Erosion, Screening, and Migration of Tungsten in the JET Divertor

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1 Introduction

Tungsten (W) is currently applied as plasma-facing material (PFM) [1] for the divertor in JET [2], ASDEX-Upgrade [3], and foreseen in ITER [4]- the next step fusion plasma device starting operation in less than a decade. The erosion of W by plasma impact determines on the one hand the lifetime of divertor components [5, 6] and on the other hand erosion can have vital impact on the plasma performance as it governs the W influx to the confined region [7, 8]. Certainly, the screening of W by the divertor geometry from the confined region and the transport of W into the plasma determines the final content of W in the plasma core, but the W source itself affects substantially this process. Thus, the quantification of the W source induced by the impact of a mixture of impinging hydrogenic species, intrinsic and extrinsic impurity species as well as the helium ash is essential to understand and predict the impact of W on the fusion-relevant plasma itself. The final goal is to identify parameters to tame the W source and transport in order to avoid potential critical W concentrations in the core as well as ensure a long lifetime of plasma-facing components (PFCs) suitable for a reactor.

In this paper, we focus on plasma-surface interaction (PSI) studies with W plasma-facing components (PFCs) performed in JET operating with ITER-like wall (JET-ILW), thus, Beryllium (Be) first wall and full W divertor in hydrogen (H) and deuterium (D) plasmas and expectations for the upcoming operation in tritium-containing plasmas (T). The final years of JET-ILW operation provided access to parameters which determine the W-related PSI [9], permitting a detailed description of the W source in the divertor closest in
dimension to the one in ITER. Critical is in general the estimation of the net W erosion source related to one specific plasma and magnetic configuration in a fusion device which can be used to benchmark the available PSI codes (e.g. ERO [10], WallDYN [11], etc.) and plasma-edge codes (e.g. SOLPS-ITER [12]) concerning the W erosion, transport, and deposition which is usually defined as W migration.

Optical emission spectroscopy of the eroded W atoms provides plasma- and configuration-resolved gross erosion information, but in the case of W is the role of re-deposition very prominent and the re-deposition factor most critical in view of the source strength [13]. Post-mortem analysis after a campaign gives in principle access to the erosion and deposition pattern, but integrated over a large number of configurations and plasma conditions which makes a direct correlation to a single plasma condition in general very challenging. We present an integrated view on the PSI related to W PFCs utilising a dedicated campaign in H-mode plasma conditions accumulating 900 seconds at ITER divertor-relevant conditions [14] and providing unique information about macroscopic-measurable W net erosion compared with spectroscopically determined W gross erosion in quasi-steady-state conditions. This is complemented by a number of dedicated experiments with variation of single critical parameters such as e.g. impact energy, impinging impurity composition, and screening. The following subjects will be addressed in:

- **Section 2**: Effective W sputtering yields and fluxes as function of impact energy ($E_{in}$) of intrinsic (Be, C)[15] and extrinsic impurities (N, Ne) as well as ions of hydrogenic isotopes (H, D) are determined and discussed. This includes in particular also the interplay between intra- and inter-ELM induced W sources caused by the influx composition [16, 17] and energy distributions [17, 18] in these two plasma phases. The sputtering threshold energy and the spectroscopic composition analysis provide an insight in the dominating species and plasma phases responsible for the W sputtering.

- **Section 3**: The interplay between net and gross W erosion will be analysed considering the effects of prompt re-deposition, thus, the return of sputtered and ionized W to the surface within one Larmor radius or gyration time [19], and of surface roughness, thus, the difference between smooth bulk-W and rough W-coated components [20]. Both effects impact on the balance equation of local W erosion and deposition as well as on surface states and morphologies found after tile extraction [21]. Optical emission spectroscopy (OES) provided the gross erosion rates and pattern and post-mortem analysis (PMA) the corresponding net erosion and deposition pattern in the divertor. However, PMA covers the net migration path over hours of different plasma operation including the transport of W to remote divertor areas [22] and to the main chamber.

The experimental results will be brought in perspective to the expected W sources in JET-IIW in the DT phase and in ITER in the different phases of operation towards high performance plasmas [24]. The particular role of intra- and inter-ELM erosion of W as well as the gross and net erosion in both divertor legs in attached and detached divertor conditions will be reviewed in section 4.

