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An analytical expression for ion velocities at the wall including the sheath electric field and surface biasing for erosion modeling at JET ILW

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Abstract. For simulation of the plasma-facing components' erosion in fusion experiments, an analytical expression for the ion velocity just before the surface impact including the local electric field and an optional surface biasing effect is presented. Energy and angular impact distributions and the resulting effective sputtering yields were produced for several experimental scenarios at JET ILW mostly involving PFCs exposed to an oblique magnetic field. The analytic solution has been applied as an improvement to earlier ERO modeling of localized, Be outer limiter, RF-enhanced erosion, modulated by toggling of a remote, magnetically connected ICRH antenna. The effective W sputtering yields due to D and Be ion impact in Type-I and Type-III ELMs and inter-ELM conditions were also estimated using the analytical approach and benchmarked by the spectroscopy.

Key words: Plasma-surface interaction, JET, ITER-like wall, beryllium, erosion, oblique magnetic field, electric field, ELM.

1. Introduction

Modeling is a key for understanding observations at the recently installed JET ITER-like wall (ILW) and extrapolation of the obtained knowledge to ITER. The JET-ITER-Like-Wall (JET-ILW) [1] comprises a tungsten (W) divertor and beryllium (Be) main chamber wall thus matching the material configuration planned for ITER. Estimating plasma facing components (PFC) sputtering by plasma ions is an important issue for ITER as erosion determines the life time of PFC, impacts on the tritium retention by co-deposition with Be and leads to an increase of impurities in core plasma and consequent reduction in fusion plasma performance. For correct calculation of the sputtering yields for PFCs in the presence of an oblique magnetic field the accurate expression for the sheath electric field must be included.

Earlier it was found that the ICRH (Ion Cyclotron Resonant Heating) enhances erosion at PFCs connected to active antennas [2] Electrical effects induced near the wall by the ICRH antenna can be treated as an additional biasing. For correct calculation of the sputtering yields for PFCs the suggested in [3] analytical expression (AE) for the ion velocity at the surface is modified to take into account the surface biasing (SB) effect. Results are presented in the current paper. The AE have been applied as an improvement to the earlier ERO modeling [2] of RF-enhanced localized erosion at a JET outboard Be limiter magnetically connected to a remote ICRH antenna. By including this effect as an additional negative SB of up to 200V [4] and taking into account an oblique magnetic field we obtained an increase of the sputtering yield by a factor of 2-3. The comparison of the simulated RF-enhanced Be emission with experimental observations and the earlier ERO simulations is presented. Furthermore, a correlation between Be light emission close to the inner wall guard limiter at the mid-plane (solid Be, octant 7X) and the ICRH antenna 'D' is reported. The possible scenarios for this effect are discussed.

W sputtering from divertor plates during ELMs is expected to be the dominant impurity source. The analytical procedure for reproduction of initial distribution function of ion velocity in ELM basing on the "Free-Streaming" model [5] and experimental results is suggested. The linear dependence of the ELM target ion impact energy on the pedestal electron temperature measured in Type-I ELM discharges [6] was extrapolated to lower pedestal temperatures, which correspond to the occurrence of Type-III ELMs. The W sputtering flux due to D^+ and Be^{2+} ion impact in Type-I and Type-III ELMs and inter-ELM conditions were estimated using the analytic approach [3] and benchmarked by the spectroscopy.

2. The analytical expression for the ion motion in the sheath taking into account SB

For modeling of the erosion of the PFC surfaces with additional surface biasing we take into account the local electric field depending on the surface biasing in the AE for the ion velocity just before the surface impact [3]:

$$\begin{cases} \Delta t_k = \dfrac{-Vy_k - \sqrt{Vy_k^{\,2} - 2(y_k - y_{k+1})(\eta E(y_k) - Vx_k \omega \sin\alpha)}}{(\eta E(y_k) - Vx_k \omega \sin\alpha)} \\ Vx_{k+1} = Vx_k + \omega \Delta t_k (Vy_k \cdot \sin\alpha + Vz_k \cdot \cos\alpha) \\ Vy_{k+1} = Vy_k - \eta \cdot E(y_k) \cdot (\Delta t_k) - \omega \cdot \Delta t_k \cdot Vx_k \sin\alpha \\ Vz_{k+1} = Vz_k - Vx_k \cos\alpha \cdot \omega \Delta t_k \end{cases} \tag{1}$$

