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INTRODUCTION

JET is equipped with a first wall material combination comparable to the ITER selection comprising beryllium (Be) in the main chamber and tungsten (W) in the divertor and some recessed wall areas. Be is selected owing to its low atomic number, its low tritium retention and excellent getter properties, but material erosion limits the lifetime of plasma-facing components PFCs made of Be. Initial ERO modelling of the shaped Be first wall modules close to the ITER separatrix predict high erosion rates and limited armour lifetime [1]. However, uncertainties in the modelling, in particular in the atomic data and sputtering yields, still exist and further bench- mark under ITER-comparable tokamak conditions is required.

The ITER-Like Wall in JET (JET-ILW) demonstrated successful plasma operation [2], strong reduction of the C content (x20), and high plasma purity ($Z_{eff} \simeq 1.2$) [3]. Equipped with its bulk Be limiters, the JET-ILW allows the study of Be erosion by optical emission spectroscopy and observation of various transitions of BeI (e.g. 457nm), BeII (e.g. 527nm) and the BeD A-X band [4] under different plasma conditions and surface temperatures. The total Be sputtering consists of the bare physical sputtering [5] and the chemical assisted physical sputtering [6] – sometimes referred as swift chemical sputtering. However, the composition of the total sputtering, its dependence on the impact energy and temperature, the strength of the chemical assisted physical sputtering are not known for a high temperature plasma edge conditions as present in the JET-ILW or in future ITER.

Here, deuterium plasmas in limiter configuration have been used to vary the local electron temperature (T_e) in the scrape-off layer (SOL), or better, scanning the impact energy of the impinging deuterons (E_i), as well as, to vary the PFC surface temperature (T_{surf}) by plasma impact as they are only inertially cooled. The increase of T_{surf} is expected to inhibit the sputtering channel via BeD which thermally decomposes at about 540K according to studies in PISCES [7].

1. EXPERIMENTAL SET-UP AND PLASMA CONDITIONS

Two dedicated experiments in limiter configuration with contact point on the poloidal limiters at the high field side (fFig.1a) were carried out in order to study the Be sputtering yield with respect to a) its composition related to chemical and physical sputtering, and b) its dependence on the local T_e, respectively, the impact energy E_i. In experiment (i), initially performed for a global gas balance study, 34 identical plasma discharges (B_t = 2.5T, I_p = 2.0MA, P_{tot} = 2.0MW) had been executed consecutively. Typical, global time traces for central electron temperature T_e^C, central density n_e^C, injected P_{in} and radiated power P_{rad} for the last discharge of the series are depicted in (Fig.1b); the averaging window in the plateau phase used for analysis is indicated.

Each plasma pulse in experiment (i) ratchets up the limiter temperature until equilibrium is reached between heating and cooling. As all plasma parameters remain constant the experiment provides a scan of surface temperature which is monitored by IR thermography. The latter represents the tile base temperature T_{base} which rises from 470K and 670K in the observation chord of the spectroscopic system used (line-of-sight in Fig.1a) observes one tile in poloidal direction away from the plasma contact point.

Experiment (ii) aims in the study of the Be sputtering as function of the impact energy E_i of the deuterons, respectively, of the local temperature T_e and density n_e at the contact point under comparable limiter temperature conditions. Six ohmic discharges ($B_t = 2.8T$, $I_p = 2.0MA$), timely separated to allow sufficient cool down time, have been performed varying $T_e^C = 1.7-3.4keV$ and $n_e^C = 2.7-7.0\times10^{19}\,m^{-3}$ by deuterium fuelling. Initial results on the Be sputtering yield in connection with ERO modelling have been presented in [8]. The local plasma temperature has been determined in-situ by the line ratio analysis of two BeII lines at 467nm and 436nm which shows a strong dependence on T_e, but is practically independent of ne in the range of $5\times10^{17} - 1\times10^{20}\,m^{-3}$ which covers the conditions in the JET SOL and edge layer [9]. Assuming Te = Ti, the energy of deuterons can be estimated by approximately $E_i = 5\times T_e$.