### 2 Physical Sputtering of Tungsten

The main mechanism for erosion of tungsten under steady-state or ELM-like particle loads is physical sputtering which can be described by a binary collision approximation (BCA). The projectile is thereby an energetic atom or ion present in the plasma which hits the target material, the tungsten matrix, and transfers energy to overcome the surface bind-
ing energy of individual W atoms. Fig. 1a) describes the sputtering yield of W atoms by different impinging plasma fuel and impurity ions under perpendicular impact angle. The threshold energies for the different ion species depend on the mass confirming the advantage of the detached divertor regime with impact energies below the threshold for all considered intrinsic and extrinsic impurities. Fig. 1b) describes the shift of the energetic threshold for the three hydrogenic isotopes as well as the increase in magnitude with mass increase. W sputtering by hydrogen isotopes occurs only at high impact energies as e.g. present during Edge Localise Modes (ELMs)- so-called intra-ELM sputtering. However, steady-state operation at electron temperatures $T_e$ above $80\ eV$ in the near scrape-off layer (SOL), reached e.g. in hybrid H-mode plasmas, results in impact energies $E_{in}$ of about $400\ eV$ which is sufficient to sputter W significantly by deuterons, too. In the case of tritons, the equivalent $T_e$ to observe significantly W sputtering drops to about $50\ eV$ whereas for protons no W sputtering in the steady-state phase will occur as the required $T_e$ in the near-SOL would be around $200\ eV$.

The situation is different in baseline H-mode plasmas in JET-ILW operating in D and H. The applied plasma fuelling is usually leading to lower $T_e$-values in the near-SOL in comparison with hybrid plasmas. Consequently, W sputtering by protons and deuterons is negligible in the phases between ELMs (inter-ELM sputtering), but corresponding plasmas operating with T as fuel species will lead to a significant inter-ELM contribution in the W sputtering by triton impact. However, these theoretical sputtering yields are calculated under the assumption of a monoenergetic impact by a single ionic species on a smooth surface and represent gross erosion yields without any redeposition. Transfer to experimental conditions in JET need to consider the energy distribution of impinging ions (Maxwellian distribution for L-mode or between ELMs) and - apart from hydrogenic ions - also the mixture of different ionisation stages. Fig. 1c) shows measurements of gross erosion yields of W in JET-ILW L-mode plasmas in front of the bulk W outer divertor for hydrogen and deuterium. The threshold energy for both cases is within the error bars identical and lays between $T_e = 8\ eV$ and $T_e = 10\ eV$. This confirms that indeed at these low impact energies impurities are responsible for the W sputtering and not ions of hydrogen isotopes. Considering the impurity influx composition in JET-ILW, solely the impact of Be ions has to be taken into account as C and O concentrations are at least one order of magnitude lower in the impinging ion flux than Be [9]. The impurity levels have been determined in-situ by optical emission spectroscopy to amount between 0.5% and 1.0%. The sputtering behaviour is also representative for unseeded intra-ELM conditions.

**FIG. 1:** a) Physical sputtering yield of W hit by fusion-relevant ions. b) Physical sputtering of W by energetic hydrogen isotope ions. c) Measurement of the W sputtering yield in the outer divertor of JET in ICRH-heated L-mode discharges in D and H plasmas.
of baseline H-mode conditions. In the case of seeded species, additional sputtering of the seeding species, at JET-ILW typically Ne or N ions, need to be considered. Both species can dominate the W sputtering until radiative cooling of the plasma due to the seed gas [25] leads to a reduction of the impact energy of the seed ions at the W target below the sputtering thresholds.

The calculated physical sputtering yields in BCA exclude the recently observed channel via chemically assisted physical sputtering (CAPS) and release of WD molecules [26]. The appearance of this channel depends on the fuel content in the near W surface, which results in a surface temperature dependence, and the hydrogenic ion flux to the W target plate. The parameter space in ASDEX Upgrade and JET, both with inertially cooled W PFCs, is overlapping, thus, it can be expected that CAPS is present in JET-ILW at least at surface temperatures up to 350°C, too. CAPS might occur at a reduced activation and threshold energy for sputtering, but on the other hand it might also reduce the bare physical sputtering by dilution at the surface as it is likely concurrent process. Detailed studies are foreseen to investigate CAPS further in H, D, and T JET-ILW plasmas. For the interpretation of experimental erosion yields as done e.g. by the ERO code, one must consider the angular dependence of the physical sputtering yield as well as sheath effects in the strong magnetised edge plasmas. Typically for the JET-ILW divertor is an averaged impact angle of about 60° at a toroidal magnetic pitch angle of 1° – 3° onto the surface. Both effects lead in the case of Be ion impact on W to an increase of the erosion yield by e.g. a factor 1.7 at $E_{\text{in}} = 200\text{eV}$ in comparison with the corresponding monoenergetic impact case under normal incidence. Further details are described in [19] for a benchmark experiment on the bulk W target tile including also the Maxwellian energy distribution of the impinging Be ions.

