EUROfusion

WPJET1-CPR(17) 17081

I Borodkina et al.

An improved estimation of intra-ELM tungsten sputtering at JET ITER-like Wall

Preprint of Paper to be submitted for publication in Proceeding of 16th International Conference on Plasma-Facing Materials and Components for Fusion Applications

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Intra-ELM tungsten sputtering in JET ITER-like Wall: analytical studies of Be impurity and ELM type influence

I. Borodkina[1,2], D. Borodin[1], S. Brezinsek[1], I.V. Tsvetkov[2], V.A. Kurnaev[2], C. Guillemaut[3,4], M. Maslov[4], L. Frassinetti[5] and JET Contributors[*]

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK
[1]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung - Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[2]National Research Nuclear University (MEPhI), Kashirskoe sh.,31, Moscow, Russia
[3]Instituto de Plasmas e Fusao Nuclear, Instituto Superior Tecnico, Universidade Lisboa, Portugal
[4]CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[5]Department of Fusion Plasma Physics, KTH Royal Institute of Technology, Stockholm, Sweden
** See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 26th Fusion Energy Conference (Kyoto, Japan, 17-22 October 2016)*

E-mail: i.borodkina@fz-juelich.de

Abstract. The W source strength in JET H-mode discharges depends on the W sputtering in the inter and the intra-ELM phase due to impinging hydrogenic ions (D or H) and impurities (mainly Be). The coupled approach using analytical expressions and Langmuir probe (LP) measurements is applied to model the ELM ion parallel transport and the W sputtering flux in intra-ELM and inter-ELM conditions in JET-ILW hydrogen and deuterium plasmas. The impact of the Be ion charge and the Be concentration in the impinging ion flux on the W sputtering was estimated. Be^{2+} concentrations of 0.5% and 1% in the impinging ion flux increases the W sputtering fluence per ELM by 20-30% and 35-55% correspondingly with respect to pure deuterium plasma; the charge state of Be ions has no substantial effect on W sputtering in the intra-ELM phase. The W sputtering source under inter- and intra-ELM conditions in JET hydrogen plasma discharges is validated by optical emission spectroscopy for different ELM types.

Key words: tungsten, sputtering, ELM, JET ITER-like wall, Langmuir probe, spectroscopy

1. Introduction

Understanding and control the plasma-wall interaction during edge localized modes (ELM) is one of the key issue for future fusion devices including ITER [1]. Tungsten (W) sputtering from the divertor target plates during ELM impacts is expected to be the dominant impurity source under inter-ELM detached conditions as required in a reactor [2]. A W impurity concentration in the plasma core above $5{\cdot}10^{-5}$ can lead to plasma core cooling and inhibit fusion reactions in ITER [3]. The high ion impact energy E_{in} threshold for W sputtering by deuterons and tritons prevents erosion under steady state conditions, however ELMs with highly energetic impinging deuterons can exceed the threshold [4]. Type I ELMs were shown to be the dominant source for W sputtering [5], therefore, it is important to estimate precisely the intra-ELM influx of sputtered W numerically, validate the model with relevant experiments for instance at JET ITER-like wall (ILW) [6]. The obtained model can then be extrapolated to paced ELMs expected for ITER.

The analytical approach for interpretation of the Langmuir probe (LP) measurements ("LP-Analytic") described in [7] were shown to allow estimating W gross erosion in unseeded JET-ILW Type-I and Type-III ELMy H-mode experiments in deuterium plasma. In the present work the impact of the Be ion charge and the Be concentration in the impinging ion flux on the W sputtering under intra-ELM conditions was estimated. The LP-Analytic approach was applied to assess the W sputtering flux in hydrogen plasma JET-ILW discharges. In hydrogen plasmas the W sputtering flux is lower than in deuterium plasmas due to a lower Be ion flux to the target and the higher sputtering threshold for protons than for deuterons. In the paper the analysis of JET ELMy H-mode discharges in hydrogen for different types of ELMs is presented. The sputtering source under inter- and intra-ELM conditions is estimated and benchmarked by optical emission spectroscopy of WI in these discharges.

