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Experimental estimation of tungsten impurity sputtering due to Type I ELMs in JET-ITER-like Wall

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Abstract

The ITER baseline scenario, with 500 MW of DT fusion power and Q = 10, will rely on a Type I ELMy H-mode, with ΔW = 0.7 MJ mitigated ELMs. Tungsten (W) is the material now decided for the divertor plasma-facing components from the start of plasma operations. W atoms sputtered from divertor targets during ELMs are expected to be the dominant source under the partially detached divertor conditions required for safe ITER operation. W impurity concentration in the plasma core can dramatically degrade its performance and lead to potentially damaging disruptions. Understanding the physics of W contamination in the plasma core is important and a primary input for this is the target W source due to sputtering during ELMs and inter-ELMs. It has been established that the ELMy target ion impact energy has a simple linear dependence with the pedestal electron temperature measured by Electron Cyclotron Emission (ECE) and that Langmuir Probes (LP) ion flux measurements are reliable during ELMs due to the surprisingly low electron temperature. Therefore, in this paper, LP and ECE measurements in JET-ITER-Like-Wall (ILW) unseeded H-mode experiments with ITER relevant ELM energy drop have been used to estimate the W sputtering flux from divertor targets in ELM and inter-ELM conditions.

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** See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia*

1. Introduction

The ITER baseline scenario, with 500 MW of DT fusion power and Q = 10, will rely on a Type I ELMy H-mode, with ΔW = 0.7 MJ mitigated ELMs, see [1]. Partial divertor detachment with nitrogen (N), neon (Ne) or argon (Ar) impurity seeding will also be required to maintain the inter-ELM power load at managable level. Tungsten (W) is the material now decided for the divertor plasma-facing components from the start of plasma operations. Under the partially detached divertor conditions envisaged for ITER, W atoms sputtered from divertor targets during ELMs are expected to be the dominant impurity source. In ITER, W impurity concentration in the plasma core above 5 x 10^{-5} can degrade fusion performance and may lead to potentially damaging disruptions, see [2]. Understanding the physics of W contamination in the plasma core is important and a primary input for this is the target W source mainly due to sputtering during ELMs.

The JET-ITER-Like-Wall (JET-ILW) [3] comprises a W divertor and beryllium (Be) main chamber wall thus matching the material configuration planned for ITER. Due to the high energy threshold for physical sputtering of W by deuterium ions (D^+), the dominant Be ion species, Be^{2+}, contributes to W sputtering in the divertor between ELMs (inter-ELM), see [4]. During ELMs, the experimental W sputtering yield due to D^+ ($Y_{D/W}$) can be estimated providing that the target ion flux, the ion impact energy (E_i) and the ion impact angle (θ_i) are known. It has already been established in [5] that electrons have low target temperature (T_e) in ELM conditions and can be repelled by biased Langmuir Probes (LP) surfaces to allow reliable ion flux measurements, and also that the maximum E_i has a simple linear dependence with the maximum pedestal T_e ($T_{e,\max}^{ped}$) measured by Electron Cyclotron Emission (ECE). Therefore, experimental estimation of the W sputtering source using ECE and LP measurements seems feasible and has been attempted here.

A high power unseeded H-Mode discharge performed in JET-ILW (#82237) where the W sputtering source has already been estimated using W I spectroscopy [6] has been used for this purpose. This experiment has been chosen for the slow (~ 10 Hz) and large Type I ELMs with ITER relevant energy (up to ~ 0.3 MJ). The divertor configuration used in #82237 features a vertical inner target with a horizontal outer target (OT), see Fig. 1. The present work has been focused on the use of ECE $T_{e,\max}^{ped}$ measurements and LP J_{sat} measurements to estimate the W sputtering source on the horizontal OT in ELM and inter-ELM conditions. This new method does not rely on any assumptions on atomic physics and provides independent high time resolution (~ 10 μs) target measurements which can be compared to W I spectroscopy.

Before estimating the W sputtering source, it is essential to have an idea of $E_{i,max}$ in this experiment by using ECE pedestal temperature (T_e^{ped}) measurements (Section 2). Then, the experimental W sputtering yields due to D^+ and Be^{2+} in ELM and inter-ELM conditions can be estimated by calculating the different ion impact angle distributions

(Section 3). Finally, OT W sputtering sources deduced from LP measurements have been compared to similar estimates made with W I spectroscopy [6] (Section 4).

