Understanding tungsten erosion during inter/intra-ELM periods in He-dominated JET-ILW plasmas

A. Huber[1], S. Brezinsek[1], V. Huber[2], E. Solano[3], G. Sergienko[1], I. Borodkina[4], S. Aleiferis[5], A. Meigs[6], D. Tskhakaya[4], M. Sertoli[6], M. Baruzzo[7], D. Borodin[1], P. Carvalho[8], E. Delabie[9], D. Douai[10], A. Kirschner[1], K. Lawson[6], Ch. Linsmeier[1], J. Mailloux[6], S. Menmuir[6], Ph. Mertens[1], E. Pawelec[11], J. Romazanov[1], A. Shaw[6] and JET contributors

[1]*Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, 52425 Jülich, Germany*

[2]*Forschungszentrum Jülich GmbH, Supercomputing Centre, 52425 Jülich, Germany*

[3]*Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*

[4]*Institute of Plasma Physics of the CAS, Prague, Czech Republic*

[5]*NCSR 'Demokritos' 153 10, Agia Paraskevi Attikis, Greece*

[6]*CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

[7]*ENEA for EUROfusion, via E. Fermi 45, 00044 Frascati (Roma), Italy*

[8]*Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal*

[9]*Oak Ridge National Laboratory, Oak Ridge, TN 37831-6169, USA*

[10]*CEA, IRFM, F-13108, Saint-Paul-Lez-Durance, France*

[11]*Institute of Physics, University of Opole, Opole, Poland*

E-mail: A.Huber@fz-juelich.de

Keywords: helium plasma, tungsten erosion, tungsten divertor, optical emission spectroscopy, plasma-material interactions, JET-ILW

PACS: 52.70.Kz, 52.25.Vy, 52.40.Hf, 52.55.Fa, 52.25.Fi

Abstract

Tungsten erosion was quantified during inter/intra-ELM periods in He-dominated JET-ILW plasmas by optical emission spectroscopy. The intra-ELM tungsten sputtering in helium plasmas, which dominates the total W source, prevails by a factor of ≈ 4 over inter-ELM sputtering in the investigated ELM frequency range from 90Hz-120Hz. He ions are mainly responsible for the W erosion during the ELMs in He plasmas. The strong in/out asymmetry of the ELM induced W erosion is observed in He plasmas even at high ELM frequencies beyond 100Hz. In Ohmic/L-mode plasmas and during the H-mode inter- ELM plasma phases both He^{2+} and Be^{2+} ionic species are major contributors to the W erosion. Their contribution depends on the divertor Te: for T_e > 15eV both species cause significant W sputtering, for T_e < 15eV, Be^{2+} ions are solely responsible for the W erosion. Tungsten erosion during in both inter and intra-ELM periods in He-dominated plasmas are significantly larger than in deuterium plasmas. It is 15-25 times larger during the inter-ELM phase and in L-mode discharges at T_e=25-30eV. On the other hand, the ELM-induced W source is by a factor of 3 larger than in D plasmas.

1. Introduction

Tungsten (W) is foreseen as plasma-facing material (PFM) for the divertor in the next step fusion plasma device, ITER [1]. W is selected because of its high threshold energy for physical sputtering [2], good power-handling capabilities with high melting point [3] and low retention of radioactive tritium (T) in the plasma-facing components (PFCs) [4,5]. W erosion can seriously limit the lifetime of the respective wall components [6]. On the other hand, the influx of W into the confined region can lead to a dilution of the core fusion plasma and increased energy losses due to radiation, which in turn could have a decisive impact on the plasma performance [7,8]. The mechanism of erosion of the tungsten is mainly determined by the material of the surfaces of the first wall, which is the source of the main impurities in the plasma, and by the choice of the fuelling gas. By exchanging deuterium for helium in a machine with ITER-like wall which contains Be and W materials, the effect of the fuel gasses on the character of edge and divertor physics, such as the W erosion and nature of the Be impurity source can be studied.