3. CONTRIBUTORS TO THE TOTAL BE SPUTTERING YIELD

The temporal evolution of the brightness of BeI, BeII, BeD, D_2 and Dg at the averaging time window in the discharge (t = 10.5−11.5s) is shown in Fig.2. The increase of the surface temperature leads to a reduction of all photon fluxes related to Be whereas Dg remains constant in all discharges, indicating both constant plasma conditions and identical impinging fluxes to the limiter. In the same way the BeD A-X band emission decreases, the D_2 d-a emission increases indicating a shift in the release mechanism of deuterium. The line emission resulting from the Be ion (BeII at 527nm) is hereby representative for the total Be sputtering source, including bare physical sputtering and chemical assisted physical sputtering, and the band emission of BeD (BeD A-X band head 496.0nm to 499.4nm) is solely representative for the branch of sputtering related to chemistry. The line emission originating from the Be atom (BeI at 457nm) results from physical sputtering and the fraction of sputtering via BeD which dissociates via BeD+e→Be+D+e′, thus, the particle flux ratio of BeI to BeII even provides information on the dissociation chain. The application of appropriate inverse photon efficiencies, so-called S/XB, for the BeII 527nm line [9,10] and the normalisation to the impinging ion flux, determined by Dg leads to the total Be sputtering yield $Y_{Be}^{tot} = Y_{Be}^{phys}$ Be $+ Y_{Be}^{chem}$.

In figure 3a), Y_{Be}^{tot} is shown as function of measured temperature of the observed Be tile T_{base} determined by IR-thermography. It should be noted that Tbase is measured before the actual start of the discharge and that during plasma impact an incremental temperature increase of about xxT until the measurement window at t =11s occurs, however, this is not homogenous within the observation spot. A clear linear drop of Y_{Be}^{tot} with increasing temperature can be seen in the first nine identical plasma discharges till the maximum reachable temperature of the Be tile has been reached. This strong reduction in Y_{Be}^{tot} by 33% is caused by the reduction of Y_{Be}^{chem} which vanishes almost completely at the highest T_{base} according to the BeD emission described before. Therefore, we can conclude that for the given plasma conditions, $T_e = 15eV$ and $n_e = 6\times10^{18}\,m^{-3}$, determined by local BeII and Balmer-line ratio analysis, about 1/3 of Ytot Be is coming from Y_{Be}^{chem} and 2/3 from regular physical sputtering Y_{Be}^{phys} . This composition is in good agreement with MD modelling predictions [11] for the BeD release at an impact energy of 75eV which we can assume for this experiment considering $T_e = T_i$. From a comparable analysis using BeI at 457nm instead of BeII we obtain a reduction of Y_{Be}^{tot} by 25% which indicates that the preferred dissociation is via the molecule BeD (75%) and only about 25% is following the destruction in plasma via $BeD + e \rightarrow BeD^+ + e + e'$. We note, that measurement of BeII provides still the total Be erosion flux, however, the interpretation as bare physical sputtering is incorrect as the chemical assisted sputtering provides an additional sputtering channel. Further information can be obtained by comparing the reduction of Y_{Be}^{tot} with the change of the core concentration c_{Be}, deduced from Z_{eff} [3], as shown in Fig.3b: under constant plasma conditions, c_{Be} drops in the same manner as Y_{Be}^{tot} with Tbase by about 30%. Comparing the absolute values, the erosion yield corresponds to twice the concentration in the plasma which suggests that the ratio between gross and net erosion is also a factor 2.

