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Migration of tungsten eroded from divertor tiles in ASDEX Upgrade

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Abstract

Tungsten migration in ASDEX Upgrade was investigated by analysis of deposition on long term sample probes and by erosion and deposition studies using two probe manipulator systems in the midplane and the outer divertor plate respectively. Divertor retention was determined by measuring the total tungsten production in the divertor and comparison with the spectroscopically measured tungsten content in the confined plasma. The fraction of tungsten deposited on limiters in the main chamber compared to deposition in the divertor was determined by injecting tungsten into the main plasma using laser ablation and determining the deposition of these atoms on collector probes. The ratio of inner divertor to outer divertor tungsten deposition was obtained from surface analysis of long term sample probes.

Keywords: ASDEX Upgrade; High Z wall material; Erosion and particle deposition; Impurity transport

1. Introduction

High Z materials are proposed as plasma facing material in low temperature, high density divertor plasmas because of the high threshold energy for physical sputtering. Additionally, the small ionization length of eroded atoms and the large gyro radius of high Z ions lead to very local redeposition of eroded material. Long term migration in many subsequent erosion and redeposition events may, however, transport high Z material from the divertor to the main plasma chamber and constitute a plasma contamination source.

After two experimental periods — one where only 8 W-coated divertor tiles were installed and one with a fully W-coated divertor — the erosion and long term migration of W was investigated. Impurities released from the main chamber walls (B, C, Fe) or from the divertor (W) could be distinguished.

Additionally, time resolved information from a plasma boundary probe system and a divertor probe system on W erosion and deposition in single discharges could be obtained. Laser blow-off in the main plasma vessel with simultaneous optical spectroscopy gave information on the plasma boundary shielding and W transport into the divertor.

Combining time resolved and long term deposition information, a complete pattern of impurity production, divertor retention and long term migration could be obtained.

2. Diagnostics

Long term sample probes are routinely installed at various locations in the divertor and main vessel of ASDEX Upgrade to monitor the modification of the plasma facing surfaces over a whole experimental period. To study plasma surface interaction processes in distinct discharges, two probe manipulator systems were installed, which allow to expose material probes into the midplane scrape-off layer and in the outer divertor target plate (Fig. 1). Both manipulators are equipped with a magazine to allow probe exchange between two subsequent discharges. An air lock system allows to replace the magazine for ex-situ analysis of the probes without breaking the vacuum in the manipulator. Deposition of impurities from the discharge is mea-

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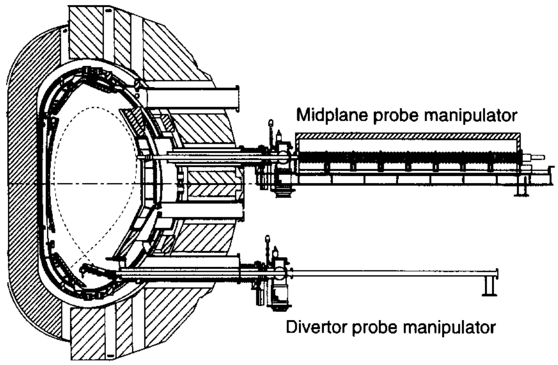

Fig. 1. Poloidal cross-section of ASDEX Upgrade with midplane and divertor probe manipulator systems.

sured by exposure of clean graphite probes and subsequent surface analysis by Rutherford backscattering (RBS) and proton induced X-ray emission (PIXE). To study erosion processes, thin layers of the respective material are established on the graphite probes by vapor deposition or deposition from HF plasma discharges. By measuring the layer thickness before and after exposure, it is possible to determine the effective erosion by the plasma. If the plasma temperature and density are known, e.g., from Langmuir probe measurements, erosion yields can be determined as well [1].

In addition to the probe surface analysis, the tungsten behavior was observed by spectrometers in the visible and the VUV range. A grazing incidence spectrometer is used to monitor the concentration of tungsten in the main plasma by measuring the emission of a tungsten quasicontinuum spectral line array [2]. Since atomic excitation rates for distinct tungsten ions are scarce and subject of large errors, absolute calibration of the spectroscopic measurements was performed by injection of a known amount of tungsten using laser blow-off (LBO) and comparison with the increase of the total bolometric radiation [2].