Operation of H-modes in helium-4 plasmas is intended as one option for the low activation phase of ITER in order to develop plasma scenarios for the future deuterium-tritium (DT) operation as well as to commission the operationally relevant ITER systems and the plasma diagnostics in a friendly non-nuclear environment [9]. In addition, the alpha particles generated in DT fusion reactions in the active phase of ITER reinforced the need to understand in detail the interaction processes between W and He. To date, however, most of the plasma-wall interaction studies in tokamaks with a completely metallic wall, such as JET [10] and ASDEX Upgrade (AUG) [11], have been executed in deuterium (D) or protium (H) plasmas. Pure helium plasmas make up a negligible portion of the discharges carried out in these tokamaks [12].

An intensive He campaign at JET-ILW is planned for 2021 after the DTE2 campaign. To get the urgently needed information about the He plasmas, such as a L-H transition threshold or some aspects of PWI physics, a short campaign with helium plasma discharges with D-neutral beam injection (D-NBI) was carried out during the recent JET campaign [13].

This paper focuses on the analysis of the gross erosion of tungsten during inter/intra-ELM periods in the inner and outer legs of the JET-ILW divertor in the He-dominated H-mode as well as L-mode plasmas.

- **Methods for evaluation of W erosion in the JET-ILW divertor**

The identification of the W atomic sources was carried out at JET with the ITER-like wall (JET-ILW) with the help of optical emission spectroscopy (OES). This is mainly based on the observation of the most prominent WI transition ($5d^5(^6S)6s\ ^7S_3 \rightarrow 5d^5(^6S)6p\ ^7P_4^o$) at λ = $400.9nm$ of the sputtered W atoms aiming to determine the gross erosion.

Particle fluxes of sputtered W atoms, , are gained from line-of-sight integrated photon fluxes, I_{WI}, by applying inverse photon efficiencies, S/XB, according to the multi-machine scaling law [14,15,16]:

, (1)

(2)

The S/XB values during the inter-ELM phases as well as in L-mode plasmas result from an electron temperature which is determined by an array of Langmuir probes (LP) in the divertor region. In the intra-ELM phase, electron temperatures of T_e = 70-100 eV are assumed at the strike point, which provide S/XB values of $\approx$50 according to equation 2. Note that the inverse photon efficiencies, S/XB, in the temperature range between T_e=50 eV and T_e=200 eV are only weakly dependent on electron temperature T_e: they increase slightly from value of 48 to 53.6. Hence, the evaluation of the particle fluxes of sputtered W atoms is not sensitive to our assumption of S/XB = 50. Quite similar values for S /XB for the intra-ELM phases were used in [6,17,18]. This enables a direct comparison of the W erosion results with these earlier works.

Three approaches with the new algorithm for the subtraction of the continuum radiation were used to provide a quantitative measure of the W-erosion in the outer as well as in the inner divertor regions:

1) the combination of two spectroscopic systems, KT3 (the mirror-linked divertor spectroscopy system on JET) and PMT (the W photomultiplier filterscope diagnostics), with good spectral and temporal resolution;

2) the second approach based on the calculation of the accumulated photon flux, dt, instead of the instantaneous photon flux;

3) an approach based on spectroscopic imaging with the help of two digital cameras with the same two-dimensional view, equipped with interference filters of different bandwidths centred on the W I (400.88 nm) emission line.

These methods allow distinguishing the erosion source in the intra-ELM phase from the erosion in the inter-ELM phase. The detailed description of these three approaches are given in the [19] paper.

3 Experimental Results

3.1 Experiment in helium plasmas

Identification of erosion sources in helium plasmas is one of the important research topics of the plasma-wall interaction. This study was recently carried out on ^{4}He plasmas in the JET-ILW with B_t=1.8 T, Ip=1.2-1.7 MA and was compared with deuterium plasmas. The additional input power is introduced into the He plasmas by the Deuterium Neutral Beam Injection (D-NBI). In order to ensure minimal contamination of the helium plasmas in this study, the examined pulses were only carried out with helium gas injection (no injection of hydrogenic species). Fig.1 shows the time evolution of a H-mode helium discharge in JET-ILW with B_t/I_p=1.8T/1.2MA in low-triangularity magnetic equilibria (average triangularity of δ=0.22) with the outer strike point positioned on the horizontal divertor plate (so-called tile 5). During the He pulses, the divertor cryopump operated as usual, removing hydrogenic species. Argon frosting was not used to pump helium gas. With sufficient NBI heating power, the coherent M mode is observed at the L-H transition. A similar finding was made earlier in the hydrogen and deuterium plasmas [20]. As the input power increases, small ELMs appear, an effect which is mixed with the M-mode followed by isolated large ELMs, described here as Type I ELMs [13].

