DIVIMP tungsten erosion and transport simulations of an ELM cycle in a JET type-I ELMy H-mode plasma

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Abstract

Tungsten target erosion and transport has been simulated using the kinetic trace impurity code DIVIMP for a baseline type-I ELMy H-mode plasma in JET (JPN #73569, I_p=2.2MA, B_t=2.2T, δ = 0.2, P_{NBI}=13MW, n=0.75n_{GW}). DIVIMP calculations are performed on 2D background plasmas, dynamically evolved in time using the integrated code suite JINTRAC [1]. Tungsten sputtering due to deuterium, and small percentages of beryllium and neon are included. It is observed that tungsten source is dominated by physical sputtering due to deuterium at the ELM peak. In the simulation the ELM period leads to a burst of sputtering followed by a period of high divertor leakage, thus, effectively fuelling core plasma with tungsten. Thus, already without self-sputtering, an average tungsten core concentration approximately $0.8*10^{-5}$ is calculated. Including self-sputtering leads to a tungsten run-away process at the ELM peak significantly increasing the tungsten source prior and during the high-leakage period and subsequently leading to a more pessimistic estimate of tungsten core contamination.

Introduction

Divertor plasma-facing components (PFC) made of tungsten (W) are presently foreseen in ITER for the activated operational phase due to low fuel retention in bulk material, the absence of co-deposition, and low physical sputtering at semi-detached conditions [2]. Erosion of W due to physical sputtering by impurities and in particular during edge-localised modes (ELMs) may, however, lead to significant W contamination of the core plasma, strong radiation, and thus to reduction of plasma performance. Thus, W concentrations, c_W, in core below several 10^{-5} are required for reactor relevant plasmas [3].

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[*] See the Appendix of F. Romanelli et al., Proceedings of the 23rd IAEA FEC 2010, Daejeon, Korea

In this study, the kinetic code DIVIMP [4] is used to simulate W transport in an ELM period of a low triangular type-I ELMy H-mode JET plasma: JET shot #73569, I_p=2.2MA, B_t=2.2T, δ = 0.2, P_{NBI}=13MW, n=0.75n_{GW}. DIVIMP is utilized in a post-processing fashion on a series of 2D background plasmas, dynamically evolved in time using integrated code suite JINTRAC [1]. Three neon seeding cases of $1*10^{18}$/s, $1*10^{19}$/s, and $2*10^{19}$/s are studied [1]. W sputtering is calculated using Eckstein 1993 yield formula including sputtering due to deuterium, beryllium and neon [5], the charge states and densities of which are given by JINTRAC [1]. The W gross erosion rate given by DIVIMP is normalised to match the erosion rate given by JINTRAC. The prompt re-deposition of W is included. Self-sputtering is included in one additional simulation to estimate W self-sputtering during an ELM. ELMs are divided into 10 time slices, with a duration of 10^{-4}s per slice.

Results

The outer strike point (OSP) electron temperature, T_e, estimated by JINTRAC is 1000 eV at the ELM peak at t=0.1 ms and decays almost linearly to 200 eV by t=0.4 ms, for all the seeding cases (fig. 1a). The inner strike point (ISP) T_e estimated by JINTRAC is 800 – 1000 eV at the ELM peak at t=0.1 – 0.2 ms and decays to around 100 eV by t=0.4 ms. The OSP T_e does not drop as dramatically as the ISP T_e due to nearly constant OSP electron density, n_e, whereas at the ISP n_e rises by a factor of 8 within t=0.3 – 0.6 ms (fig. 1b).

The W erosion is strongly dominated by sputtering at the ELM peak (fig. 1c). Approximately 93 % of the tungsten erosion occurs within t=0.1 – 0.3 ms. Around 96 % of the total tungsten sputtering is caused by deuterium. The prompt re-deposition appears to lead to net erosion approximately one order of magnitude lower than the gross erosion. The leakage fraction, which is defined as the fraction of gross sputtered particles leaking to the core, is highest during t=0.2 – 0.6 ms, during which $f_{leak} \approx 6 - 10$ % (fig. 1d). The leakage peaks in the temperature decay period of the ELM where the temperature gradient in the SOL begins to form, but the collisional coupling to background plasma is still low to pull the W ions back to the plates due to friction. Even after the period of strong leakage, the leakage fraction remains comparably high in the order of 1 – 3 %, which is estimated to be lead to core c_W of the order of 10^{-5} in steady-state conditions with peak target T_e above 100 eV [6].