The flux of neutral tungsten atoms above the target plates is monitored by a boundary layer spectrometer in the visible range [3]. A swivel mirror allows to scan radially over inner and outer target plate during a discharge. However, since excitation rate coefficients for the observed WI spectral line are not known yet, only the radial shape of the line emission profile can be measured.

In the present paper the information from all these different diagnostics are collected to establish a flux pattern of W eroded from the divertor tiles.

3. Experimental results

3.1. Target plate erosion

Target plate erosion was determined by exposing graphite test tile probes with 1–20 nm W-markers using the divertor probe manipulator [1]. In L-mode discharges with high divertor density and low temperatures, the observed effective erosion yield was close to the detection limit ($\lesssim 1.5 \times 10^{-5}$). Low density Ohmic discharges provide a scenario with a low density — high temperature divertor plasma. Consequently, a higher effective erosion yield of $\simeq 5 \times 10^{-4}$ was found in such discharges. The maximal erosion yield of 10^{-3} was observed in ELM'y H-mode discharges. Using a rotating cylindrical collector probe with the midplane manipulator system, time resolved measurements of the tungsten flux in the scrape-off layer were done in such discharges. A clear correlation between phases with high divertor heat load due to ELM pulses and tungsten scrape-off layer (SOL) flux was found. Since the measured plasma temperature between ELM's is very low compared to the peak values in an ELM pulse, the tungsten erosion in H-mode discharges will be mainly determined by the ELM's.

In all cases, the observed erosion yields were lower by 1–2 orders of magnitude compared to calculations for a deuterium plasma with 1% C^{4+} impurity [4]. This is attributed to the effect of prompt local redeposition, which leads to a decrease of the observable net erosion.

3.2. Long term tungsten migration

In order to investigate impurity redeposition, an array of long term collector probes is installed on the vessel walls of ASDEX Upgrade and analyzed for surface deposits after each discharge campaign. During the campaign 1995/1996 a number of W coated test tiles were installed in the divertor. Two of these test tiles failed, leading to flaking of the coating, melting and evaporation of a total of 4×10^{21} W atoms. After 200 OH and 430 NB heated discharges the W tiles were removed. Together with the W tiles, the long term collector probes, numerous carbon tiles from the inner and outer divertor plate, the inner heat shield and from protection limiters were removed and analyzed for high Z deposits. The location of the W coated tiles and analyzed carbon divertor tiles is shown in Fig. 2.

Deposited W atoms could only be found on the tiles of the lower divertor. Neither on the long term probes on the vessel walls nor on the main chamber structures the W concentration exceeded the sensitivity of the analyzing method. Using proton induced X-ray emission by 1.5 MeV H^+ a sensitivity of 10^{15} W atoms/cm^2 was reached.

A radial profile of the W deposit on the divertor plates is shown in Fig. 3 for three different sectors of ASDEX Upgrade. The similarity of the three sets of data indicates toroidal symmetry of the deposition. Only in direct neighborhood to the eroded W tiles a higher deposition could be seen decaying very fast to both toroidal directions, the enhancement never exceeding a factor of two. Integrating over the total divertor area only about 3×10^{20} W atoms could be found indicating that part of the erosion may have consisted in droplet emission which were not recovered on the analysed probes.

The deposition on the divertor shows a pronounced pattern with high deposition on the inner plates, following the radial variation of the incident plasma flux, while at the outer plates the deposition is lower, rather uniform with an indication of an increase toward larger radii. This pattern reflects the inner/outer asymmetry of the energy transport to the divertor plates in ASDEX Upgrade. Typically, plasma temperatures in the inner divertor are lower by a factor of 2 compared to the outer divertor. Therefore, in the inner divertor deposition conditions prevail, while on the outer divertor plate erosion of the previously deposited material transports the atoms towards the cooler outer edge of the divertor fan. For geometric reasons the position of the separatrix intersection with the divertor plates is very stable at the inner plate for a large variety of configurations, while at the outer plates large shifts occur during the start up of an individual discharge, but also between Ohmic and neutral beam heated discharges. Therefore the total deposition in the inner divertor is about twice the deposition of the outer divertor and strongly peaked even integrating over an entire discharge period.