2. E_i estimates during ELMs using ECE measurements

As shown on the example in Fig. 2 obtained from TRIM [7], the W sputtering yield depends strongly on E_i for the different possible ion species striking the divertor targets. Previous studies [5] have shown that ELMy electrons have a surprisingly low target T_e. As shown on Fig. 3, exponential fit of reconstructed ELMy I-V characteristic from the strike point Langmuir Probe in a Type I ELMy H-mode discharge similar to # 82237 yields Te ~ 20 – 30 eV. This means that electrons can be repelled by LP biased surfaces during ELMs to allow ion flux measurements. Indeed, according to the "Free-Streaming" model, it appears that during ELMS, electrons must transfer most of their parallel energy to the ions in order to maintain quasi-neutrality, see [8-10]. Therefore, LP ion saturation current (J_{sat}) measurements in A.m^{-2} can be coupled to perpendicular heat flux density ($q_\perp$) measurements in W.m^{-2} from Infrared thermography (IR) to derive the sum of E_i with the electron impact energy (E_e) in eV as follows:

$$E_i + E_e = \frac{q_\perp}{J_{sat} \sin\theta_\perp}, \quad (1)$$

with $\theta_\perp$ the field line angle with the OT (~ 2 - 3º in JET-ILW). It has been previously verified [5] on several Type I ELMy H-mode discharges in JET-ILW that E_i + E_e has a simple linear dependence with the $T_{e,\max}^{ped}$ such that:

$$\max(E_i + E_e) \approx \alpha T_{e.\max}^{ped} \quad (2)$$

with α = 5.23 according to the "Free-Streaming" model [8-10], see Fig. 4. Since the electron parallel energy is almost entirely transferred to the ions on their way to the target, the model assumes that the perpendicular electron energy ($E_{e,\perp}$) is the only component left in E_e such that:

$$E_e = E_{e,\perp} = T_e^{ped}. \quad (3)$$

Thus, $E_{i,max}$ during ELMs is:

$$E_{i,\max} = (\alpha - 1)T_{e,\max}^{ped} = 4.23 T_{e,\max}^{ped}. \quad (4)$$

Here, the #82237 JET-ILW Type I ELMy H-mode discharge already used to study the OT W sputtering source with W I spectroscopy [6] is considered. According to ECE measurement coherently averaged with the method descibed in [11], $T_{e,\max}^{ped}$ is ~ 0.6 keV here (Fig. 5a), which means that following (4), $E_{i,max}$ ~ 2.5 - 3 keV.

In inter-ELM conditions, it is considered, as in [4], that the ion impact energy ($E_{i,inter-ELM}$), T_e, and the target ion temperature (T_i) are such that:

$$E_{i,\mathrm{inter}-ELM} = 3T_e + 2T_i \, . \quad (6)$$

In #82237, the maximum T_e from LP measurements is not higher than ~ 30 eV and if it is assumed that $T_i \approx T_e$, $E_{i,inter-ELM}$ should not exceed ~ 150 eV. For simplification, it is assumed in this work that both species of interest, namely D^+ and Be^{2+}, have the same $E_{i,max}$ and $E_{i,inter-ELM}$.

3. Impact angle distribution in ELM and inter-ELM conditions

The W sputtering yield due to D^+ and Be^{2+} ($Y_{D/W}$ and $Y_{Be/W}$ respectively) that we are trying to evaluate here also depend on the ion impact angle (θ_i), as shown on Fig. 6. Since the variation of $Y_{D/W}$ and $Y_{Be/W}$ with θ_i can be up to an order of magnitude, it is crucial to estimate the distribution of this angle in ELM and inter-ELM conditions for D^+ and Be^{2+}.

In inter-ELM conditions, $Y_{D/W}$ is neglected and only $Y_{Be/W}$ is considered. According to kinetic analytical calculations [12] considering a target plasma close to experimental inter-ELM conditions with Maxwellian distribution of energy for ions and electrons, T_e = T_i = 30 eV, electron density n_e = 10^{19} m^{-3}, magnetic field B = 3T and $\theta_\perp$ = 3°, the distribution of inter-ELM θ_i should reach its maximum around ~ 20º for Be^{2+}, see Fig. 7.

During ELMs, despite $E_{i,max}$ ~ 3 keV in average in JET-ILW, the target T_e remains close to the inter-ELMs level. As in the example shown in Fig. 3, T_e in #82237 should not be above ~ 30 eV in ELMy conditions. However, the higher number of ionization per D_α photon required to match LP ion flux measurements in [5], when the recycling coefficient is assumed to be around unity, is an evidence of higher n_e of the order of ~ 10^{20} m^{-3} during ELMs. Also, according to the "Free-Streaming" model [8-10], the high energy ELMy ions have a very narrow energy distribution when they reach the target. Kinetic analytical calculations [12] with these conditions and the same B and $\theta_\perp$ as the inter-ELM case, yield a distribution of θ_i reaching its maximum around 22° for D^+ and 25° for Be^{2+}, see Fig. 8a and b.