where $\eta = q/m$, $\omega = qB/Mc$, Δt is a particle transit time in a sub-layer, y is the distance from the surface, y_k is a sub-layer coordinate, α is an angle between the magnetic field and the surface normal. The sheath electric field $E(y)$ is calculated as:

$$E(y) = \frac{kT_e}{qr_d} Q \left(a + 2 \cdot c \cdot \frac{y}{r_d} \right) \exp(-a \cdot \frac{y}{r_d} - c \cdot \left(\frac{y}{r_d} \right)^2) \tag{2}$$

where parameters a, Q [2], c [7] depend on the dimensionless target potential ψ_t influenced by the value of surface biasing as following:

$$\psi_t = \frac{e(U_t - U_{pl})}{kT_e} = \frac{e(U_{sf})}{kT_e} - \ln\left(\frac{S_t}{S_t + S_{rs}} + \frac{S_{rs}}{S_t + S_{rs}} \exp\left(-\frac{e\Delta U_{bias}}{kT_e} \right)\right) \tag{3}$$

where S_t, S_{rs} are the areas of the target and the return surface, U_{pl} is the plasma potential at the sheath/presheath boundary, U_{sf} is surface floating potential relative to U_{pl} ([8] (2.60)), U_t is the target potential, U_{rs} is return surface potential, $\Delta U_{bias} = U_t - U_{rs}$ is a negative surface biasing. In figure 1 the scheme of potentials is presented. As the area of return surface is usually much larger than that of the target ($S_t \langle\langle S_{rs}$), the return surface potential remains equal to the floating potential and the target potential in the presence of SB can be calculated as:

$$\frac{e(U_t - U_{pl})}{k \cdot T_e} = \frac{e(U_{sf})}{kT_e} + \frac{e\Delta U_{bias}}{kT_e}, \tag{4}$$