During the present campaign with W tiles covering the divertor strike point erosion can only be expected at the outer divertor tiles, while W atoms reaching the main chamber will predominantly be deposited on the inner tiles. Also, intrinsic impurities, such as carbon and boron, will be predominantly deposited onto the inner tiles, thus protecting the W plate from erosion. Indeed, surface analysis of the W tiles removed from the inner divertor after the 1995/1995 campaign showed deposited layers at the strike point with thicknesses of several μm consisting mainly of carbon, but with additions of Fe, Cr, Ni of up to 10^{17} cm^{-2}. Also, the same deposition pattern could be observed for deuterium in codeposited layers as reported in [5].

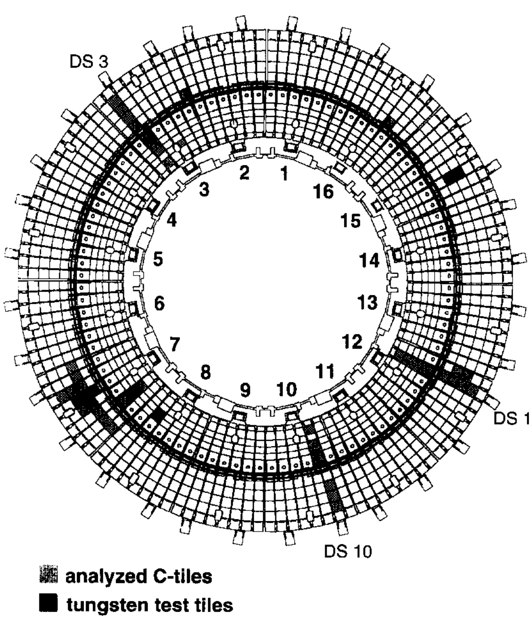

Fig. 2. View from top onto the target plates with positions of long term sample probes in the last graphite divertor experimental period with tungsten test tiles.

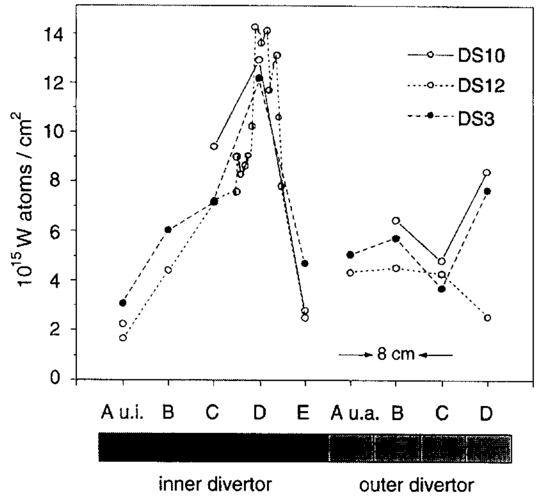

Fig. 3. Poloidal distribution of tungsten deposition on the target plates measured at three different toroidal positions (divertor sectors 3, 10 and 12; see Fig. 2). The measured tungsten surface density is plotted in radial direction along the target plate surface from the inner side to the outer side of the torus. The shaded bar denotes the radial extent of inner (Au.i.–E) and outer (Au.a.–D) target tiles.

3.3. Correlation between divertor and midplane deposition

Beside the divertor retention capability for tungsten eroded at the target plates, the exhaust capability of the scrape-off layer is another important parameter determining the tungsten concentration in the confined plasma region. To determine the fraction of the total tungsten flux from the main plasma, which is transported down to the target plates, tungsten was injected into the plasma by repetitive laser blow-off pulses. In these discharges, graphite collector probes were exposed by the manipulator systems in both the midplane scrape-off layer and the outer target plate. For the divertor, additional measurements were done in similar discharges without laser blow-off to determine the intrinsic deposition due to erosion of tungsten from the target plates.

