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Tungsten Erosion at the Auxiliary Limiters in ASDEX Upgrade

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Introduction

In order to test the reactor compatibility of high-Z plasma facing components (PFC), a step-by-step increase of tungsten coated PFCs towards a full tungsten machine is pursued at ASDEX Upgrade. At present, almost 70% of the total PFC area consists of W-coated graphite tiles. The enhancements for the 2005 campaign focused on the auxiliary limiters, which receive the highest load of the main chamber components. ASDEX Upgrade has 12 poloidal limiters on the low field side: a pair of side limiters for each of the 4 ICRH antennas and a pair of guard limiters at each side of the 2 neutral beam ducts, which are between the two ICRH antenna doublets. The toroidal width of the guard limiters was increased from 10 to 20 cm and the radial distance to the plasma was changed from 12 mm to 6 mm behind the position of the ICRH limiters to allow for a better power load sharing between the limiters. One of the ICRH limiters from antenna 4 and one guard limiter is equipped with W-coated tiles.

The remaining W layer thickness on the 2004 guard limiter tiles was measured by X-ray fluorescence and Rutherford backscattering and gave a net erosion of about 150-300 nm with a rather uniform poloidal profile. At one position X-ray fluorescence gave 1.2 μm at mid campaign [1] and 1.5 μm after the end of the campaign. This value is an outlier in the data set and is assumed to be due to an erroneously large measurement value of the layer thickness before installation. The campaign integrated spectroscopically determined gross erosion is roughly consistent with values between 50-75 nm.

Tungsten influx is monitored on 9 lines-of-sight by measuring WI line radiation at 400.8 nm. The Balmer-ε transition at 397 nm is used to monitor the deuterium influx. The measured photon fluxes are transformed into ion fluxes using the number of ionisations per emitted photon, i. e. the (S/XB) value. For tungsten (S/XB)=20 is used [2], and for H_ε, the atomic value (S/XB)=1.3×10^4 is multiplied by a factor of 1.5 as a rough estimate for the molecular flux contribution [3]. Erosion yields are calculated by dividing the W flux density Γ_W by the deuterium flux density Γ_D (see [1] for details). The quantity $Y_{eff} = \Gamma_W/\Gamma_D$ is an effective yield. It includes the sputtering by deuterium as well as by plasma impurities. The interpretation of Y_{eff} is based on the physical sputtering of tungsten [4, 5]. For thermal plasma ions with kinetic ion energy at the wall of roughly $(2+3Z)k_BT$ and an ion flux of D^+ with an admixture of 1% C^{4+}, Y_{eff} is dominated by carbon sputtering and is 10^{-4} at 6.6 eV and 10^{-3} at 28 eV. Sputtering by pure D^+ ion flux reaches 10^{-4} at 54 eV. Thus, only D sputtering by fast ions is relevant. For D sputtering, Y has a broad maximum of $\approx10^{-2}$ at E=6 keV with $Y > 8\times10^{-3}$ for E=2-28 keV.

Maximum W influx densities from the ICRH limiter are $\Gamma_W \approx 10^{20}\,\mathrm{m^2s^{-1}}$ and transiently $\Gamma_W \approx 10^{21}\,\mathrm{m^2s^{-1}}$ being about a factor of 10 above the maximum values previously observed during the 2004 campaign at the guard limiter, which was positioned 12 mm behind the ICRH limiter. In contrast to the 2004 results, such high values can not solely be due to sputtering by fast NBI ions as will be demonstrated below. Here, a dominant contribution by thermal impurity ions must be present. Estimates of the W confinement time and the measured W concentrations in the plasma show, that the total source from the two limiters is still low compared to the source at the inner heat shield [6].