The spectrogram of inboard Mirnov signal (not presented here), shows quiet periods in between large ELMs, which is the typical behaviour for the Type I ELM phase, and thus confirms the statement about the Type I ELMs. Based on Langmuir probe measurements at the outer strike point, the electron temperature in between ELMs was in the range of T_e = 24–28 eV.

The examined helium plasmas are characterized by a high ELM frequencies (90-130Hz) and low pedestal electron temperatures of $T_{e,ped} < 400$eV and Z_{eff} is kept in the range of 2.05-2.1. It demonstrates a plasma stored energy (W_{dia}) of ≈1.1 MJ with an ELM energy loss of $\Delta W_{ELM} \approx$ 0.12 MJ (the loss of stored plasma energy during the ELM). The P_{sep} ( ) required to reach the type I ELMs in helium is of the order of 4-5.5 MW, which is 2-2.5times the L-H transition threshold value of 2.2 MW. Measurements of He, D, and H concentrations in the JET sub-divertor region are carried out with Optical Penning Gauge Spectroscopy [21,22]. During the D-NBI injection, the concentration of He, $c_{He}=n_{He}$ /(n_{He} + n_D + n_H) decreases slightly with the pulse evolution and the mean value of c_{He} over the Type I ELM phase type was about 0.85. The measurements confirm the presence of mixed He-dominated plasmas.

3.2 Intrinsic impurities in helium plasmas

Similar to the deuterium plasmas, the dominant intrinsic impurity in JET-ILW-He plasmas is Be. Be is produced by the erosion of the first wall made of beryllium by fuel ions and charge exchange neutrals [10]. The remaining C concentration in these plasmas was about $c_C \approx 0.07\%$, which is at least one order of magnitude lower than Be concentration. These mixed helium/deuterium (85%/15%) plasmas demonstrated an effective ion charge of Z_{eff} = 2.07 ± 0.03, mainly determined by Be impurity. The pure mixed (He / D) plasmas without impurities should have Z_{eff} = 1.92. Therefore, the ΔZ_{eff} observed in our experiments is 0.12-0.18, which corresponds to a Be concentration of 3% to 4.0%. The impurity flux towards the W divertor is determined by optical emission spectroscopy. For the calculation of the Be concentrations, the Be II (527nm) spectral line is used. The measurements result in values between 3.2% and 3.8% related to the ion saturation flux: , where is the averaged charge of this mixed He/D plasmas and the S/XB factor for the Be II (527nm) emission line is about 65 in the T_e range 25eV-30eV and $n_e = 5\times 10^{19} m^{-3}$. Similar results are achieved and taking into the account the concentrations of c_D=15% and c_{He}=85% and using the following S/XB values: 15 and 120 for the emission lines D_α and He I (668 nm), respectively. The S/XB values used here were taken from the ADAS database [23]. In the following analysis, we will use the c_{Be} values of 3.5%.

3.3 The charge state distribution of impurities and helium

The sputtering process depends strongly on the charge state of the impinging ions. It is therefore important to know the charge state distribution of impurities and He ions, which is defined by the ionization, recombination and transport processes of impurities and He ions in plasmas [24]. In the coronal equilibrium the distribution of the impurity particles amongst the different charge states is purely a function of T_e, with no dependence on n_e. However, at the plasma edge the local coronal equilibrium cannot be assumed for the calculation of the charge state distribution. Typically, the plasma in the non-coronal equilibrium can be described by the product of the electron density and residence time, $n_e \times \tau$ [25,26].