The average number of tungsten particles leaking into the core during one ELM can be calculated $N^{W}_{ELM}=\sum \langle \Gamma_W(t_i)\rangle \langle f_{leak}(t_i)\rangle t_i \approx 2.5*10^{15}$, where $\langle \Gamma_W(t_i)\rangle$ and $\langle f_{leak}(t_i)\rangle$ are calculated for each point $t_i \in [0.0ms - 0.9ms]$ by taking the average of the values at t_{i-1}, t_i, and t_{i+1}. At the start and end points of the time distribution the averages are taken over the values at t_i and $t_{i+/-1}$. Assuming Bohm-like tungsten core confinement time of $\tau_W \approx 1\mathrm{s}$ and an ELM frequency f_{ELM} = 15Hz, this gives an average tungsten density in the core $\langle n_w \rangle \approx N_W^{ELM} f_{ELM} \tau_W / V_c \approx 3.75 * 10^{14} / m^3$, where $V_c \approx 100\mathrm{m}^3$. Assuming a flat core profile with $n_e \approx 5*10^{19}/\mathrm{m}^3$, and T_e= 2keV gives estimates of core c_W approximately $0.8*10^{-5}$ and the tungsten core radiated power $P_{rad} \approx n_e n_W R_W V_{core} \approx 937\mathrm{kW} \approx 0.08*P_{NBI}$, where R_W (T_e=2keV) $\approx 5*10^{-31}\mathrm{Wm}^3$ [7]. The deduced c_W is just about the threshold of the acceptable contamination according to [2]. A lower limit of $\tau_W \approx 0.1\mathrm{s}$ is calculated and deduced in [1, 8], taking into account the flushing effect of ELMs. Hence, the lower limit for estimated P_{rad} would be in the range of 100kW and for the estimated c_W around 10^{-6}.

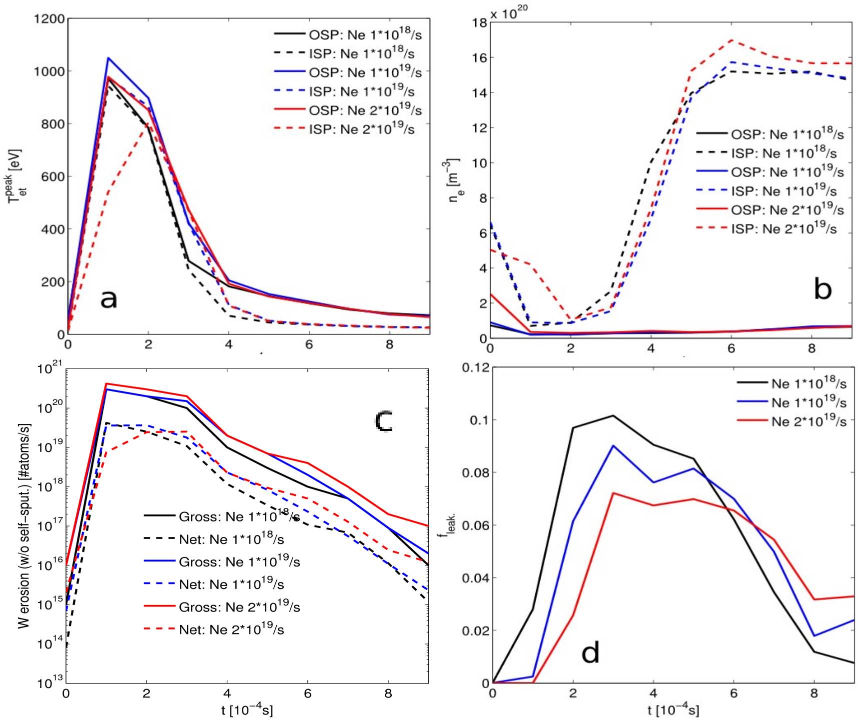

Figure 1. Electron temperature (a) and density (b) of the inner and outer strike point, W erosion current w/o self-sputtering included (c), and leakage fraction (d) as a function of time through the ELM.

In this estimate, the self-sputtering of tungsten has been ignored. An additional simulation reveals that the self-sputtering yield is above unity for t= 0.1 – 0.3 ms leading to a run-away process in the simulation. For the other time-slices the enhancement given by self-sputtering is around 10 – 30%. Due to the self-sputtering run-away, the tungsten source is significantly increased especially prior and during the period of strong leakage, thus giving more pessimistic estimates for the amount of core confined tungsten.

Conclusion & Discussion

Tungsten erosion and transport was simulated for an ELM-cycle of a baseline type-I ELMY H-mode JET plasma of low triangularity. The physical sputtering of tungsten was strongly dominated by sputtering due to deuterium at the ELM peak. Tungsten leakage is predicted to be high during the ELM decay period. Thus, the ELM period consist of a burst of sputtering followed by a period of strong divertor leakage effectively fuelling the core plasma with tungsten. Already without self-sputtering, the estimated $<c_W>$ in core is calculated approximately $0.8*10^{-5}$. The self-sputtering yield is above unity for the ELM peak heat flux, and around 20 – 30 % for the remainder of the ELM period. Thus, including self-sputtering leads to a run-away process in the simulation which would very likely lead to an increase of the c_W in core above the threshold of 10^{-5}. These calculations assumed Bohm-like core confinement time of 1s. Due to the flushing effect of ELMs, the core confinement time of tungsten can be significantly lower, the lower limit being around $\tau_W \approx 0.1\mathrm{s}$ according to [1, 8]. Thus, the estimates given here may be lowered by a factor 5 – 10 due to lower core confinement of W.

Strong leakage during the ELM decay period is mainly due to absence of a significant density induced target cooling. In case of stronger density increase, the divertor cooling after the ELM peak would probably be sufficient to suppress W leakage significantly. In addition, T_e of 1keV at the ELM peak as predicted by JINTRAC is extremely high leading to significant W source and leakage. These kinds of plasmas are probably not going to be executed with ILW because much lower target temperatures need to be achieved.

Acknowledgments

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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