Earlier experiments in ASDEX Upgrade [13] and JET-ILW [16] studied the variation of inter-ELM and intra-ELM contributions to the gross W erosion in the divertor. In the case of cold divertor conditions with impact energies close to or below the sputtering threshold for W sputtering, solely the intra-ELM phase dominates the W source as the inter-ELM contribution is switched off [9]. In the case of hot and strongly attached divertor conditions is the situation more complex as shown in fig. 2a). Fig. 2a) is describing the fraction of intra-ELM sputtering to the total W source in the outer divertor of JET-ILW in deuterium baseline H-mode plasmas. The variation in composition depends on the actual impinging ion flux distribution, impact energies, and the ELM frequency. The latter limits usually the spectroscopic analysis as the time resolution is often insufficient.

![FIG. 2: a) Variation of the inter- and intra-ELM sputtering of W in JET-ILW baseline plasmas [16] b) Variation of the contribution of Be ions to the intra-ELM W sputtering in D plasmas. c) Variation of the intra-ELM W sputtering with impinging hydrogen isotope.](image-url)
to separate the intra- and inter-ELM phases due to high ELM frequencies and averaged signals are used for analysis. However, de Harder et al. [16] could separate both contributions and found up to 80% intra-ELM sputtering under attached conditions in the JET-IIW operational space on the bulk W outer divertor target.

Further insight provides an analytical model introduced by Borodkina et al. [17] which describes the intra-ELM sputtering source as function of the pedestal temperature ($T_{ped}$), which determines the impact energy of ions assuming a free-streaming transport during the ELM crash [18], the impinging species composition, and the magnetic field ($B_t$). Fig. 2b) shows the change of the W erosion per ELM impact as function of the Be ion ($Be^{2+}$) fraction in the impinging ion flux to the target in D plasmas derived from the analytical model considering $B_t = 3.0T$ and $n_{e,ped} = 1 \times 10^{20} m^{-3}$ as further input parameter. With rise of $T_{ped}$ thus indirectly with the monoenergetic projectile energy $E_{in}$ during the ELM crash, an increase of the W erosion per ELM occurs. The addition of e.g. 1.0% Be$^{2+}$ leads to an increase of up to 40% in the total erosion with respect to the pure D case. The exchange of the hydrogen isotope ion in the model, as shown in fig- 2c), reveals a strong isotope dependence of the W erosion per ELM impact with twice as high erosion by tritons in comparison with deuterons at the same initial pedestal conditions. The fraction of Be ions was kept constant in this study whereas it might rise in addition during T plasma operation due to higher sputtering of Be from the main wall due to charge-exchange neutrals [9]. Please note, that the observations in D plasmas are consistent with recent studies in DIII-D [23] where the main impurity (carbon) fraction in the flux to the target plate dominates the W sputtering in the intra-ELM phase over the impinging deuterons.

3 W erosion in quasi-steady-state plasma conditions

The critical question to address is: How can the in-situ observed gross erosion rates determined by OES be related to net erosion rates and where does the deposition take place for a specific plasma condition. PMA provides the distribution where net erosion and net deposition takes place, however, this is integrated over a typical campaign which lasts in JET about 20 plasma hours and consists of mixtures of different magnetic configurations and plasma conditions. General trends can be obtained by sorting along magnetic configurations [27], but it is challenging to connect this in general to a single plasma condition which can be modelled as the overall W net erosion is very small.