Fig. 2 shows the mean charge $\langle Z \rangle$ of beryllium and helium as a function electron temperature T_e for various values of $ne \times \tau$. In this contribution we use polynomial fits applied in [27] which were calculated with help of ADAS for $n_e = 10^{20}$ m^{-3}, which is a typical value for the scrape-off layer (SOL) in the divertor region. One can see from the Fig. 2 that the mean charges of Be and He are $\langle Z \rangle^{Be}$ = 2.0-2.2 and $\langle Z \rangle^{He}$ = 1.85 for typical values of the non-coronal parameter of $ne \times \tau = 0.3 \times 10^{17}$ m^{-3} s and for the T_e=24-28eV measured by the LPs during the inter-ELM phase,. During the ohmic phase at the T_e =10eVthe mean charges are: $\langle Z \rangle^{Be}$ = 2.0 and $\langle Z \rangle^{He}$ = 1.2 for Be and He respectively..

3.4 Physical sputtering of W: role of impurities and fuel species

The major erosion mechanism of tungsten in tokamaks is physical sputtering, which can be calculated with the static-dynamic TrimSP package (Monte-Carlo code SDTrimSP [28] using the Eckstein fitting formula, [29].) under assumption of a smooth target surface. Fig.3a shows the calculated physical sputtering yield of W atoms by impinging hydrogenic (D and T), helium and the Be particles at normal incidence as function of the mono-energetic impact energy, E_{in}, of the projectiles. One can see that the sputtering yield by He is more than an order of magnitude greater than by deuterium at the relevant divertor temperatures under the attached conditions. Fig.3b shows the ratio of the sputtered W atoms by Be and He at different Be concentrations: c_{Be}=1%, 2% and 3.5%. At the impact energy of 1keV, which is the typical energy of the impinging ions during ELMs, the ratio is about 0.2. This value shows that the main intra-ELM sputter is helium, not Be. In contrast to the intra-ELM phase, during the inter-ELM phase and L-mode the contributions of both species, Be as well as He, are significant depending on the divertor T_e: for the E_{in} >180eV, main channel of sputtering is due to sputtering by He and for the E_{in}< 180eV, is due to Be. For twice ionised Be and He the E_{in}=180eV corresponds to the T_e of ≈22.5eV.

3.5 Erosion of W during the inter-ELM periods

The JET W photomultiplier filterscope diagnostics (PMT) [30] collects W I (400.9nm) emission light transmitted via fibre optics to Photo Multiplier Tubes (PMTs) with a time response of up to 10 kHz and it is able to resolve the high ELM frequency, of order 100 Hz, observed in He plasmas. The disadvantage of this diagnostics is the collection of the W line emission along with the plasma continuum. The contribution of the latter is of the same order as or even larger than the W I line emission.

The combination of two spectroscopic systems, PMT[30] and KT3[31] with good temporal and spectral resolution, respectively, can separate both contributions [19]. This approach enables to evaluate the intensity of the plasma background continuum by comparing the photon fluxes of these two measurements during the flat top phases of the analysed discharge, as shown in Fig. 4. To compare these two measurements, the PMT signal is integrated over the time window of 40 ms, which is similar to the time exposure of KT3 spectroscopy, and corrected by taking into account the geometry of the KT3 lines of sight. Fig. 4 demonstrates the linear dependence between two signals, PMT and KT3, with a clear offset, I_{offset} = 4.82×10^{16} ph/(s m^2 sr), in the W filterscope (PMT) measurements, which is due to the plasma continuum with predominant contribution of the bremsstrahlung. The subtraction of the offset results in $I_{WI} \approx 2.5\times10^{16}$ ph/(s m^2 sr), which corresponds to the inter-ELM-induced W sputtering of $\times10^{19}$ atoms/s integrated over the entire outer strike point. Here an S/XB ratio of 37 is taken into the account (for T_e=30eV).