The small difference between ELM and inter-ELM conditions in terms of θ_i distribution suggests that the latter is more influenced by the ion gyration than the sheath effects. Indeed, if the electric field of the Debye sheath had a strong effect, the θ_i distribution should be much closer to 90°. As shown in Fig. 6, shallow θ_i around ~ 20° at high $E_{i,max}$ are associated with significant W sputtering yields.

4. Estimation of W impurity sputtering in ELM and inter-ELM conditions

Given the θ_i distribution obtained previously in inter-ELM, the average $Y_{Be/W}$ should be around ~ 0.01 in these conditions, according to Fig. 6. During ELMs, the average W sputtering yield due to Be^{2+} and D^+ should reach $Y_{Be/W}$ ~ 0.6 and $Y_{D/W}$ ~ 0.03 respectively, considering the ELMy θ_i distributions previously calculated. Since the Be concentration in the impinging ion flux is expected to be around ~ 0.5 % in unseeded JET-ILW Type I ELMy H-mode experiments [4], all the required parameters are known to estimate the W sputtering source on the OT by using LP J_{sat} measurements.

The W sputtering flux due to the cumulated effect of D^+ and Be^{2+} in ELM and inter-ELM has already been estimated in [6], using W I spectroscopy. However, this method relies on the assumption that the number of ionizations per emitted photon from W I has a constant value of ~ 20, as suggested in [13]. In reality, this quantity is T_e and possibly n_e dependent and the conditions between ELM and inter-ELM can change significantly. Thus, an uncertainty on the number of ionizations per photon and consequently on the estimated W sputtering source remains. Moreover, the mirror-link system viewing the OT and analyzing the light in three wavelength ranges with Czerney–Turner spectrometers [14] has a time resolution limited to 40 ms which is slow compared to the typical ~ 1 ms duration of the Type I ELM events studied here. Typical measurements made during ELMy H-mode discharges with this diagnostic in JET-ILW cumulate light from several ELMs and inter-ELMs and only very slow Type I ELMs like in #82237 can be isolated once or twice over the duration of the experiment (~ 5 s). Thus, these measurements cannot be coherently averaged and ELMs must be very similar all along the discharge in order to consider ELMy W I spectroscopy data representative of a typical ELM.

Since LP J_{sat} measurements are accurate during ELMs and inter-ELMs [5], independent estimation of the W sputtering source based on this signal provides an opportunity for a comparison with the W I spectroscopy technique. This new method involving the LP has the advantage of not relying on any assumptions on atomic physics and benefits from the high time resolution of the J_{sat} signal (~ 10 μs) required during ELMs and allowing coherent averaging like in Fig. 5b. However, it assumes that relation (4) is true for any Type I ELMy H-mode and that $E_{i,max}$ remains constant at ~ 3 keV over the entire OT for a duration of Δt_{ELM} ~ 1 ms in average (duration of T_e^{ped} drop in Fig. 5a) in each ELM event.

The W sputtering flux densities $\Gamma_{W,ELM}$ and $\Gamma_{W,inter\text{-}ELM}$ in $m^{-2}.s^{-1}$ due to ELM and inter-ELM ion flux respectively have been calculated as follows:

$$\Gamma_{W,ELM} \approx \frac{J_{sat,ELM}}{e} \sin(\theta_\perp)\left(Y_{D/W}(3k\,\mathrm{eV}, 22°) + 0.005 Y_{Be/W}(3k\,\mathrm{eV}, 25°)\right)\Delta t_{ELM}\, f_{ELM}\,, \tag{7}$$

$$\Gamma_{W,\text{inter}-ELM} \approx \frac{0.005 J_{sat,\text{inter}-ELM}}{e} \sin(\theta_{\perp}) Y_{Be/W}(150\,\text{eV}, 20°), \quad (8)$$

with $J_{sat,ELM}$, $J_{sat,inter\text{-}ELM}$ and f_{ELM} the ELMy J_{sat}, the inter-ELM J_{sat} both measured in A.m^{-2} by the LP and the ELM frequency in s^{-1}. Thus, the ELM and inter-ELM experimental perpendicular ion flux density profiles shown on Fig. 9a and obtained from the LP allow the estimated $\Gamma_{W,ELM}$ and $\Gamma_{W,inter\text{-}ELM}$ profiles shown on Fig. 9b for the discharge #82237.