2. Modelling of ion parallel transport and W sputtering yields under intra-ELM conditions

The LP-Analytic interpretation for LP flux measurements was suggested for reproduction the initial velocity distribution of ions leaving pedestal during ELMs to take into account the energy and angular distribution of incident ions in calculation of intra-ELM W effective sputtering yields. This approach is based on a) "Free-Streaming" model [8] and b) the linear dependence of ion impact energy during ELM on the pedestal electron temperature ($T_{e,\max}^{ped}$) [4, 9] measured by Electron Cyclotron Emission (ECE) [10]. Moreover, the electron temperature at the target during ELM was found to be low (T_e ~ 30 eV) in comparison with the ion energy. Outer divertor target (OT) W sputtering flux calculated using the LP-Analytic approach under ELM and inter-ELM conditions was in good agreement within a factor of 2 with the estimates made with W I spectroscopy [11].

The estimations [7] were conducted using the following assumptions: 1) the Be concentration in the impinging ion flux was expected to be around ~ 0.5% in unseeded type I ELMy H-mode experiments which is consistent to Be migration studies; 2) the Be intrinsic plasma impurity was assumed to be dominated by Be^{2+} ions [2]. However, heating power increases the Be content in the plasma [11] and causes a larger Be flux to the divertor which leads to an increase in W sputtering. In this work we assess the impact of uncertainties in the Be ion charge and the Be concentration in the impinging ion flux on the W sputtering flux under intra-ELM conditions in D plasma. In figure 1 the dependence of W sputtering fluence per ELM on pedestal temperature is shown in the assumption of different amount of Be^{2+} in the ion incident flux under Type-I ELM conditions of JET pulse #82237 ($T_e = 23eV, n = 10^{14} cm^{-3}, B = 3T, \Gamma_{i\_ELM} = 3.1\cdot 10^{23} m^{-2}s^{-1}, \Gamma_{i\_\mathrm{int}erELM} = 1.3\cdot 10^{23} m^{-2}s^{-1}$). One can see that the presence of 0.5% and 1% of Be^{2+} in the impinging ion flux increases the W sputtering fluence per ELM with respect to pure deuterium incident flux by 20-30% and 35-55% correspondingly. Moreover this effect increases with a decrease of the pedestal temperature. The influence of Be ion charge in the impinging ion flux on the W sputtered fluence during ELMs was also analyzed under intra-ELM conditions of #82237 for different pedestal temperatures. In figure 2 one can see that Be ionization state has no substantial effect on W sputtering in the intra-ELM phase as the plateau of the W physical sputtering yield vs. impact energy is reached already even in case of Z=1 Be^+ ions. However this effect can be more significant for smaller pedestal temperatures and respective ELMs.

3. W sputtering assessment in JET-ILW hydrogen plasma discharge with varying ELM regime

The mentioned above LP-Analytic approach could also be applied for estimation of W sputtering source under intra-ELM conditions in hydrogen plasma since in the frame of the 'Free-Streaming' model [8, 12] a trivial linear dependence of ELMy target ion impact energy on the pedestal electron temperature does not depend on the mass of ions (equation (36) in [12]). In figure 3 the comparison of W sputtering fluence per ELM in deuterium and hydrogen plasma is presented which is calculated using the LP-Analytic approach under conditions corresponding to JET pulse number #82237. In hydrogen plasmas the W sputtering flux is lower than in deuterium plasmas due to a) a lower Be ion flux to the target because of the lower main chamber Be source (for impact energy of 100eV the effective Be sputtering yield is 0.02 for protons and 0.04 for deuterons at normal incidence) and b) the higher sputtering threshold for protons than for deuterons (14.3eV and 9.5eV, respectively). However, the difference between hydrogen and deuterium plasma cases diminishes with the pedestal temperature increasing due to reaching of the plateau of the W physical sputtering yield vs. impact energy.