3.6 Erosion of W during the intra-ELM periods

The accumulated photon flux dt is used to evaluate the W erosion fluxes during the intra-ELM phases. This method could provide the clear separation of the ELM induced W sputtering fluxes from the inter-ELM-phase [19]. Fig.5 shows time traces of the accumulated photon fluxes dt collected from the outer and inner divertor legs. The time traces of the photon fluxes I_W are also shown., The dt signal shows the slope between the ELMs, which is determined by the photon fluxes from the W-sputtered atoms as well as by the plasma continuum. However, during an ELM event there is a jump in the accumulated photon flux. The height of this jump corresponds to the emitted WI photons during the ELM event. For the ELM event shown in Fig.5, approximately 1.3×10^{18} atoms per ELM and 2.53×10^{18} atoms per ELM are eroded in the inner and outer divertor legs, respectively. These values correspond to the W sources of 1.3×10^{20} atoms/s and 2.53×10^{20} atoms/s for ELM frequency of f_{ELM}=100Hz. Thus, the intra – ELM W source is in the outer divertor is larger than the source during the inter-ELM phase, of 6.7×10^{19} atoms/s, evaluated in the section 3.5. We can conclude that the intra-ELM tungsten sources in He plasmas, analogously to the D plasmas, dominate the total W source. The intra-ELM sputtering prevails by a factor of ≈ 4 over inter-ELM sputtering in the investigated ELM frequency range from 90Hz-120Hz.

Figures 6a and 6b show the number of sputtered W atoms as function of the ELM frequency in deuterium and helium plasmas. Here the total number of W atoms in the outer (inner) divertor area is integrated over the entire outer (inner) strike point. It should be noted that in the small number of the examined He plasmas the H-mode plasmas show relatively high ELM frequencies and we do not have information about the W sputtering for the f_{ELM} below 80Hz. One sees that the W sputtering and sources in the helium plasmas are significantly larger than in deuterium plasmas. The W source in the outer divertor is higher by more than a factor of 3 in the He plasmas than in deuterium. In D plasmas the in/out asymmetry of the W erosion decreases strongly with ELM frequency demonstrating a nearly symmetric W source in both divertor legs at frequencies above 70 Hz. In contrary to the D plasmas, the He plasmas show strong in/out asymmetry in the W sputtering as well as in W source even at high ELM frequencies beyond 100Hz. At $f_{ELM}\approx$ 100Hz the outer divertor cross W source is larger by a factor of about 2.

3.7 Tungsten sputtering yields in Ohmic/ L-mode plasmas and in H-mode inter- ELM plasma phases

Figure 7 shows the measured gross erosion yields of W in JET-ILW helium plasmas. We should mention from the beginning that the contribution of the He^+ to W sputtering is negligible. The significant fraction of the He^+ in He plasma is expected for the T_e below 10eV. But as mentioned in the section 3.4 the dominant sputtering of the W for the E_{in} <180eV (below the T_e=22.5eV if we consider the twice ionised ions,) is due to Be. For the calculation of the W sputtering yields in the T_e range beyond 20eV, where the He^{2+} is the major W sputterer, the tungsten particle flux is normalized to the total He^{2+} ion flux measured by Langmuir probes in the corresponding divertor legs. The saturation ion current collected by LP can be written as

(2)

where A is the area of the probe, n_{jS} is the density of the Zj ion charge at the edge of the sheath and v_{jB} its Bohm-velocity.

Riemann proposed a Generalized Bohm Criterion for a multi-species plasmas [32]. There are two solutions that satisfy the Generalized Bohm Criterion:1) ions reach their individual Bohm velocity at the sheath edge and 2) ions reach the common sound speed, c_S. An expression for the common sound speed, c_S, for plasmas with multiple ion species was determined by Tokar [33]:

(3)

where Γ_i represents the specific flow of one plasma species out of the κ plasma species. Experiments in two ion species plasmas gave ion speeds that is in agreement with the mentioned second solution [34]. Therefore we are going to use solution two, with common sound speed, here.