At the end of the first year of operation, a series (C30C) of 151 identical D discharges in

![FIG. 3: a) Magnetic configuration used (tile 3/5) and compared to corner (tile 4/6). b) Averaged temperature distribution at the OSP. c) Averaged spatio-temporal evolution of the temperature during an ELM. d) Spectroscopic footprint of the WI photon flux density at the OSP averaged over inter and intra-ELM phases.](image-url)
H-mode were executed \((JPN\#83261 – 83791): \) magnetic field, \(B_t = 2.0T\), plasma current: \(I_p = 2.0MA\), purity: \(Z_{eff} = 1.2, \) additional power \(P_{aux} = 12.0MW\ NBI [6]\) with static magnetic configuration (fig. 3a) over the whole divertor phase of the plasma. This series of identical unseeded discharges had an integral exposition time in the H-mode phase of more than 900s in attached conditions for both divertor legs with more than 30 000 comparable ELMs \(t_{ELM,duration} = 2ms\) and in total 2500s in divertor configuration at much lower impinging flux. The inboard strike-line (ISP: \(T_e = 7eV\) and \(n_e = 2.5 \times 10^{20}m^{-3}\)) was located on tile 3 at a location often used in the campaign and which still represented a clean W-coated CFC surface without Be deposition as OES indicated. The outer strike-line (OSP: \(T_e = 35eV\) and \(n_e = 6 \times 10^{19}m^{-3}\)) was located on a part of the bulk-W divertor (tile 5, stack C) which could be correlated to the exposure in this period of plasma operation before tile removal. Fig. 3b) shows the heat load footprint on the target plate, measured by infrared thermography, averaged over intra-ELM and inter-ELM phases and fig. 3c) depicts the footprint of a coherent-averaged ELM. The complex pattern due to the lamellae and the global shadowing is visible as well as the fact that the ELM-footprint (intra-ELM phase) is about 1.8 times wider than the averaged footprint which is determined by the inter-ELM phase. We assume a comparable footprint on the bulk W divertor also for the impinging ions. Fig. 3d) shows for one representative discharge the spatio-temporal evolution of the erosion flux measured by WI at \(\lambda = 400.9mm\) at the outer target plate. The spectroscopic system averages over inter and intra-ELM phases resulting a comparable footprint to the IR thermography pattern. The integrated W gross erosion from the outer target plate was deduced from this system considering the total exposition time in the experiment and applying inverse photon efficiencies for the given plasma parameter. However, a complementary multichannel OES system equipped with interference filters providing high temporal resolution on the cost of spatial resolution (3cm spots) was used to resolve the intra-ELM phase and permit the comparison of inter- and intra-ELM distributions for both divertor legs. Figure. 4a) shows for the inner divertor leg the statistical analysis of \(BeII\) photon flux, representative for the impinging Be flux, the \(WI\) photon flux, representative for the W erosion flux, as well as the \(D_\alpha\) photon flux which reflects a combination of recycling flux prior to the ELM impact and recombination due to ougassing after the ELM impact [6]. The inner strike line prior the ELM is close to semi-detachment \((T_e = 7eV)\) resulting in an impact energy of the impinging ions below the physical sputtering threshold of Be on W as described in fig. 1c). Thus, the W sputtering in the inner leg is solely determined by the intra-ELM phase. The
situation is different in the outer leg, where $T_e = 35\text{eV}$ at the OSP is sufficient to have inter-ELM sputtering by impinging the Be ions which counts for about 30% of the gross W erosion; this is in-line with the statistical analysis in fig. 2a). Thus, 70% of the gross W sputtering in the outer leg occurs in the intra-ELM phase considering different particle interaction areas on the target for both phases.

A complete poloidal set of PFCs was extracted and analysed post-mortem which included W-coated CFC tiles at the ISP and bulk W lamella at the OSP. A few W lamellas where coated prior installation with a thin $3\mu m + 3\mu m$ Mo double layer as erosion marker. PMA revealed that the top W layer was completely removed at the location of the OSP [21] and half of the erosion could be attributed to the 900s H-mode phase in C30C; the rest is attribute to comparable other H-mode plasmas and L-mode phases which have been summed up over the complete first year of operation at this location. Comparison of the W source spectroscopy in the intra- and inter-ELM phases with the post-mortem analysis provides a pair of gross and net W erosion: OES determines the W gross erosion to $40 - 60g$ and PMA the W net erosion to $2.4 - 4.8g$ over the 900s considering the interaction area in the circumference of the outer divertor. This corresponds to a high re-deposition fraction of more than 94% averaged over both phases.