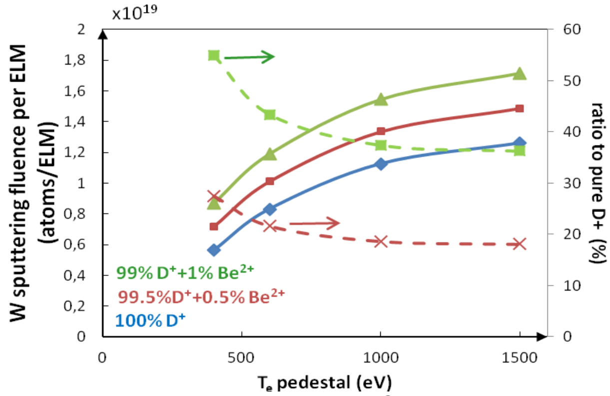

Figure 1. Influence of assumed Be^{2+} concentration in incident ion flux on the estimated W sputtering fluence per ELM (intra-ELM only) in D plasma.

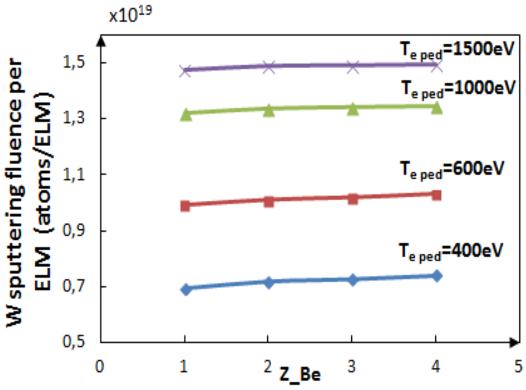

Figure 2. Influence of Be ionization state in the impinging ion flux on the W sputtering fluence per ELM at different pedestal temperatures.

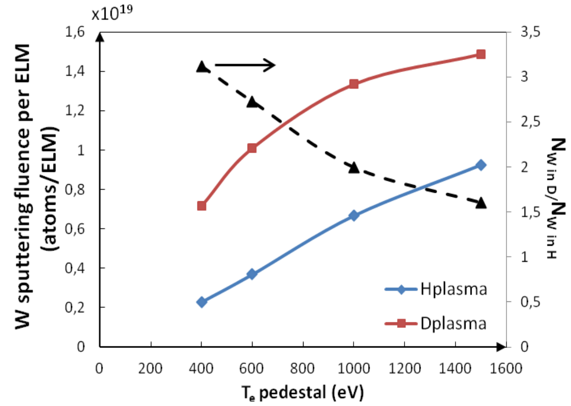

Figure 3. The intra-ELM W sputtering fluence as a function of pedestal temperature estimated by the LP-analytic approach in D (red curve) and H (blue curve) plasmas.

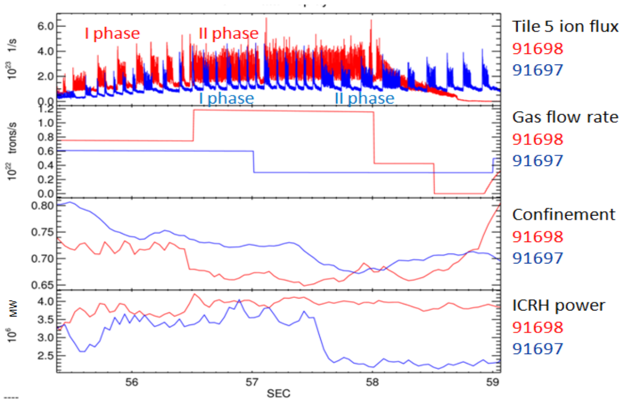

Figure 4. OT (tile 5) ion flux measured by LP, the gas flow rate, the confinement parameter H98Y and ICRH total power for H plasma JET-ILW pulses #91698 and #91697.

Two JET-ILW H-mode discharges #91698 and #91697 in hydrogen plasma were analyzed. The divertor configuration used in these discharges features a vertical inner target with a horizontal bulk tungsten OT (tile 5). In figure 4 the OT ion flux measured by LP, the gas flow rate, the confinement parameter H98Y and ICRH total power are shown for these pulses as time traces. Two time windows with different ELM frequencies could be determined for each discharge. In the first phase of #91698 (55.4 – 56.5 s) and in whole #91697 the compound ELMs were observed: for instance a large Type I ELM followed by high frequency smaller ELMs (likely Type III ELMs). In figure 5 one can see the example of ion saturation profile for compound ELM from #91697 II phase. In the second time window of #91698 (56.5 – 58.0 s) there is the regime with low plasma temperature and high ELM frequency. ELM frequency and pedestal temperature for two time windows of considered #91697 and #91698 with different gas low rates and ICRH power are given in table 1. The pedestal temperature and density were analyzed using High Resolution Thomson Scattering (HRTS) fits [13] corresponding to the pre-ELM profiles. In the case of compound ELMs two types of fits could be used based on the HRTS profiles before the large ELMs and before the small ELMs. In figure 6 the clear difference between those fits for a selected compound ELM from the #91698 (55.4 – 56.5s) is presented demonstrating that after a large ELM the plasma remains at low density and low temperature phase. From figure 4 and table 1 one can see that in #91698 the quite typical situation is observed when the increase of a gas flow rate leads to transition from compound ELMs regime to a pure type III ELMs thereby reducing confinement and increasing ELM frequency. In a difference to that in #91697 the confinement drops due to reduction in ICRH power which leads to changes in the pedestal "regime", mostly through the lowering particle confinement.