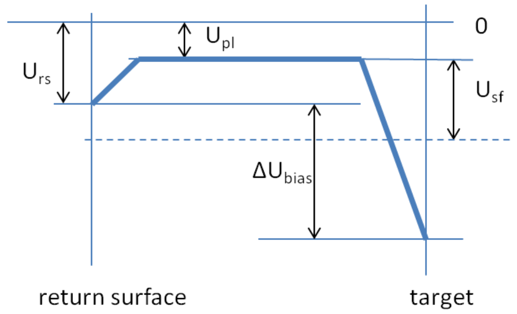

Figure 1. Scheme of potentials in the presence of the applied surface biasing

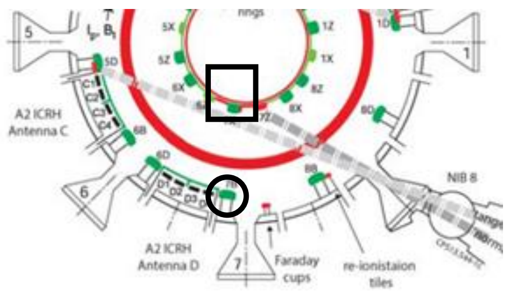

Figure 2. The JET top view with the considered Be limiters

3. Simulation of enhanced by RF-emission erosion of JET Be limiter

For improving earlier ERO modelling [2] of localized, Be outer limiter, RF-enhanced erosion, modulated by toggling of the remote ICRH antenna ‘C’ the AE given above has been applied. The considered antenna and the limiter (solid Be, octant 7B, defined by a circle) are shown in figure 2. This effect has been associated with self-biasing by the intense RF electric fields at the corners of the antenna magnetically connected to the affected limiter. In modeling an additional negative SB has been applied up to -200V in accordance with the previous measurements [4]. Figure 3 presents the sputtering coefficients in the assumption of the low-recycling plasma scenario calculated with the AE (α=85.8°, B=1.9T, n=10^{12} cm^{-3}, T_i= T_e =5eV) and obtained in the earlier simulations which did not account for the influence of the oblique magnetic field [2]. These sputtering coefficients were calculated assuming 50% D concentration in the surface interaction layer of the Be limiter (‘ERO-min’) [9]. For comparison the case of a pure Be target (‘ERO-max’) was also calculated with the AE. It is shown that an additional negative surface biasing more than -50V can explain the observed 2-3 fold increase in erosion (characterised by Be spectroscopy) in ‘ERO-min’ assumption. This provides additional confidence in ‘ERO-min’ fit for the physical sputtering yields for the plasma-wetted areas of PFCs. The updated model leads to an increased effect, which matches the experiment, due to the properly treated angular factor in the sputtering yield.

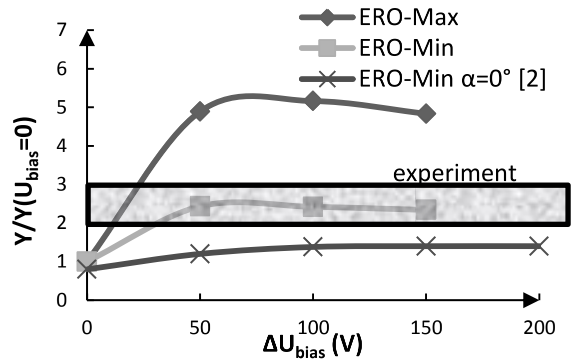

Figure 3. Comparison of the simulation with AE for different surface content, the earlier ERO modeling (ERO-min for normal incidence) and experimental observations (rectangle) of Be limiter erosion (α=85.8°, B=1.9T, n=10^{12} cm^{-3}, T_i= T_e =5eV)

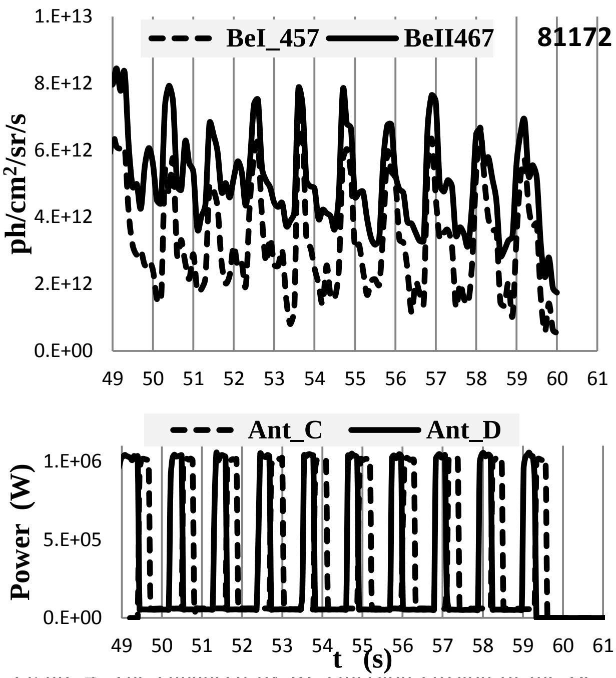

Figure 4. The enhanced by RF-emission erosion of the Be inner wall guard limiter at the mid-plane (solid Be, octant 7X) modulated by toggling of ICRH antenna ‘D’