The behaviour is to a certain extent similar to the sputtering of carbon from graphite with observation of C^+ (CII emission), representing physical and chemical erosion, and CD (CD A-X band emission), reflecting solely the chemical erosion with methane release and break-up into CD [10]. Also the chemical sputtering of graphite vanishes at higher surface temperatures as measured in TEXTOR under comparable edge plasma conditions as in JET [10]. However, the chemical sputtering process and the energy of the radicals produced is completely different between Be and C where the latter is thermally released. energy threshold for Be sputtering of about 10eV has been calculated [8] which inhibits erosion by low energetic ions or atoms as it occurs in the case of C. This fact has vital importance on the material migration behaviour in the JET-ILW as the Be erosion in the far-SOL, thus, the main chamber wall and the divertor, will be much reduced in comparison with JET-C. Note that MD modelling predicts at impact energies $E_i < 50$eV, the dominance of the Be chemical assisted physical sputtering over the classical physical sputtering before the threshold at about $E_i < 10$eV inhibits further sputtering.

4. TOTAL BE SPUTTERING YIELD AS FUNCTION OF EI

Experiment (ii) aims to determine the dependence of Y_{Be}^{tot} on Ei in the accessible range of limiter plasma conditions with the JET-ILW. As no direct measurement of the impact energy exists, we still assume the validity of $E_i \simeq 5 \times T_e$ over the full range. Figure 4 shows the measured Y_{Be}^{tot} as function of the local T_e deduced from local spectroscopy. The measured T_e in the SOL varies between 5eV and 35eV and is inverse proportional to the central plasma density which has been varied in a controlled manner by deuterium fuelling ramps. Y_{Be}^{tot} increases moderately with impact energy from e ≃ 5eV up to about $T_e > 30$eV which is in line with the increase of the physical sputtering process by deuterons. We observe the dominance of self-sputtering by impinging Be ions at $T_e > 30$eV and, thus, $E_i >$ 150eV which compromises the definition of the yield and normalisation to the deuterium ion flux. At the lowest controlled accessible $T_e \simeq 5$eV still the corresponding energy of $E_i \simeq 25$eV is above the energetic threshold energy. The measurement from experiment (a) is marked in fig.4, too, indicating the impact of Y_{Be}^{chem} at the particular single T_e values. However, the composition of the contributors to Y_{Be}^{tot} will likely change [11] in the plasma parameter range covered with a higher fraction of Y_{Be}^{chem} at lowest energies, representing the fist wall conditions in divertor plasmas, and negligible contribution at the high energetic range, representing low density conditions in plasma start-up. Overall we note that the Be sputtering yields represent effective yields due to averaging over the observation area on the 3D-geometry of the Be limiter. Variations in local plasma conditions and impact angles within the observation chord takes place. Our results provide a good data set to benchmark the ERO code which treats the involved processes on the atomistic level and can disentangle the processes in order to make predictions in more complex geometries and conditions like in ITER.

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REFERENCES

[1]. D. Borodin et al., Physica Scripta **T145**, 14008 (2011)
[2]. G.F. Matthews et al., Journal of Nuclear Materials **438**, S2 (2013)
[3]. S. Brezinsek et al., Journal of Nuclear Materials **438**, S303 (2013)
[4]. G. Duxbury et al., Plasma Physics and Controlled Fusion **40**, 361 (1998)
[5]. W. Eckstein et al., Report IPP 9/132 (2002)
[6]. D. Nishijima et al., Plasma Physics and Controlled Fusion **50**, 125007 (2008)
[7]. R.P. Doerner et al., Journal of Nuclear Materials **390-391**, 681 (2009)
[8]. D. Borodin et al., Journal of Nuclear Materials **438**, S267 (2013)
[9]. ADAS, http://adas.phys.strath.ac.uk
[10]. S. Brezinsek et al, Journal of Nuclear Materials **363-365**, 1119 (2007)
[11]. C. Björkas et al., New Journal of Physics **11**, 123017 (2009)