Tungsten Influx due to Fast NBI Ions

During the 2004 campaign, measurements of W influx from the guard limiter pointed towards a dominant fast D^+ particle contribution to the average deposited energy per deuterium ion and the sputtering of tungsten [1]. Code calculations have been performed to model the fast particle load and the respective tungsten erosion rates at the limiters in detail. The start position and velocities of the fast NBI ions were calculated with the Monte Carlo code FAFNER [7]. Subsequently, the orbit of the gyro center of the ions was calculated including pitch angle scattering and slowing down collisions. The magnetic field components were taken from the equlibrium reconstruction and also the toroidal magnetic field ripple was included in the calculation. Each particle is followed until the particle energy drops below the local value of $3k_BT_i$ or until it hits the contour of a limiter, the inner heat shield, or the divertors. A hit with a surface contour is obtained in the code, if the particle is toroidally in front of the contour and if the part of the Larmor circle, which was covered during the last time step, intersects the contour. For the collision frequencies, density and temperature profiles are taken from the experiment, while the impurities He and C are included with fixed concentrations of 15% and 1.5% and charge state distribution according to corona equilibrium. Each calculation starts with about 10000 ions to obtain the fast ion load. From the energy of the hitting particle, the sputtering yield is calculated, which finally leads after normalisation to the total erosion rate by fast NBI ions.

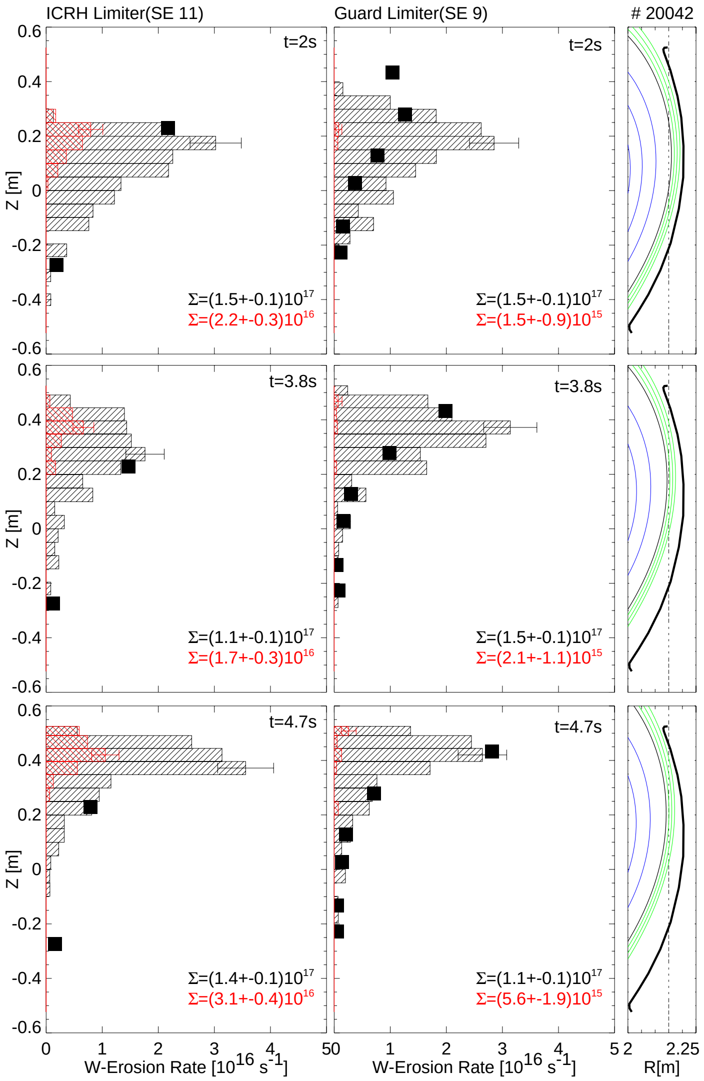

Fig.1: *Comparison of calculated W erosion rates by fast NBI ions and measured values for an H-mode plasma with 5 MW NBI heating and vertical shift of the plasma column. Red bars and labels refer to a calculation without field ripple.*