Similarly to the correlation between Be light emission close to the outer wall guard limiter (7B) and the ICRH antenna ‘C’ we found a correlation between Be light emission close to the inner wall guard limiter at the mid-plane (solid Be, octant 7X) and the ICRH antenna ‘D’ which is presented in Figure 4. The version of the direct magnetic field connection between antenna and the limiter was checked and declined since multiple tests with a field line tracing program based on EFIT show that a narrow region in front of ICRH antenna connects magnetically to a very broad poloidal and toroidal region at the inner wall. The most probable scenario of this effect is following: more RF-power concentrates in the octant close to the active antenna, the non-absorbed part of RF-power propagating towards the inner wall induces the electric field near inner limiter, opposite the antenna, that leads to sputtering increase similarly to the effect at the outer wall limiter. It should be noted that the value of emission intensity of eroded Be at the inner wall (~ 7 - 8·10^{12} ph/cm^2/sr/s) is approximately the same as at the outer wall (~ 5 - 6·10^{12} ph/cm^2/sr/s), although the intensity of RF fields might be different. In both cases the ICRH antenna operation provides 2-3 times sputtering increase. The detailed study of this effect is an issue for further investigation.

4. Modelling of the parallel transport of ELM filaments and W sputtering yields in ELMs and inter-ELM conditions

The new method of estimating the impact energy of deuterium ions (D^+) at a horizontal outer divertor target (OT) using coupled infrared thermography and Langmuir Probe (LP) measurements in JET-ILW unseeded H-mode experiments with ITER relevant ELM energy drop is presented in work [6]. It has been established that the ELMy target ion impact energy has a simple linear dependence on the pedestal electron temperature ($T_{e,\max}^{ped}$) measured by Electron Cyclotron Emission (ECE) (see Figure 5) and that the electron temperature near the surface during ELM is low ($T_e \sim 30$ eV). In [10] the W sputtering flux from divertor targets in ELM and inter-ELM conditions was estimated using only the energy in the maximum of the power flux. However, for more detailed estimation the energy and angular distribution of incident ions should be taken into account, therefore it is necessary to determine the initial distribution of ion velocities in ELM.

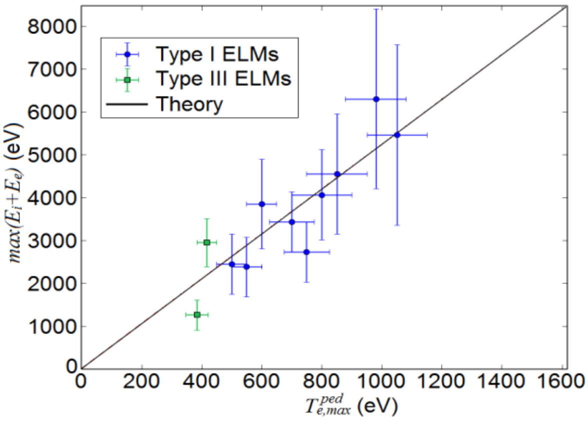

Figure 5. The ELMy target ion impact energy dependence on the pedestal electron temperature ($T_{e,\max}^{ped}$) in Type I and Type III ELM discharges

Firstly the ions were launched with the modified Maxwell velocity distribution (satisfying the generalized Bohm criterion [11]) with $T_i = \gamma \cdot T_{e,\max}^{ped}$, where parameter γ was selected using two conditions: 1) the resulting profiles of particle and power flux density at the surface should coincide with the experimental profiles of LP ion saturation current (J_{sat}) and perpendicular heat flux density ($q_\perp$); 2) the incident ion energy corresponding to the maximum of the heat flux density ($q_\perp$) should match the linear dependence on the $T_{e,\max}^{ped}$:

$$E_{i,\max} = (\alpha - 1) \cdot T_{e,\max}^{ped} = 4.23 \cdot T_{e,\max}^{ped} \tag{5}$$

where $\alpha = 5.23$ [6].

The resulting profile of ELM particle flux at the surface is obtained assuming even ion motion that is similar to the “Free-Streaming” model [5] and is also confirmed by low T_e in the sheath in the experiment [6]. For Type I ELM discharge #82237 with $T_{e,\max}^{ped}$ = 600 eV the parameter γ = 0.7. In figures 6 and 7 the comparison of the modelled and experimental normalized J_{sat} profiles and obtained incident ion energy are presented. The duration of ELM pulse at the surface is nearly 5 ms. The obtained incident ion energy corresponding to the maximum of the heat flux equals to 2.7 keV that corresponds to the linear dependence (5) for $T_{e,\max}^{ped}$ = 600 eV. Therefore, using the described above initial ion velocity distribution function in ELM we can calculate the ion impact angle and energy distributions and estimate the W sputtering yields due to D^+ and Be^{2+} ($Y_{D/W}$ and $Y_{Be/W}$) during ELM.