Given the D^+, He^+, and He^{2+} ions collected, this can be expressed by:

(4)

= (5)

where m_D and m_{He} are masses of the D and He ions, cor_D and cor_{He1+} are contribution fractions of the D and He^{1+} ions to the . They are cor_D=0.11÷0.1, cor_{He+}=0.125÷0.06 for the T_e =24-30eV measured during the inter-ELM phase. From Eq.(4) follows the expression for the :

(6)

The total He^{2+} ion flux collected by LPs in the outer divertor is used for the normalization of the total sputtered W fluxes in the outer divertor to get the W sputtering yield. The results are plotted in Fig. 7 for the inter-ELM phases as well as for the L-mode periods as a function of the divertor T_e measured by the LPs. Also results of the ohmic phase of the He discharges are plotted in this figure (data at $T_e \approx 10$eV). It should be noted that the measured eroded flux in the ohmic plasma at such a T_e can only be ascribed to Be^{2+} ions and not to He ions. These W fluxes are therefore normalized to the total averaged ion flux, , where is averaged charge of the mixed He/D plasmas (=1.1 for the T_e=10eV). For comparison, the calculated sputter yields are indicated for He^{2+} and an admixture of different concentrations of Be^{2+}. A good agreement is found between the experimentally obtained yields and the theoretical yield curve (sum of the He^{2+} and 3.5% of Be^{2+}). From the shown result we can conclude that sputtering yield curve for W can be described by erosion caused by He^{2+} and Be^{2+} ionic species: their contribution depends on the divertor T_e: for T_e=20-28eV both species significantly contribute for W sputtering, for $T_e < 15$eV, Be^{2+} ions are solely responsible for the W erosion.

Additionally, Fig.7 shows the result of the W erosion yields achieved in D plasma and published in [14]. The sputtering yield for He plasmas is higher by a factor of 15-18 than in D plasmas. In He plasmas the Be erosion on the first wall is enhanced by the sputtering due to He ions resulting in the larger flux of Be: 3.5% in contrast to the 0.5% in D plasmas. This in turn also leads to an increase in the W erosion through Be ions. Note that some moderate contribution of the Be^{3+} to the W sputtering for T_e beyond 25eV is expected. However, the modelling shows that the calculated sputtering yield, which takes into account the change in the ionization stage of the impinging Be from Be^{2+} to Be^{3+} at a constant c_{Be} = 3.5% , does not differ significantly from the sputtering yield assessed by 3.5% of Be^{2+} alone: the deviation is below 5% in the W sputtering yield.

The impact energy of the incoming ions are typically expressed in the D plasmas as $E_{in} = 2k_BTi+3Z_i\, k_BTe$, where k_B is the Boltzmann constant and the Z_i is the charge of the impinging ions. The last term in the E_{in} expression represents the gain energy of the ions through the Debye sheath due to ions acceleration and is defined by the electrical potential drop in the sheath: the electrical potential drop is $V_{sf} \approx 3k_BT_e$ in the D plasmas. This voltage drop depends, however on the mass as well as the Z of the plasma. It could be extracted from the condition of the zero current on the wall (floating conditions when the wall sits at 'floating potential' V_{sf} [35]). Setting   gives:

(6)

where m_i is the ion mass of the fuel species. Thus the voltage drop in the sheath for "He^+ dominated plasma" is $3.18k_BT_e$ ($E_{in} = 2k_BT_i + 3.18Z_ik_BT_e$) and about $3k_BT_e$ (corresponding $E_{in} = 2k_BT_i + 3.0Z_ik_BT_e$) for the plasma with He^{2+} dominant fraction. It is assumed here that $T_i = T_e$.

3.8 Intra-ELM contributions to the gross W erosion in the divertor

The free streaming model reveals that W sputtering during ELMs depends almost entirely on the density and temperature of the pedestal. In order to maintain the quasi-neutrality, the electrons transfer their parallel energy to ions during the ELMs on the way to the divertor target [36]. The resulting ions during the ELMs are almost mono-energetic with impact energy,E_{in}, up to $4.23 \times T_{e,ped}$. This energy is thus in the keV range, as observed experimentally in [37], and is sufficient to lead to significant sputtering of the W divertor targets. As show in section 3.4, the W sputtering for such energies and correspondingly during the ELMs dominates due to He.