#91697				#91698			
t (s)	$\mathbf{f_{ELM}}$ **(Hz)**	$\mathbf{T_e^{ped}}$**(eV)**	$\mathbf{P_{ICRH}}$ **(MW)**	**t (s)**	$\mathbf{f_{ELM}}$ **(Hz)**	$\mathbf{T_e^{ped}}$ **(eV)**	**Total gas flow rate (el/s)**
55.6 - 57	10.7 Compound ELMs	540 (large) 390(small)	3.5	55.4 – 56.5	10 Compound ELMs	440 (large) 350(small)	$7.5 \cdot 10^{21}$
57.57 – 58.9	6 Compound ELMs	480 (large) 380(small)	2.3	56.5 – 58.01	200	310	$11.6 \cdot 10^{21}$

Table 1. Key parameters for the two time windows of the considered H plasma JET pulses #91697 and #91698: ELM frequency, pedestal temperature, gas flow rates and ICRH power.

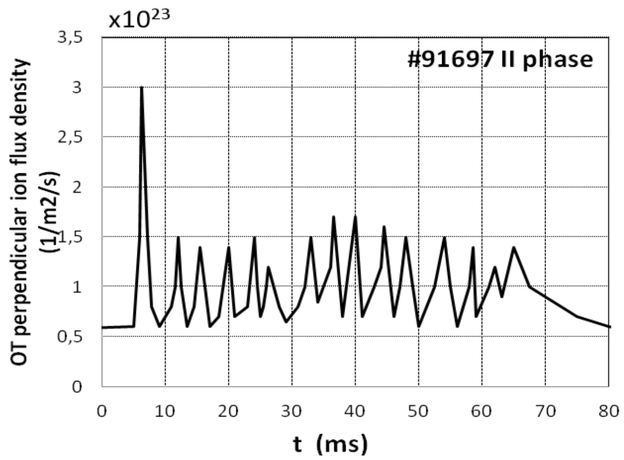

Figure 5. Perpendicular ion flux density profile at strike point from LP for one of the typical compound ELM from #91697 II phase.

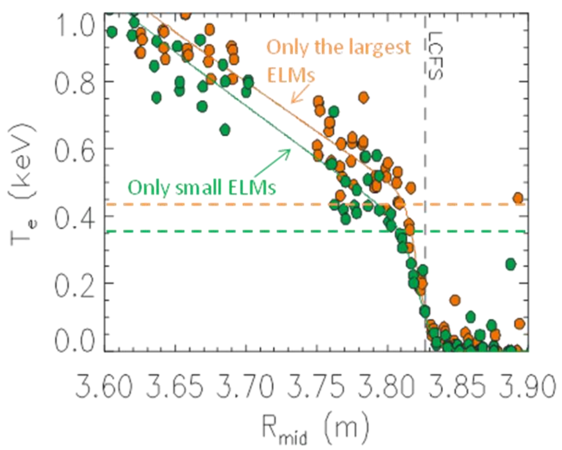

Figure 6. Example of clear difference between pre-ELM T_e pedestal profiles for the largest ELMs (red) and for small ELMs (green) for the compound ELMs in #91698 I phase obtained using High Resolution Thomson Scattering measurements