Previous $\Gamma_{W,ELM}$ and $\Gamma_{W,inter\text{-}ELM}$ profiles deduced from W I spectroscopy [6] are also shown on Fig. 9b for comparison. Both flux density profiles have less than 30 % discrepancy in magnitude. OT W sputtering fluence per ELM and OT inter-ELM W sputtering flux from both methods are provided in Table 1. Discrepancies between integrated amounts obtained from both methods of measurements do not exceed a factor ~ 2 during ELMs and are below 10 % in inter-ELM. The order of magnitude of the OT W source in discharge #82237 with ~ 10^{19} W atoms per ELM and ~ 10^{19} s^{-1} W flux during inter-ELM is confirm by both techniques. Therefore, given the assumptions and approximations made to get these estimations, this level of agreement is reasonably good.

However, the maxima of both profiles do not match radially. The peaks of the ELM and inter-ELM W flux density profiles deduced from W I spectroscopy are shifted by ~ 5 cm inboard compared to the peaks from LP measurements. It is possible that W neutrals responsible for W I radiation lines can escape the SOL through the Private Flux Region (PFR) and re-enter the SOL further away from the strike point and the target. On the other hand, LP measurements are real target data not subject to such effects.

The comparison of W sputtering flux density profiles due to ELMy D^+ and Be^{2+} on the OT shown on Fig. 9c indicate that D^+ during ELM is the main contributor to the W source in JET-ILW unseeded Type I ELMy H-modes. Indeed, in these conditions, the Be^{2+} contribution is lower by an order of magnitude because of the small Be concentration in the impinging ion flux of ~ 0.5 %, see [4].

5. Conclusions

Mitigated Type I ELMs, with ΔW = 0.7 MJ of energy, expected in ITER for the baseline scenario with 500 MW of fusion power and Q = 10, are expected to be the dominant source of W in ITER. Very small amounts of W will be tolerated in the plasma core to ensure good performance [2]. Therefore, it is critical to estimate accurately the W source due to ELM and inter-ELM sputtering.

Previous studies [5] coupling IR and LP measurements in JET-ILW H-mode experiments with ITER relevant ELM energy drop have shown that $E_{i,max}$ during ELMs is in the range 2 – 4 keV for D^+ and has a simple linear dependence on $T_{e,\max}^{ped}$. Saturation of the ion current measured by the LP during ELMs is possible thanks to the surprisingly low T_e of the order of the inter-ELM conditions which is consistent with the predictions from the “Free-Streaming” model for the description of parallel ELM transport [8-10]. According to the model, electrons have to transfer most of their parallel energy to the ions on their way to the target to maintain the quasi-neutrality of the ELM filaments. The remaining low energy ELMy electrons are therefore easy to repel by the biased LP at the targets, making the ion flux measurement possible during ELMs.

Consequently, providing that the distribution of θ_i is known, ECE T_e^{ped} measurements and LP J_{sat} measurements can be used to estimate the W sputtering source due to D^+ and Be^{2+} in inter-ELM and ELM conditions. The unseeded Type I ELMy H-mode discharge #82237, where the W sputtering source has already been estimated using W I spectroscopy [6], has been used here for this purpose.

W sputtering flux density profiles obtained from W I spectroscopy and LP measurements differ by less than ~ 30 % in magnitude an confirm the order of magnitude of the W sputtering source with roughly ~ 10^{19} atoms per ELM and ~ 10^{19} atoms.s^{-1} in inter-ELM in #82237. Since the ELM frequency in this discharge is ~ 10 Hz, the ELM W source is dominant by an order of magnitude over the inter-ELM W source.

However, the peaks of the ELM and inter-ELM W flux density profiles deduced from W I spectroscopy are shifted by ~ 5 cm inboard compared to the peaks from LP measurements. W neutral leakage in the PFR leading to W I radiation further away from the strike point and the target may be involved.

Comparison of W sputtering flux density profiles due to ELMy D^+ and Be^{2+} on the OT indicates that D^+ during ELM is the main contributor to the W source. The Be^{2+} contribution is lower by an order of magnitude because of the small Be concentration in the impinging ion flux of ~ 0.5 % in JET-ILW unseeded Type I ELMy H-modes, see [4].

Given the uncertainties linked to the assumption made on the number of ionizations per photon in W I spectroscopy and the approximations that $E_{i,max}$ remains constant at ~ 3 keV over the entire OT during each ELM event, OT W sputtering source estimates from both methods are in reasonably good agreement.