Recently, Borodkina et al. developed an analytical model [38] to evaluate the tungsten-sputtered influx and to interpret the LPs measurements. This analytical model describes well the intra-ELM W-sputtering source as a function of the pedestal electron temperature ($T_{e,\ ped}$). According to the analytical model, which takes into the account the evolution of the pedestal temperature drop during the ELM event, the average incident energy of ions, is lower than $E_{i,max} = 4.23 \times T_{e,ped}$. and is roughly $2 \times T_{e,ped}$. The comprehensive modeling of W erosion in the divertor region started recently with help of the kinetic BIT1 - PIC MC flux tube code. The preliminary result of this modeling also predicts the averaged of about $2 \times T_{e,ped}$ [39]. The total number of He^{2+} ions per ELM event collected by LPs is used for the normalization of the ELM sputtered W atoms to get the W sputtering yield. The results are plotted in Fig. 8 for the intra-ELM phase. The average incident energy of ions, $\langle E_i \rangle$ is assumed here to $\langle E_i \rangle = 2 \times T_{e,ped}$. As Fig.8 shows, a good agreement is found between the experimental results and the theoretical yield curves. W is mainly eroded during the ELMs by energetic He ions with some moderate contribution ($\approx$20%) of the Be ions.

Conclusion

In this article we report on recent experiments for the study of the tungsten sources in Ohmic/L-mode as well as in H-mode He-dominated plasmas at JET-ILW, heated with deuterium neutral beam injection (D-NBI). The He and H+D concentrations were measured spectroscopically using the ratio of ^4He and D lines in an Optical Penning gauge in the subdivertor. In the investigated cases the helium concentration was $n_{He}/(n_{He}+n_D+n_H) \approx 85\%$. Three approaches are used to provide a quantitative evaluation of the W-sputtering in the divertor regions to distinguish the erosion source in the inter-ELM phase from the erosion in the intra-ELM phase.

Similar to the D plasmas the dominant W erosion mechanism in He plasmas is the intra-ELM sputtering induced by ions with energies determined by the pedestal temperature. The intra-ELM sputtering in helium plasmas prevails by a factor of ≈ 4 over inter-ELM sputtering in the investigated f_{ELM} range from 90Hz-120Hz. W is mainly eroded during the ELMs by energetic He ions with some moderate contribution (≈20%) of the Be ions.

In deuterium plasmas, the in/out asymmetry of the W erosion decreases strongly with ELM frequency having a nearly symmetric W source in both divertor legs at f_{ELM} above 70 Hz. On theopposite, a strong in/out asymmetry is observed in He plasmas even at high ELM frequencies beyond 100Hz. At $f_{ELM}\approx$ 100Hz the outer divertor cross W source is larger by a factor of about 2.

In contrast to the intra-ELM phase, during the inter-ELM phase and Ohmic/L-mode, both species, Be and He, contribute to the W erosion depending on the divertor T_e: for the E_{in} >180eV the main sputter channel is due to He^{2+} ions and for the E_{in}< 180eV due to Be^{2+}. For twice ionised Be and He the E_{in}=180eV corresponds to a T_e of ≈22.5eV. The contribution of the He^{+} to W sputtering is negligible.

It is shown that calculated by SDTrimSP code sputtering yield curve for W can be well described by erosion due to He^{2+} and 3.5% of Be^{2+} ionic species. For the temperature range T_e<15eV Be^{2+} ions are solely responsible for the W erosion. Also a good agreement is found between the experimental intra-ELM yields and the theoretical yield curves.

The W sputtering and sources in the inter- and intra-ELM phases in the helium plasmas are significantly larger than in deuterium plasmas. The sputtering yield for He L-mode and inter-ELM plasmas is higher by a factor of 15-25 than in D plasmas. The ELM-induced W source in the outer divertor is more than a factor 3 higher in the He plasmas in comparison with deuterium plasmas.

