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The interplay of controlling the power exhaust and the tungsten content in ITER

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ABSTRACT

The main elements defining the tungsten content of an ITER plasma, i.e. the gross erosion, the prompt redeposition and the transport in the H-mode edge transport barrier are reviewed and it is investigated, whether the low tungsten concentration limit in the core calls for additional control of the divertor parameters or the ELM energy beyond the requirements set by the power handling capability of the divertor. The outcome is rather positive, since no further control seems to be required mainly because of the favourable transport in the H-mode edge transport barrier which provokes hollow tungsten profiles in the edge transport barrier for the expected pedestal parameters.

1. Introduction

In ITER, a mitigation of the power exhaust is required to ensure a long lifetime of the tungsten divertor targets [1]. In addition, the tungsten concentration in the core plasma has to be controlled and kept below $\approx 3\times 10^{-5}$ to avoid large central radiation losses [2]. While it is rather intuitive, that a reduction of the power flux impinging onto the tungsten divertor also leads to a reduced W production, it is not obvious, whether W impurity control calls for additional requirements for the edge plasma conditions beyond those associated with divertor power load control.

The average power load must be kept below 5–10 MWm^{-2}, while during an Edge Localized Mode (ELM) with typical duration of 375–750 µs, the peak energy density onto the tungsten target must not exceed 0.5 MJm^{-2} [3]. The first material limit requires operation with a partially detached divertor plasma near the strike point. This regime can be achieved in plasmas with a high upstream electron density and by provoking large radiative losses in the scrape-off layer with controlled seeding of nitrogen or noble gases. Since the inter-ELM sputtering of W is dominated by the impinging impurities, the seeded impurities become the most important eroding species. $T_{e,\,div}$ below 10 eV is required to have sufficiently low sputter yields in the range of a few 10^{-4} as has been achieved in such impurity seeded scenarios on ASDEX Upgrade [4] and JET [5]. The ELMs lead to a large increase of the sputtered tungsten source and the temporally averaged source is actually dominated by ELM induced tungsten sputtering for such scenarios in present experiments. For the plasma contamination, only the net W source is important and for most of the relevant divertor plasma conditions, it is expected to be much smaller than the gross erosion due to a strong immediate redeposition of W close to its erosion location. As the net W flux appears at the plasma boundary, the diffusion coefficient and the drift velocity of W in the edge transport barrier of H-mode plasmas are the next key ingredients determining the core tungsten concentration. The impurity transport in this region is known to be well described by neoclassical transport theory [6], which leads to a strongly drift dominated transport due to the large charge stage of W. In present day tokamaks, the drift is inwardly directed and the ELM frequency must be sufficiently high to counteract the strong peaking between ELMs and flush out W from the pedestal region. In ITER, however, the drifts are most probably reversed and point radially outward, which causes a very beneficial tendency for the W density to decrease across the pedestal. When describing the ELM transport in the pedestal with a strong increase of the diffusion coefficient, the ELM rather leads to an increase of the W density in the core instead of a reduction as observed in present experiments.

In this paper, the main ingredients which define the W concentration in the confined plasma, will be discussed and results from integrated transport simulations, which use these elements, will be shown. In Section 2, the tungsten erosion in the divertor

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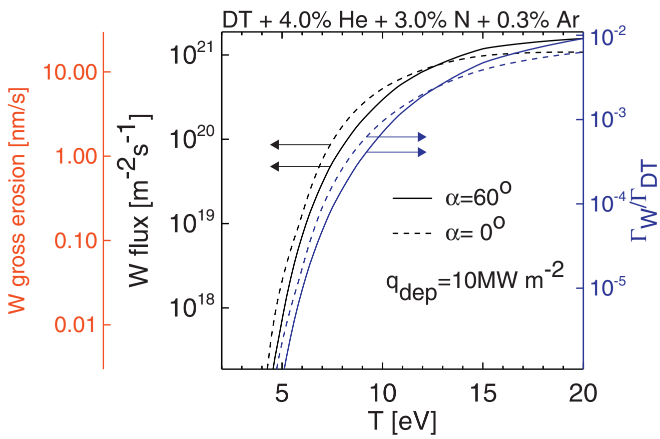

Fig. 1. The gross erosion flux for a DT-plasma with admixture of He(4%), N(3%) and Ar(0.3%) as a function of the temperature $T = T_e = T_i$ in front of the W target for a deposited power density q_{dep} of 10 MWm^{-2}. The dashed lines are for normal incidence and the solid lines for an impact angle of 60° with respect to the surface normal. The red scale gives the gross eroded thickness while the blue lines and the blue scale shows the yield with respect to the DT-flux. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and its strong dependence on the divertor temperatures will be reviewed. Furthermore, our present knowledge about the redeposition of W will be presented. The radiative scenarios, which are needed to obtain the cold divertor plasmas, will be introduced in Section 3 using a simple model for the parallel heat and momentum transport. The transport of W in the H-mode barrier is described in Section 4, while results of integrated simulations of H-mode operation in ITER are given in Section 5. The W transport in the very plasma centre, which in present machines often leads to central W accumulation [7] due to the dominance of the neoclassical pinch [8], is not discussed in this paper. Specific simulations of this effect find no accumulation in ITER H-mode plasmas [9].