The very high time resolution (~ 10 μs) of the LP J_{sat} measurements is a strong advantage which should allow the use of this new technique to estimate the W sputtering source in other conditions where ELMs are usually too fast for W I spectroscopy like seeded H-mode discharges or ELM pacing experiments.

Acknowledgments

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Table captions:

Table 1 ELMy W sputtering fluence and inter-ELM W sputtering flux on OT

Figure captions:

Fig. 1 Left: positions of LP and IR camera line of sight in JET-ILW divertor with the different Tile numbers. Right: magnetic equilibrium for #82237 and 84782 at 13 s and position of W I, D_α spectroscopy and ECE lines of sight in JET-ILW main chamber.

Fig. 2 Curves of W sputtering yields at normal incidence due to Be in red, helium (He) in green, tritium (T) in magenta and deuterium (D) in blue.

Fig. 3 I-V characteristic reconstruction obtained by cumulating I and V measurements taken by the LP in the peak ELMy ion flux of each ELM event over the discharge #84782.

Fig. 4 $max(E_i+E_e)$/5.23 in function of $T_{e,\max}^{ped}$ from coherent averaging of LP, IR and ECE measurements obtained in the discharges listed on the right.

Fig. 5 Coherently averaged (a) T_e^{ped} with standard deviation measured by ECE and (b) strike point J_{sat} over the cumulated ELM cycles of #82237.

Fig. 6 θ_i dependence of W sputtering yield due to D^+ (blue curve) and Be^{2+} (red curves) for E_i = 150 eV (dashed) and E_i = 3000 eV (plain).

Fig. 7 Distribution of Be^{2+} OT impact angle given by analytical kinetic calculations [11] with $T_e = T_i$ = 30 eV, $n_e \sim 10^{19}$ m^{-3}, $\theta_\perp$ = 3 º and B = 3 T.

Fig. 8 Distribution of (a) D^+ and (b) Be^{2+} OT impact angle given by analytical kinetic calculations [11] with T_e = 30 eV, E_i = 3 keV, $n_e = 10^{20}$ m^{-3}, $\theta_\perp$ = 3 º and B = 3 T.

Fig. 9 (a) OT perpendicular ion flux density profile from LP, (b) OT total W sputtering flux density profile from WI spectroscopy (dashed curves) and LP (plain curves) due to ELM (red curves) and inter-ELM (blue curves) and (c) contribution from D^+ (plain curve) and Be^{2+} (dashed curve) to OT W sputtering flux density profile.

Method	W I spectroscopy	LP
ELMy W fluence (atoms.ELM^{-1})	5.7×10^{18}	11×10^{18}
Inter-ELM W flux (atoms.s^{-1})	6.3×10^{18}	5.9×10^{18}