The plasma-material interaction and transport code ERO coupled with improved PIC modelling for the complex re-deposition in both phases was applied to simulate a comparable experimental case [19] in identical magnetic configuration with slightly different local plasma conditions at the OSP with $T_e = 30\text{eV}$ and $n_e = 5 \times 10^{19} m^{-3}$ instead of $T_e = 35\text{eV}$ and $n_e = 5 \times 10^{19} m^{-3}$. Fig. 4b) shows the erosion and deposition distribution along the outer target plate. Essentially, ERO can reproduce the large gross erosion, the low net erosion, and thus the high local re-deposition on tile 5 with more than 94% in average and about 99% for the sputtering dominating intra-ELM phase. ERO also included the process of W self sputtering in the present simulations which was not considered in the experimental analysis. The overall divertor screening of the gross W erosion source in this open divertor geometry and configuration is more than a factor 100 and largely determined by the prompt re-deposition of W. The residual W escaping results in a tolerable core concentration of $c_W = 5 \times 10^{-5}$. Usage of the so-called corner configuration is even more preferable from the point of W screening as residual W atoms escaping the prompt re-deposition cycle are geometrically screened and W is transported deeper into the divertor pump duct. Thin W deposition was found in the recessed areas of the pump duct which have no direct lines-of-sight to the plasma [27].

4 Conclusion

Analysis of the W gross and net erosion in the JET-ILW by means of OES and PMA after a quasi-steady-state plasma campaign revealed a large W re-deposition factor of more than 94% which can be reproduced by the ERO code for the given experimental conditions. Gross W erosion is driven by the intra-ELM sputtering whereas inter-ELM sputtering by Be ions is either completely absence (ISP) or low as 30% (OSP). Extrapolation to T operation in JET-ILW would lead to a substantial higher gross W erosion mainly caused by the larger intra-ELM contribution, but colder divertor operation might be required to inhibit a substantial inter-ELM sputtering due to tritons.

The quasi-steady-state plasma operation in the JET-ILW with 900s of H-mode is done at particle loads, ion fluxes, and fluence comparable to one discharge in the pre fusion
plasma operation (PFPO) in ITER (fig. 5). The plasma conditions at the inner divertor leg of JET-ILW are close to the required semi-detached operation in ITER. Thus, the

<table>
<thead>
<tr>
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<th>JET-ILW (C30C D)</th>
<th>ITER (FPO DT base)</th>
<th>ITER (PFPO H case)</th>
</tr>
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<tbody>
<tr>
<td>Plasma time</td>
<td>900 s (H-mode)</td>
<td>400 s (H-mode)</td>
<td>200 s</td>
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<tr>
<td>Number of pulses</td>
<td>151</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Input power</td>
<td>12 MW</td>
<td>150 MW</td>
<td>20 MW</td>
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<tr>
<td>Energy input</td>
<td>7.2 GJ</td>
<td>60 GJ</td>
<td>4 GJ</td>
</tr>
<tr>
<td>Divertor ion fluence</td>
<td>~2.0x10^{26} D/m^2</td>
<td>~2.5x10^{27} D/m^2</td>
<td>~2x10^{26} D/m^2</td>
</tr>
<tr>
<td>Divertor ion flux</td>
<td>~2.5x10^{23} D/sm^2</td>
<td>~6.3x10^{23} D/sm^2</td>
<td>~1x10^{23} D/sm^2</td>
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<td>Wetted area</td>
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<td>~2.5 m^2</td>
<td>~2.5 m^2</td>
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<tr>
<td>ELM frequency</td>
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<td>~30 Hz (pacing)</td>
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</tr>
<tr>
<td>Number of ELMs</td>
<td>30 000</td>
<td>12 000</td>
<td>-/tbs</td>
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**FIG. 5**: Comparison of the quasi-steady-state campaign in JET-ILW with ITER operational phases.

impact energy of Be ions at the vertical target plates in ITER will not cause W erosion in the intra-ELM phase, but inter-ELM sputtering will solely determine the W gross erosion. The high prompt re-deposition factor will help to minimise the net W erosion source assuming the ELMs are controlled and reduced in strength. The ERO code verified in this JET-ILW experiment can be applied to extrapolate to plasma conditions in the PFPO as well as to those in the fusion plasma operation (FPO). However, the lifetime of the W divertor would be greatly improved as well as the residual W flux into the confined plasma reduced if full ELM suppression in ITER would be achieved.

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