A comparison of calculated and measured erosion rate profiles for an H-mode discharge with 5 MW NBI heating from two 60 kV sources is shown in Fig.1. Here, a slow vertical movement of the plasma column was applied and the W influx was measured on the ICRH as well as on the NBI guard limiter. The black bars depict erosion rates on the limiter per vertical bin of 5 cm height. The spectroscopic influx densities were multiplied with the bin height and the width of the observed spot size on the limiter of 2.5 cm and are shown using filled squares. The poloidal distribution moves upwards with the plasma movement and there is good agreement between code results and measurements. The total calculated loss of fast ions on the limiter is 23-28% resulting in 12-14% power loss. Red bars represent the case without toroidal field ripple, which leads to a factor of 4.5-7(20-100) less erosion on the ICRH(guard) limiter.

Fast ions from NBI do not account for the W influx in all discharges. An example is the improved H-mode discharge #20125 at t=2.2 s with 3 MW of ICRH and 5 MW of NBI heating from a 60 kV and 100 kV source (Fig.2). The total calculated fast ion loss of 32% representing 16% of the power loss onto the limiters is by a factor of 5 not sufficient to explain the large measured influx from the ICRH limiter. A very narrow poloidal distribution together with a further increased loss rate is rather improbable and the measurement rather points to a dominant contribtuion of sputtering by sheath accelerated impurity ions being enhanced by the ICRH as is discussed in the next section.

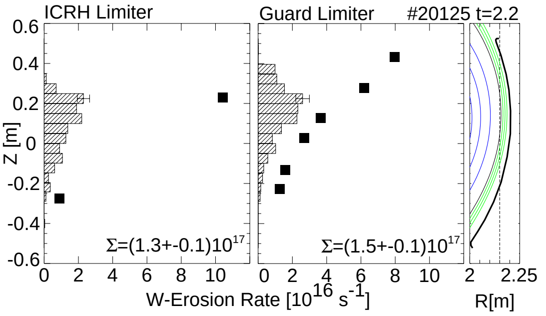

Fig.2: *Measured W erosion rates and calculated erosion due to fast NBI ions for #20125 at t=2.2 s.*

ICRH induced Tungsten Influx

Already during the 2004 campaign, ICRH was seen to increase the W influx from the guard limiter during NBI heated H-mode plasmas. For the close-by antenna doublet, which has a minimum toroidal distance of ≈0.8 m to the guard limiter, the W influx per ICRH power was observed to increase locally by a factor of ≈1.5 compared to pure NBI injection, while this factor was only ≈0.5 for the more distant (≈4 m) antennas. During the present campaign, more information about the spatial structure of the ICRH induced W flux was obtained from the W flux measurements at the ICRH side limiter. Fig.3 shows time traces of Γ_W, Γ_D, and Y_{eff} for three positions at the ICRH limiter of antenna 4 during an H-mode discharge with 5 MW NBI heating and 1.5 MW ICRH. The ICRH power is shifted slowly from antennas 3+4 to antennas 1+2 followed by a phase with pure NBI heating. Only antennas 3+4 induce a measurable additional tungsten influx with respect to the pure NBI phase. On the upper measurement position, the local influx

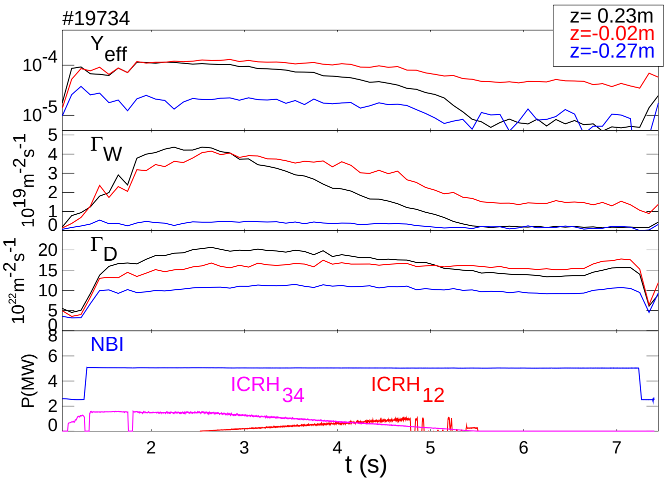

Fig.3: *Time evolution of influxes Γ_W and Γ_D and effective yield Y_{eff} for 3 positions at the ICRH limiter of antenna 4 during an H-mode discharge with shifting of the ICRH power from antennas 3+4 to antennas 1+2.*