Table 1

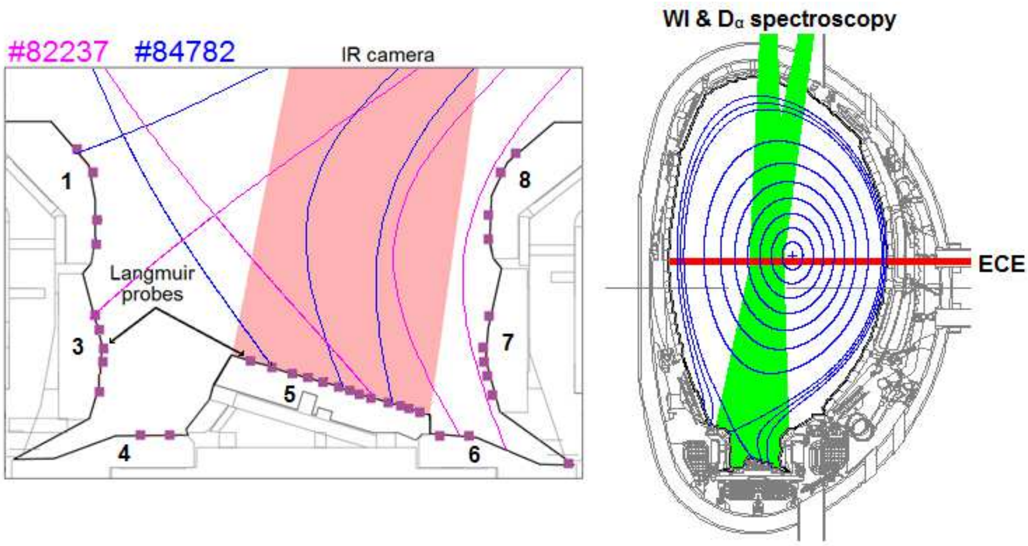
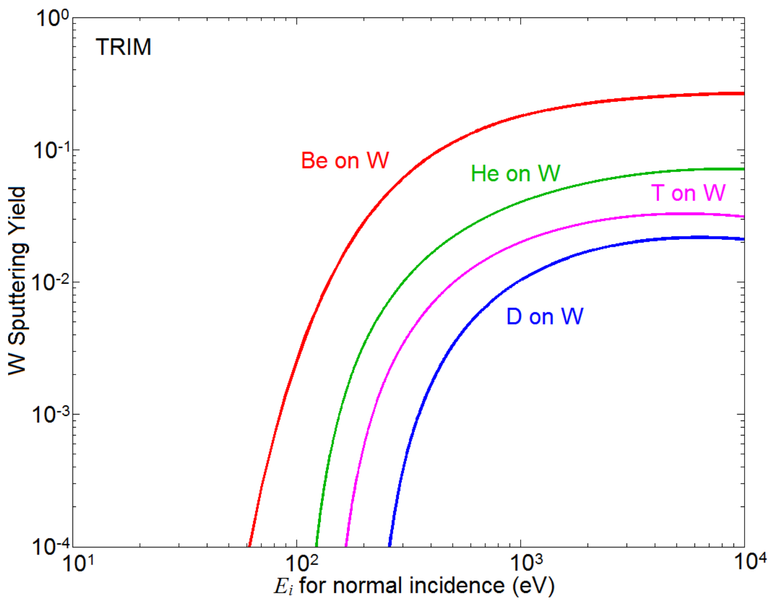
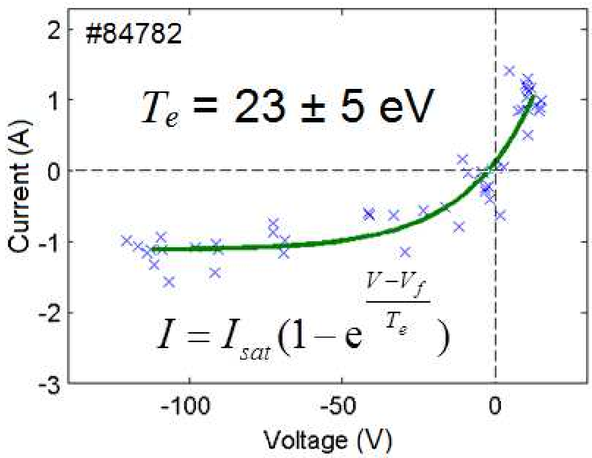

#82237
#84782
IR camera
1
3
Langmuir probes
4
5
6
7
8
WI & Dα spectroscopy
ECE

Figure 1



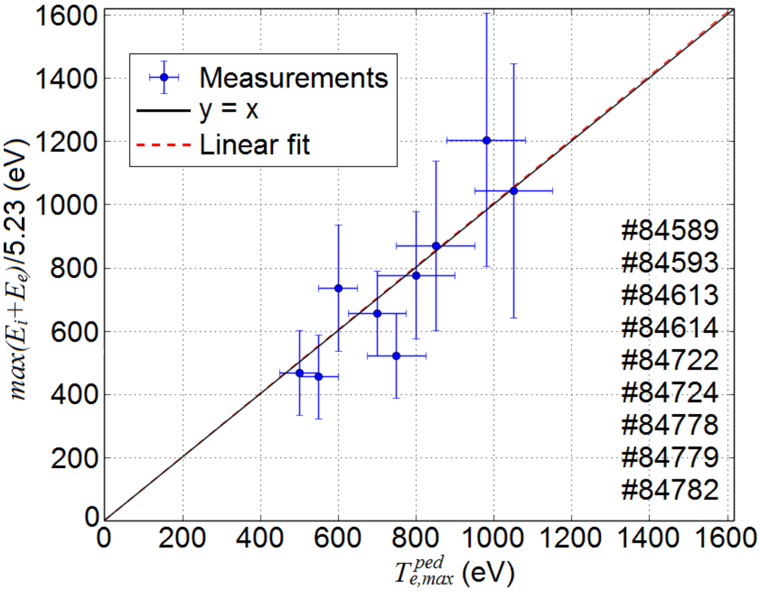
TRIM
Be on W
He on W
T on W
D on W
W Sputtering Yield
E_i for normal incidence (eV)

Figure 2



#84782
T_e = 23 ± 5 eV
$I = I_{sat}(1 - e^{\frac{V - V_f}{T_e}})$
Current (A)
Voltage (V)
2
1
0
-1
-2
-3
-100
-50
0