The W sputtering fluence during an ELM $N_{W,ELM}$, and inter-ELM W sputtering flux $\Gamma_{W,inter\text{-}ELM}$ have been calculated as follows:

$$N_{W,ELM} \approx \frac{J_{sat,ELM} - J_{sat,interELM}}{e} \cos\boldsymbol{\alpha} \cdot (Y_{D/W} + 0.005 \cdot Y_{Be/W}) \Delta t_{ELM} \quad (1)$$

$$\Gamma_{W,interELM} \approx \frac{J_{sat,inter\ ELM}}{e} \cos\boldsymbol{\alpha} \cdot 0.005 \cdot Y_{Be/W} \quad (2)$$

where α is the angle of magnetic field to the surface, the ion saturation currents $J_{sat,inter\ ELM}$, $J_{sat,ELM}$ were determined from LP measurements, the effective W sputtering yields $Y_{D/W}$, $Y_{Be/W}$ were calculated by the Eckstein formula [14] using the respective ion impact energy and angular distributions simulated as it was described in details in [7]. The Be concentration in the impinging ion flux is expected to be about ~ 0.5 % in unseeded JET-ILW H-mode experiments [2]. In the case of compound ELMs W sputtering fluence was estimated for each peak (see figure 5). For the large ELM a pedestal temperature was taken from the HRTS fit considering the largest ELMs (see figure 6). For the following smaller ELMs a pedestal temperature was taken from the HRTS fit considering the small ELMs. Δt_{ELM} is estimated as a time scale of distinctive sharp LP flux spike which corresponds to a pedestal temperature crash. For example, for the compound ELM, shown in figure 5, T_e^{ped} for the large peak and for the smaller peaks is 480 eV and 380eV, respectively, Δt_{ELM} is about 1 ms. Finally, the OT W sputtering sources retrieved from LP measurements using the analytic approach have been compared to similar estimates made with optical emission spectroscopy of W I (400.9 nm). Using the so-called S/XB ("ionization per photon") method [15] the particle flux was inferred from an absolute atomic line intensity measured by the 0.1 ms time resolution photo multiplier tube (PMT) through optical filters. The temperature dependence of the S/XB [16] was taken into account. The OT W sputtering fluence per ELM and OT inter-ELM W sputtering flux obtained by the both methods are given in table 2. In the case of compound ELM "per ELM" means "per combined large peak with all following smaller peaks". For each phase the W sputtering fluxes were estimated for the several compound ELMs and afterwards averaged. Discrepancies between values of W sputtered flux in the presense of ELMs obtained from both methods do not exceed a factor ~ 2. This proves that the assumptions and approximations made in the LP-Analytic approach allow obtaining correct estimates for W sputtering in hydrogen plasma. During the analyzed compound ELMs and Type III ELMs the W sputtering flux increases 2 - 4 times relative to inter-ELM case. However, the spectroscopy shows only 2 times flux increase probably because it is difficult to distinguish the inter and intra-ELM light emission. One can note that W sputtering influx is slightly higher in the presence of Type III ELMs than compound ELMs which is confirmed both by LP-Analytic approach and spectroscopy. It should be mentioned that the analyzed Type III ELMs have a pedestal temperature comparable with the compound ELMs.

	#91698 t (s)				**#91697 t (s)**			
	55.4 – 56.5 (I phase) Compound ELMs		56.5 – 58.01 (II phase) Type III ELMs		55.6 – 57.6 (I phase) Compound ELMs		57.6 - 58.9 (II phase) Compound ELMs	
Method	**LP – Analytic**	**WI Spectroscopy (PMT)**	**LP – Analytic**	**WI Spectroscopy (PMT)**	**LP – Analytic**	**WI Spectroscopy (PMT)**	**LP – Analytic**	**WI Spectroscopy (PMT)**
W fluence per ELM (at/m^2)	$0.6\cdot10^{19}$	$0.8\cdot10^{19}$	$2\cdot10^{17}$	$3.2\cdot10^{17}$	$2.5\cdot10^{18}$	$2.8\cdot10^{18}$	$6.4\cdot10^{18}$	$5.7\cdot10^{18}$
W flux Inter-ELM ($at/m^2/s$)	$3.5\cdot10^{19}$	$3.45\cdot10^{19}$	$3.25\cdot10^{19}$	$3.7\cdot10^{19}$	$1\cdot10^{19}$	$2.7\cdot10^{19}$	$1.3\cdot10^{19}$	$3.8\cdot10^{19}$
W flux (ELM+inter-ELM) ($at/m^2/s$)	$6.3\cdot10^{19}$	$7.6\cdot10^{19}$	$7.25\cdot10^{19}$	$8.6\cdot10^{19}$	$3.3\cdot10^{19}$	$4.6\cdot10^{19}$	$4.5\cdot10^{19}$	$5.4\cdot10^{19}$