In inter-ELM conditions, $Y_{D/W}$ is neglected and only sputtering by Be^+ ions ($Y_{Be/W}$) is considered [12]. However, ELMy D^+ ions have sufficient energy to sputter W and D^+ is the main contributor to the W source [10]. Using kinetic analytical expressions [3] and the initial velocity distribution presented above the energy and angular distributions of impact ions are obtained. The respective average W sputtering yield calculated using the Eckstein formula [13] should be around ~ 0.11 in inter-ELM case for the following plasma parameters (B = 3 T, n_e = 10^{13} cm^{-3}, T_i = T_e = 23 eV, α = 87°). During ELMs, the average W sputtering yield due to Be^{2+} and D^+ should reach $Y_{Be/W}$ ~ 0.36 and $Y_{D/W}$ ~ 0.009 respectively (B = 3T, n_e = 10^{14} cm^{-3}, α = 87°, $T_{e,\max}^{ped}$ = 0.6 keV, $T_{i\,ELM} = \gamma \cdot T_{e,\max}^{ped}$). 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 [12]. The W sputtering fluence $N_{W,ELM}$ during ELM ($\Delta t_{ELM} = 5\,ms$) and inter-ELM W sputtering flux $\Gamma_{W,inter\text{-}ELM}$ have been calculated as follows:

$$N_{W,ELM} \approx \frac{J_{sat,ELM} - J_{sat,\text{inter}ELM}}{e} \cos\alpha \cdot (Y_{D/W} + 0.005 \cdot Y_{Be/W}) \Delta t_{ELM} \tag{6}$$

$$\Gamma_{W,\text{inter}-ELM} \approx \frac{J_{sat,\text{inter}\,ELM}}{e} \cos\alpha \cdot 0.005 \cdot Y_{Be/W} \tag{7}$$

where $J_{sat,ELM} = 0.84 MA/m^2, J_{sat,\text{inter}ELM} = 0.3 MA/m^2, \alpha = 87^o$ were determined from LP measurements for the discharge #82237 [10].

Finally, OT W sputtering sources retrieved from LP measurements and analytic approach have been compared to similar estimates made with W I spectroscopy [14]. OT W sputtering fluence per ELM and OT inter-ELM W sputtering flux from both methods are provided in Table 1. Discrepancies between amounts obtained from both methods do not exceed a factor ~ 2 during ELM and in inter-ELM. Therefore, the assumptions and approximations made in LP- Analytic approach allow obtaining correct estimates of W sputtering. One can see that the amount of sputtered W during ELM is the same as during 1s of the tokamak operation in inter-ELM. Therefore in the presence of analyzed ELMs ($\Delta t_{ELM} = 5\,ms$, f = 10 Hz) the W sputtering flux increases 10 times in comparison to the inter-ELM flux.

The W sputtering influx during Type – III ELM discharges (#81881, #81883) was analyzed similarly to Type-I ELM discharges. In figure 5 it is shown that Type – III ELM discharges also correspond to the linear dependence of the ELM target ion impact energy on the pedestal electron temperature. The calculations described above were also carried out for the discharge #81881 (B = 2.4 T, α = 88°, $T_{e,\max}^{ped}$ = 450eV, f = 1250 Hz). The W sputtering fluence during ELM ($\Delta t_{ELM} = 0.35\,ms$) and inter-ELM W sputtering flux is 4.2·10^{14} atoms/ELM and 5.2·10^{16} atoms/s respectively. So, in the presence of such ELMs ($\Delta t_{ELM} = 0.35\,ms$, f = 1250 Hz) the W sputtering intensity increases 10 times in comparison to the inter-ELM conditions. Thus, the coupled analytic expressions and LP measurements allow estimating the W sputtering fluences in unseeded JET-ILW Type I and Type III ELMy H-mode experiments.