Figure 3



Measurements
y = x
Linear fit
#84589
#84593
#84613
#84614
#84722
#84724
#84778
#84779
#84782
0
200
400
600
800
1000
1200
1400
1600
$T_{e,max}^{ped}$ (eV)
$max(E_i+E_e)$/5.23 (eV)

Figure 4

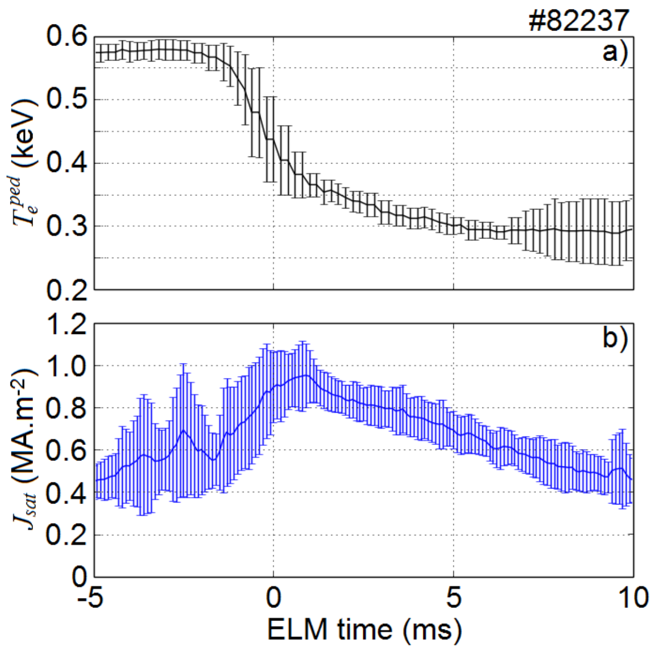
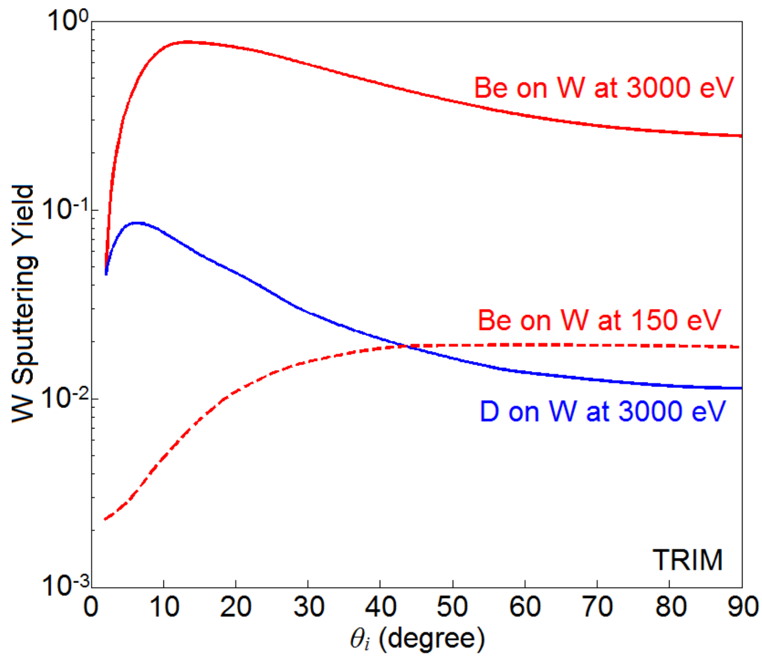
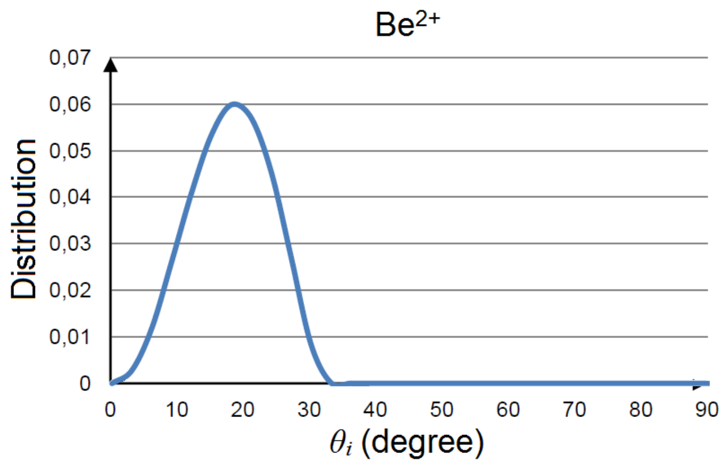