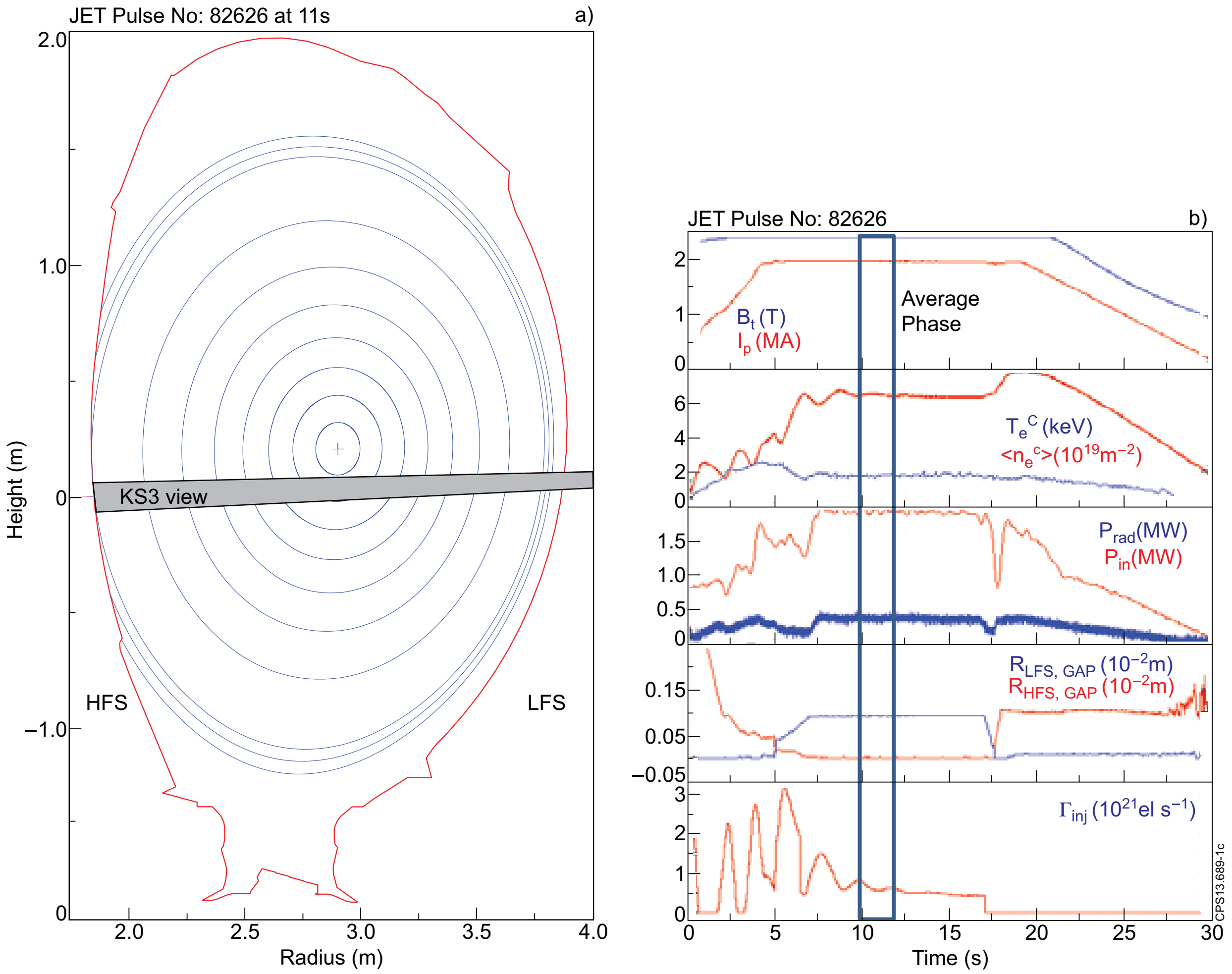

Figure 1: a) Applied limiter shape in the experiments. b) Evolution of global parameters for the last discharge of experiment (i) (JET Pulse No: 82592−82626)