Table 2. OT ELMy W sputtering fluence and OT inter-ELM W sputtering flux in the discharge #91698 and #91697. The ELMy W fluence is calculated as $N_{W,ELM}$ plus *Inter-ELM W flux multiplied by* Δt_{ELM}.

4. Conclusions

The analytical interpretation of Langmuir probe flux measurements is applied to model the intra-ELM ion parallel transport and the W sputtering flux in intra-ELM and inter-ELM conditions in JET-ILW hydrogen and deuterium plasmas. The impact of the Be ionization state and the Be concentration in the impinging ion flux on the W sputtering was estimated for deuterium plasma. Be^{2+} concentrations of 0.5% and 1% in the impinging ion flux increases the W sputtering fluence per ELM by 20-30% and 35-55% correspondingly with respect to pure deuterium plasma; the Be ionization state has no substantial effect on W sputtering in the intra-ELM phase as the plateau of W physical sputtering yield vs. impact energy is reached even in case of Be^+ (Z=1) ions with the lowest surface impact energy.

It is shown that estimated by the LP-Analytic approach W sputtering flux from the outer divertor tile in JET ELMy H-mode discharges in hydrogen plasma with different types of ELMs is in a rather good agreement (within a factor of 2) with passive absolute W I spectroscopy measurements mimicking the eroded W influx. Thus, the LP-Analytic approach is shown to be suitable for estimating W sputtering fluences in JET-ILW H-mode experiments in hydrogen plasma. During the analyzed compound ELMs and Type III ELMs the W sputtering intensity has increased 2 -4 times relative to inter-ELM case. It should be mentioned that the analyzed Type III ELMs have a pedestal temperature comparable with the compound ELMs. However, in the real ITER operation scenario Type I ELMs will probable be mitigated to Type III ELMs with much lower pedestal temperature. It is also important that a full or partial detachment is likely to be used in ITER leading for suppression of the inter-ELM erosion.

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work has been initiated within the FZJ - MEPhI strategic partnership.

References

[1] Loarte A 2014 *Nucl. Fusion* **54** 033007
[2] Brezinsek S 2015 *Journal of Nuclear Materials* **463** 11–21
[3] Kallenbach A et al 2005 *Plasma Phys. Control. Fusion* **47** B207–22
[4] Guillemaut C et al. 2015 *Plasma Phys. Control. Fusion* **57** 085006
[5] Den Harder N et al. 2016 *Nucl.Fusion* **56** 026014
[6] Matthews G F et al. 2011 *Phys. Scr*. **T145** 014001
[7] Borodkina I et.al. PSI-22 2017 *Nuclear Materials and Energy* doi: 10.1016/j.nme.2017.03.031
[8] Fundamenski W, Pitts R A 2006 *Plasma Phys. Control. Fusion* **48** 109–156
[9] Guillemaut C et al. 2016 *Phys. Scr.* **T167** 014005 (7pp)
[10] de la Luna E et al 2004 *Rev. Sci. Instrum*. **75** 3831
[11] van Rooij G V et al. 2013 *J. Nucl. Mater.* **438** (Supplement) S42–47
[12] Moulton D, Ghendrich Ph, Fundamenski W, Manfredi G and Tskhakaya D 2013 *Plasma Phys. Control. Fusion* **55** 085003
[13] Frassinetti L 2012 *Rev. Sci. Instrum*. **83** 013506
[14] Behrisch R, Eckstein W 2007 *Topics Appl.Physics* **110** 33-187
[15] Pospieszczyk A et al. 2010 *J. Phys. B: Atomic Mol. Opt. Phys*. **43** 144017
[16] Laengner M., Brezinsek S., Coenen J.W.et al. 2013 *J. Nucl. Mater*. **438** S 865–70