It was shown that in He plasmas the Be erosion on the first wall is enhanced by the sputtering due to He ions resulting in the higher influx of Be. The beryllium concentration, measured by optical spectroscopy, is about 3.5% in the investigated plasma discharges and is larger than the typical values of 0.5% in D plasmas. This in turn leads to an increase in the W erosion by means of Be ions in He discharges.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] Pitts R A et al 2017 Nucl. Mater. Energy **12** 60
[2] Janeschitz G ITER JCT and HTs 2001 J. Nucl. Mater. **290-293** 1
[3] Jenkins H D B and Roobottom H K 2004 CRC Handbook of Chemistry and Physics 85th edn (Boca Raton, FL: CRC Press)
[4] Hirai T et al 2003 Phys. Scr. **T103** 59
[5] Ogorodnikova O et al 2003 J. Nucl. Mater. **313–316** 469
[6] Brezinsek S et al 2019 Nucl. Fusion **59** 096035
[7] Pütterich T. et al 2013 Plasma Phys. Control. Fusion **55** 124036
[8] Dux R et al 2009 J. Nucl. Mater. **390–391** 858
[9] Aymar R et al 2002 Plasma Phys. Control. Fusion **44** 519
[10] Brezinsek S et al 2015 J. Nucl. Mater. **463** 11
[11] Neu R et al 2013 J. Nucl. Mater. **438** S34
[12] Hakola A et al 2017 Nucl. Fusion **57** 066015
[13] Solano E R et al 2021 submitted to the Nucl. Fusion
[14] G. J. van Rooij et al., J. Nucl. Mater. 438 (2013) S42
[15] M. Laengner et al., J. Nucl. Mater. 438 (2013) S865
[16] S. Brezinsek et al., Phys. Scr. T170 (2017) 014052
[17] Den Harder N et al. 2016 Nucl. Fusion **56** 026014
[18] Abrams T et al 2019 Phys. Plasmas **26** 062504; doi: 10.1063/1.5089895
[19] Huber A et al 2020 Nucl. Mater. Energy **25** 00859; https://doi.org/10.1016/j.nme.2020.100859
[20] Solano E R et al 2017 Nuclear Fusion **57** 022021
[21] Kruezi U et al 2020 JINST 15 C01032
[22] Vartanian S, Delabie E, Klepper C C et al 2021 Fusion Eng. Des. **170** 112511
[23] Summers H P 2006 The ADAS User Manual, version 2.6 (www.adas.ac.uk/manual.php)
[24] Gervids V I et al 1987 Reviews of Plasma Physics **12**, ed. by M.A. Leontovich, B.B. Kadomtsev (Consultants Bureau, New York)
[25] Kallenbach A et al 2016 *Plasma Phys. Control. Fusion* **58** 045013
[26] Huber A and Chankin A V 2021 Nucl. Fusion 61 036049
[27] Mavrin A A 2017 Journal of Fusion Energy 36 161
[28] Mutzke A et al 2019 SDTrimSP Version 6.00 (IPP 2019-2) (Garching: Max-Planck-Institut für Plasmaphysik) (https://doi.org/10.17617/2.3026474)
[29] Eckstein W 2007 Sputtering Yields. In: Sputtering by Particle Bombardment. Topics in Applied Physics, vol 110. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-44502-9_3
[30] Morgan P D et al 1985 Rev. Sci. Instrum. **56** 862–4
[31] Meigs A et al 2010 Rev. Sci. Instrum. **81** 10E532
[32] Riemann K U 1995 IEEE Trans. Plasma Sci. 23 709 .
[33]Tokar M Z 1994 Contrib. Plasma Phys. 34 139
[34]Lee D, Hershkowitz N and Severn G 2007 Appl. Phys. Lett. 91 041505
[35] Stangeby P C 2000 The Plasma Boundary of Magnetic Fusion Devices (Bristol: Institute of Physics Publishing)
[36] Moulton D et al. 2013 Plasma Phys. and Control. Fus. **55** 085003

[37] Guillemaut Ch et al. 2018 Nucl. Fusion **58** 066006; https://doi.org/10.1088/1741-4326/aab7b1
[38] Borodkina I et al. 2020 *Phys. Scr.* **2020** 014027
[39] Tskhakaya D private communications