#82237
a)
b)
T_e^{ped} (keV)
J_{sat} (MA.m^{-2})
ELM time (ms)
0.6
0.5
0.4
0.3
0.2
1.2
1.0
0.8
0.6
0.4
0.2
0
-5
0
5
10

Figure 5



W Sputtering Yield
Be on W at 3000 eV
Be on W at 150 eV
D on W at 3000 eV
TRIM
10^0
10^{-1}
10^{-2}
10^{-3}
0 10 20 30 40 50 60 70 80 90
θ_i (degree)

Figure 6



Be2+
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0
Distribution
0
10
20
30
40
50
60
70
80
90
θi (degree)

Figure 7

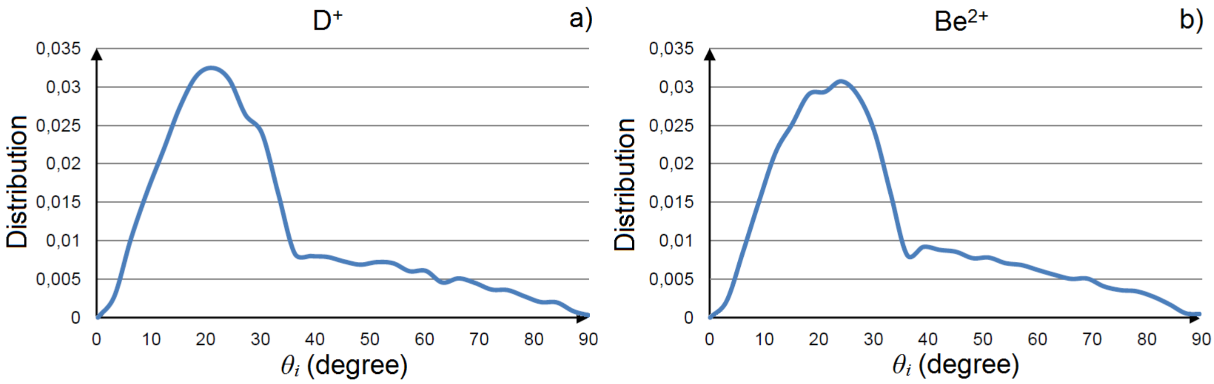
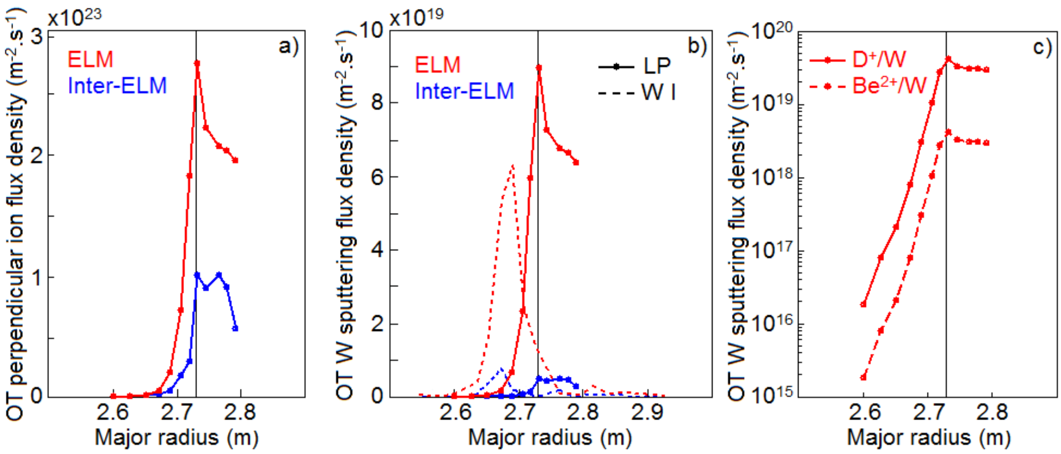

D+
a)
0,035
0,03
0,025
0,02
0,015
0,01
0,005
0
Distribution
0
10
20
30
40
50
60
70
80
90
θi (degree)
Be2+
b)
0,035
0,03
0,025
0,02
0,015
0,01
0,005
0
Distribution
0
10
20
30
40
50
60
70
80
90
θi (degree)

Figure8



x10^{23}
a)
ELM
Inter-ELM
OT perpendicular ion flux density (m^{-2}.s^{-1})
Major radius (m)
x10^{19}
b)
ELM
Inter-ELM
LP
W I
OT W sputtering flux density (m^{-2}.s^{-1})
Major radius (m)
c)
D$^+$/W
Be^{2+}/W
OT W sputtering flux density (m^{-2}.s^{-1})
Major radius (m)

Figure 9