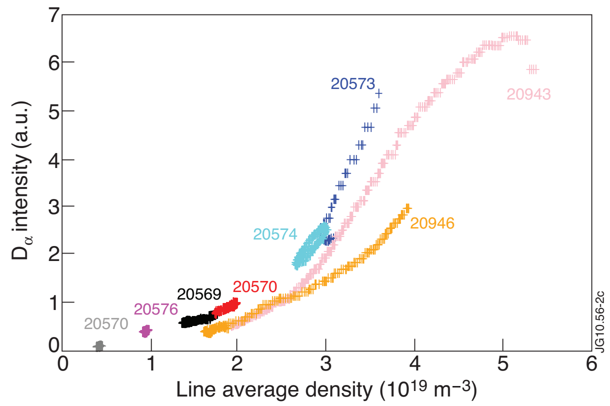

Figure 1: Beryllium limiter D-alpha emission versus line average density for time = 7-12s for the discharge numbers indicated.

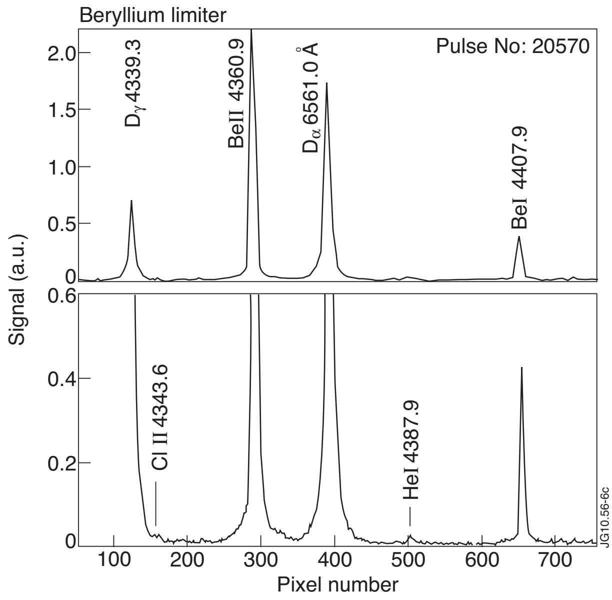

Figure 2: Spectrum from the beryllium limiter for Pulse No: 20570.

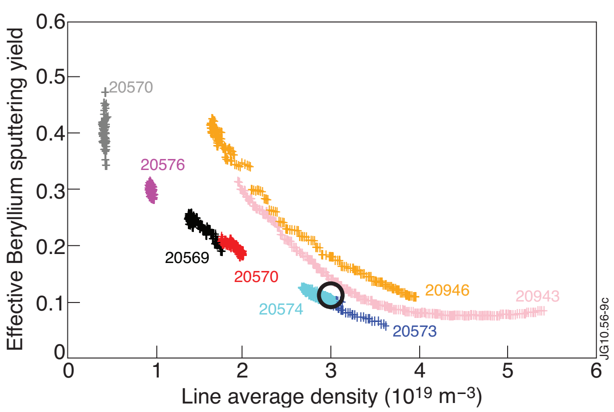

Figure 3: Limiter beryllium sputtering yield versus line average density. The black circle at 3.0e19m-3 is the data point using D-gamma rather than D-alpha (see text).

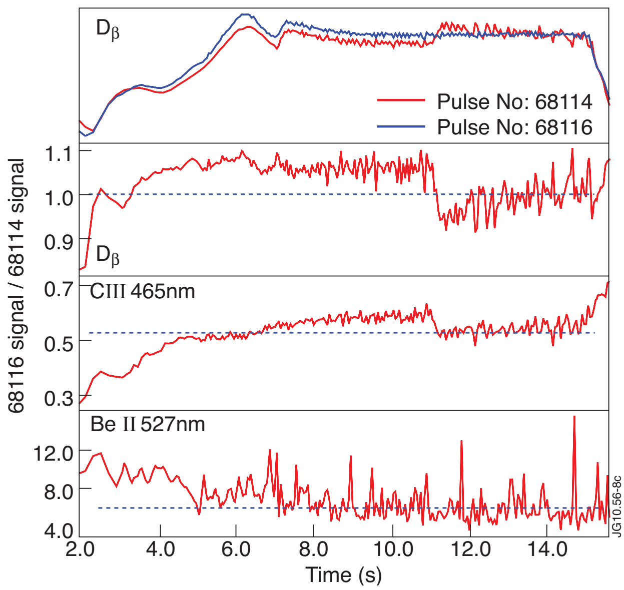

Figure 4: Comparison of two discharges (Pulse No's: 68114 reference, 68116 after heavy Be evaporation) for D-beta 486nm, C III 465nm and Be II 527nm spectral lines.

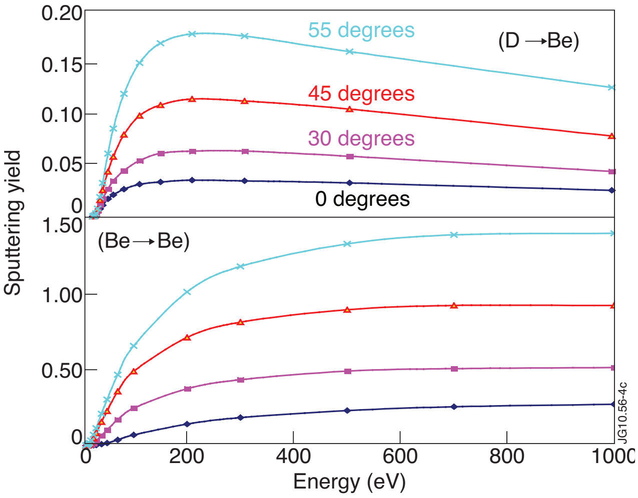

Figure 5: TRIM.SP beryllium physical sputtering yields [9] versus impact energy for different angles of incidence.

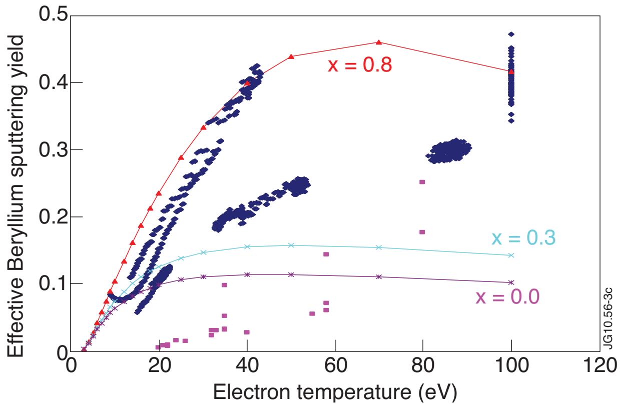

Figure 6: Experimental Be yield data (diamonds for limiter data, squares for divertor data) comparison with model data (curves for x=0.0, 0.03 and 0.8).