density per ICRH power is now a factor of 65 larger compared to the pure NBI case.

The localised increase of Γ_W rules out a predominant contribution of ICRH induced fast ions to the W erosion which would lead to a flat toroidal distribution. This argument is supported by the fact that also in cold ohmic discharges a strong W influx is observed when ICRH is switched on. Further analysis was therefore based on the assumption that the sheath rectification effect yields the predominant contribution to the increased W influx. The additional average sheath potential $\Delta\Phi_{rf}$ causes a higher energy of the sputtering ion on the target which leads to an increased erosion yield. For a D^+ plasma with an admixture of 1% C^{4+} the difference of the effective yields ΔY_{rf} with and without additional sheath potential is only weakly dependent on the edge temperature. In Fig.4, ΔY_{rf} is shown versus $\Delta\Phi_{rf}$ for T=5, 10, and 20 eV. In NBI heated plasmas, ΔY_{rf} was gained from discharge phases with and without ICRH on antennas 3+4, while in ohmic plasmas, there is no measurable W influx without ICRH. The differences of the Y_{eff} values have been normalised to 1 MW of ICRH power. The highest difference was found in a low density ohmic discharges with values up to $\Delta Y_{rf} < 7\times10^{-4}$, while NBI heated plasmas gave $\Delta Y_{rf} < 1\times10^{-4}$. These ranges are overlayed in Fig.4 and yield a range of sheath potential increases up to $\Delta\Phi_{rf} < 50$ V and $\Delta\Phi_{rf} < 15$ V respectively. For the low density ohmic discharge, ΔY_{rf} reaches about similar values at ICRH and guard limiter, while in NBI heated plasmas, ΔY_{rf} at the guard limiter is lower by roughly a factor of 5. The evaluated $\Delta\Phi_{rf}$ values do not take into account possible ICRH induced increases of the carbon fraction and are estimated to be an upper bound. More detailed determinations should include a measurement of the local carbon fluxes, which are forseen for future campaigns.

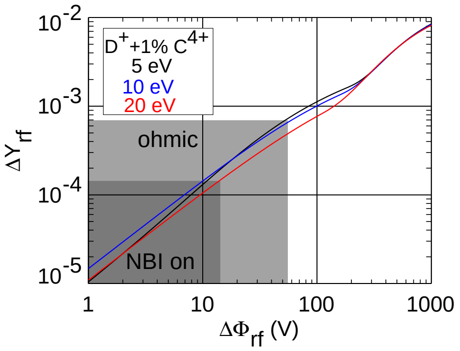

Fig.4: *Calculated difference of Y_{eff} with and without ICRH induced sheath potential $\Delta\Phi_{rf}$ and range of measured differences normalised to 1 MW of ICRH power.*

Conclusion

At the tungsten coated outboard limiters of ASDEX Upgrade, W influx densities are only detectable when NBI or ICRH are used. NBI leads to a sputtering by fast D^+ ions and code calculation of the fast ion sputtering are in good agreement with measured distributions. Thus, the total rate can quite reliably be predicted. Fast ion transport onto the limiters is mainly due to the magnetic field ripple. ICRH most probably leads to an enhancement of the erosion yields from sheath accelerated impurity ions via a rise of the sheath potential. The local variations of erosion rate with/without ICRH can not be predicted so far. Presently, there is a lack of complete influx profile measurements and the total ICRH induced rate change can only be estimated.

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