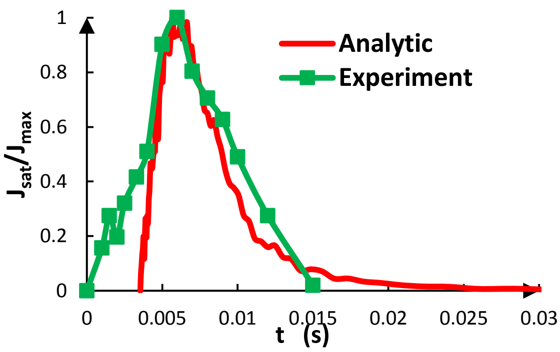

Figure 6. The modelled and experimental normalized profiles of ion saturation current during ELM ($T_{e,\max}^{ped}$ = 0.6 keV, γ=0.7).

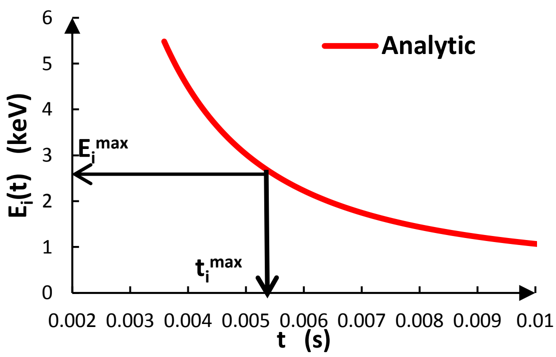

Figure 7. Time dependence of the ELMy target ion impact energy obtained by the LP – Analytic approach ($T_{e,\max}^{ped}$ = 0.6 keV).

Method	W I spectroscopy [14]	LP - Analytic
ELMy W fluence (atoms/ElM)	$5.7\cdot10^{18}$	$9.8\cdot10^{18}$
Inter-ELM W flux (atoms/s)	$6.3\cdot10^{18}$	10^{19}
ELMy flux / Inter-ELM flux	10	10.8

Table 1. OT ELMy W sputtering fluence and OT inter-ELM W sputtering flux in the discharge #82237

5. Conclusions

An analytical expression for the ion velocity just before the surface impact including the local electric field and an optional surface biasing effect is presented in this work. The AE has been applied for improving earlier estimates [2] of RF-enhanced localized erosion at a JET outboard Be limiter magnetically connected to a remote ICRH antenna. It is shown that an additional negative surface bias more than 50V can explain the observed 2-3 fold increase in the local erosion (characterised by Be spectroscopy), assuming 50% D concentration in the surface interaction layer. The updated model leads to an increased effect, which matches the experiment, due to the properly treated angular factor in the sputtering yield. This studied outboard limiter effect is understood as a result of self-biasing at one flux tube extremity by the intense RF fields at the corners in the “near field region” of the antenna connected at the opposite flux tube extremity.

RF-enhanced Be spectral emission correlated with antenna ‘D’ toggling was also observed at a Be inner wall guard limiter. The remote limiter effect is possibly a similar self-biasing caused by residual RF fields not absorbed in the plasma core and reaching the inner-wall (therefore a “far-field” effect).

The analytical procedure for reproduction of initial ion velocity distribution in ELM basing on the “Free-Streaming” model and experimental results is suggested. OT W sputtering flux retrieved from LP measurements and analytic approach in Type I ELM and inter-ELM conditions is in good agreement with the estimates made with W I spectroscopy. The W sputtering fluxes during Type – III ELM discharges were analyzed using the suggested LP and analytic approach. It is shown that Type – III ELM discharges also correspond to the linear dependence of the ELM target ion impact energy on the pedestal electron temperature. In the presence of analyzed Type I and Type III ELMs the W sputtering flux increases 10 times in comparison to the inter-ELM conditions. Thus, ion flux density profiles obtained from the LP and analytical approach allow estimating the W sputtering fluences in unseeded JET-ILW Type I and Type III ELMy H-mode experiments.

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