2. Tungsten erosion in the divertor

The gross erosion of tungsten, i.e. the primarily removed atoms from the plasma facing surface, is quantified by the yield Y for physical sputtering, which is a function of the mass, the energy and the impact angle of the impinging element [10]. The dependence of the yield on the kinetic energy of the projectile E_{kin} is characterised by a steep rise when the energy is above the threshold energy E_{th} followed by a weak evolution for energies above a few E_{th}. E_{th} is large for D(229 eV), T(154 eV) and ^{4}He(121 eV) and therefore, W sputtering is usually dominated by impurities, i.e. in ITER by the intrinsic Be(74 eV) or the puffed impurities N(46 eV), Ne(39 eV), Ar(27 eV), Kr(35 eV) or Xe(45 eV).

For the usual situation, with a grazing incidence of the magnetic field onto the target, the sheath has a typical width of a few Larmor radii of the main ion species and the orbits of the impinging impurity ions are bent towards the surface normal due to the electric field in the sheath. The average impact angle can be calculated by Monte Carlo codes and several authors find roughly a 10° wide distribution with a maximum at 60–70° with respect to the surface normal [11–15], i.e. 20–30° with respect to the surface. At this impact angle, the yield is larger than the yield at normal incidence for $E_{kin} \gg E_{th}$ (e.g. $Y(60°)/Y(0°) = 1.66$ for N at $E_{kin}/E_{th} = 10$), while for $E_{kin} \approx E_{th}$, the yield is reduced (e.g. $Y(70°)/Y(0°) = 0.15$ for N at $E_{kin}/E_{th} = 2$) [10].

The gross erosion flux density Γ_W versus temperature $T = T_e = T_i$ at a fixed deposited power flux density $q_{dep} = 10$ MWm^{-2} is shown in Fig. 1 for a DT-plasma, where the DT-flow to the target Γ_{DT} has additional impurity flows $\Gamma_i = \Gamma_{DT} f_i$ with fixed fractions f_i, i.e. He(4%), N(3%) and Ar(0.3%). The mean kinetic energy of an ion at the target is estimated by $E_{kin} = 2T + Ze\varphi$ using a potential drop of $\varphi = 3T_e/e$ within the sheath [16], while the mean charge Z comes from the ionisation balance with a 0D inclusion of transport effects using a residence time τ and $\tau n_e = 10^{17}$ $m^{-3}s$ (see [17] for details). The recombination energies and the mean kinetic energy of the electrons per deposited ion $E_{kin,e} = 2ZT_e$ are added to the kinetic ion energies to obtain the total deposited power per ion $E_{dep,\,i}$, such that $q_{dep} = \Gamma_{DT} \sum_i f_i E_{dep,i}$. The gross W flux is depicted for two impact angles, i.e. $\alpha = 0°$ and 60° to the normal onto the surface. Both curves shows a steep decrease for temperatures below 10 eV. For $T < 12$ eV, the flux at 60° is below the flux for normal incidence and is above the normal incidence values for higher T. Dividing Γ_W by Γ_{DT} gives the effective yield Y_{eff}, whose curves and scale are shown in blue. The gross thickness change of the W target is shown by the red scale using a W atomic density of 6.3×10^{28} m^{-3}.

The local gross W erosion flux can be measured with good temporal resolution in present experiments by spectroscopic observation of line radiation emitted by neutral tungsten. Especially for the WI-line at 400.9 nm, the S/XB-factor which relates particle and photon flux is well known [18,19]. Spectroscopic measurements at JET [5,15,18,20] and ASDEX Upgrade [4,21] confirm the strong temperature dependence of the sputtering yield as well as an increase with increasing impurity concentration. Furthermore, a strong increase of the W influx during ELMs is observed and it is found, that for discharges which achieve low T_{div} between ELMs, the total W^0 influx is dominated by the sputtering during ELMs, since the 20–40% time averaged power loss during ELMs [22] happens at much higher temperatures of the divertor plasma.

However, the net erosion is in most situations much smaller than the gross erosion due to the especially high local redeposition of tungsten. This is due to the low ionisation length λ_{ion} of W^0, which is often much smaller than the gyro radius ρ_{W^+} of W^+, leading to a prompt redeposition during the first gyration of W^+ [23]. For a homogeneous plasma and a cosine angular distribution of the starting velocities of W^0, the fraction of particles that do promptly redeposit is independent of the absolute value of the starting velocity and leads to a simple analytic expression [24]

$$f_{\rm redep} = \frac{1}{1 + (\frac{\lambda_{ion}}{\rho_{W^+}})^2} \qquad (1)$$

where ρ_{W^+} shall be the Larmor radius for purely perpendicular ion velocity. However, with decreasing λ_{ion} also the ionisation length λ^+_{ion} of W^+ might drop below ρ_{W^+} and eventually even multiple ionisations of W need to be considered to correctly describe the path of the eroded W. Furthermore, λ_{ion} is often below the width of the magnetic pre-sheath (MPS) $w_{MPS} \approx 5\rho_{DT}$ [25] and the effect of the electric field on the orbits in the MPS has to be included. Multiple ionisations lead to a decrease of $f_{\rm redep}$, while the electric field increases the redeposition fraction [26]. For the latter effect, the velocity distribution of the sputtered W atoms is important and is usually assumed to follow the energy distribution given by Thompson [27]. It peaks at rather low energies around half the surface binding energy $E_s = 8.68$ eV and has consequently quite low mean values even for large projectile energies (see [26]). The inclusion of multiple ionisations, electric fields, and eventually forces due to Coulomb collisions [25] calls for the application of code calculations, which become rather expensive when considering the full velocity distribution of W [25].

The characteristic lengths mentioned in the previous paragraph are shown in Fig. 2 as a function of the divertor temperature. A B-field of 6 T with a grazing angle of $\alpha = 3.2°$ to the target is chosen representing the values at the outer divertor for the ITER reference scenario for inductive operation with toroidal field $B_T = 5.3$ T. The

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