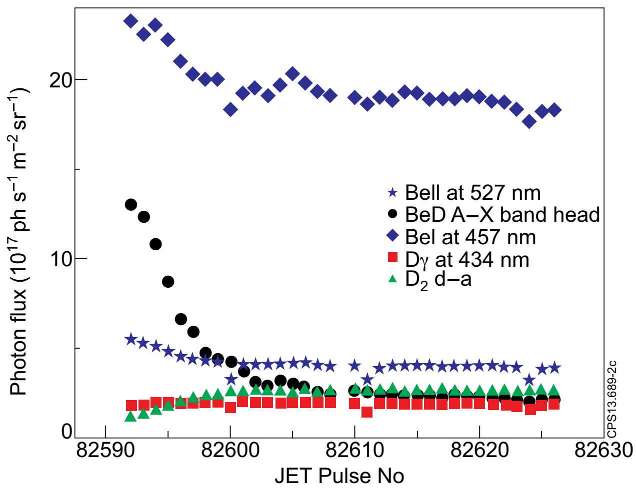

Figure 2: Experiment (i) Discharge to discharge evolution of Be and D photon fluxes with constant plasmas.

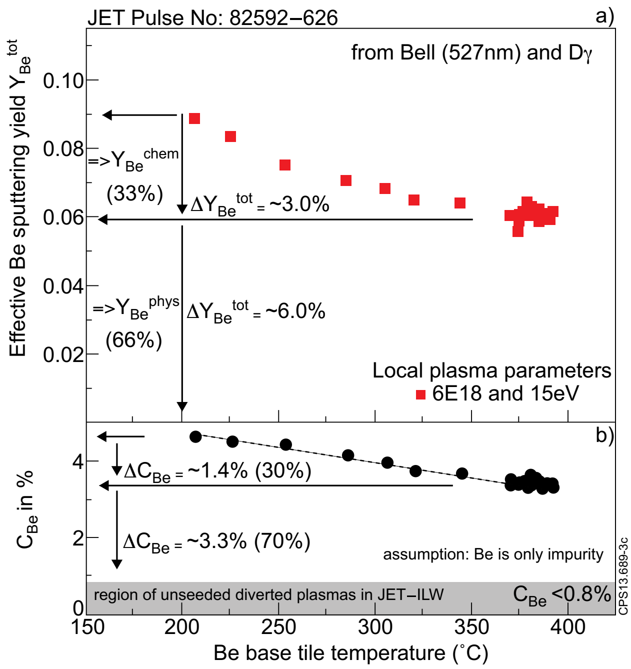

Figure 3: Experiment (i): a) Contributors to Y_{Be}^{tot} as function of T_{base}. b) Variation of c_{Be} with Tbase.

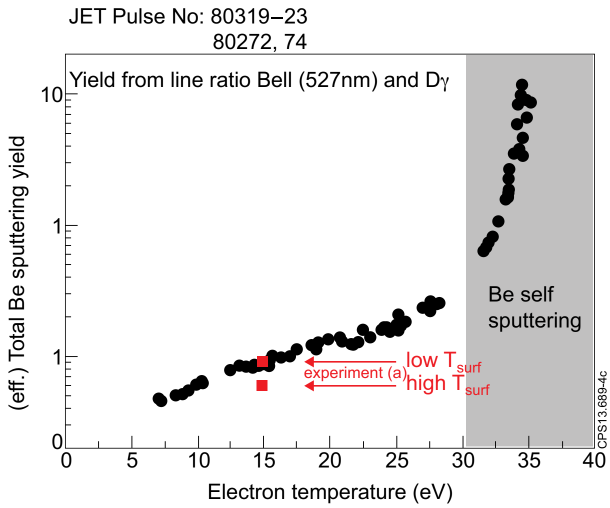

Figure 4: Y_{Be}^{tot} as function of the local Te in experiment (ii).