Fig. 4a shows the radial tungsten deposition profile at the outer divertor plate with and without laser blow-off. The fraction originating from the LBO injection is given by the difference of these curves and plotted in Fig. 4b. A direct measurement of the corresponding tungsten flux in the midplane by exposure of a collector probe is, however, not possible, because the poloidal flux range covered by the divertor measurement corresponds to a layer of only a

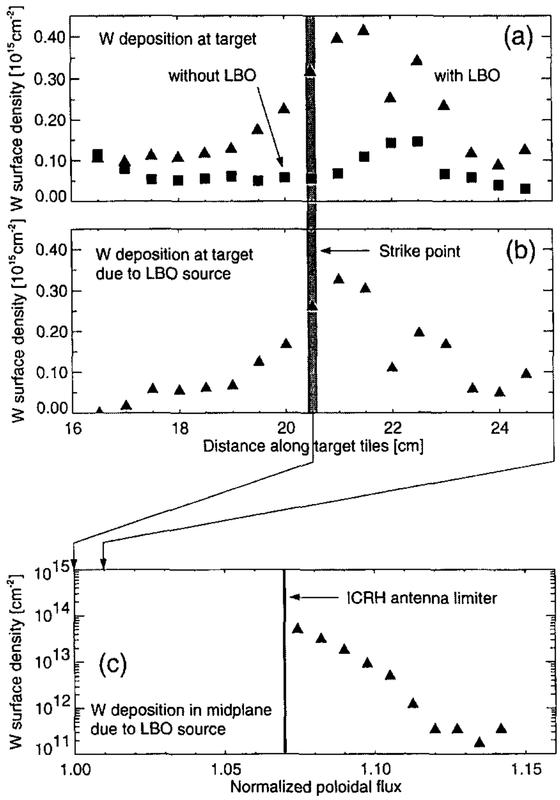

Fig. 4. Tungsten flux deposited on collector probes at outer divertor plate (a) and midplane scrape-off layer (c) in a discharge series with repetitive 20 Hz laser blow-off pulses.

few mm thickness directly at the midplane separatrix (Fig. 4c). The heat flux in that region is too high for the midplane collector probe, and therefore exposure is restricted to the limiter shadow of the ICRH protection limiters.

One can, however, compare the total particle flux into the divertor with the total particle flux crossing the last closed flux surface as defined by the ICRH limiters, which can be determined from the midplane collector probe measurement. The probe collects tungsten ions passing through an effective surface area, which is given by the product of the connection length between the ICRH antennas and the slit width of the probe shielding. Integration over the radial profile of the W surface density as shown in Fig. 4c (with the radial coordinate expressed in units of the normalized poloidal flux) and multiplying with the ratio of the total plasma surface over the effective collecting surface results in 1.25×10^{17} tungsten ions crossing the last closed surface per 10^{18} injected atoms. The radial decay length of 8 mm explains the absence of significant tungsten deposition at the main vessel walls.

Integrating over the deposition profile at the outer divertor plate results in a total deposition of 2.85×10^{17} tungsten ions per 10^{18} injected atoms at the outer divertor. Analysis of long term sample probes yields a 2:1 ratio of deposition into inner and outer divertor respectively. Taking this in account, we obtain a total divertor deposition of 8.55×10^{17} tungsten ions per 10^{18} injected atoms. Despite the large uncertainties in this evaluation, especially regarding the assumed toroidal uniformity, this is a good agreement between the number of injected atoms and the total number of deposited atoms. The resulting ratio of divertor deposition to main chamber deposition is approximately 7:1. Because of the dominance of parallel transport over radial transport, tungsten ions crossing the separatrix are mainly swept into the divertor and only a small part will reach main chamber limiters or even the vessel wall by radial diffusion.

3.4. Global migration pattern of tungsten

Summarizing the results collected so far, it is possible to establish a global pattern for the migration of tungsten in ASDEX Upgrade. The calculation was done for a series of Ohmic discharges with $\bar{n}_e = 2.5 \times 10^{19}$ m^{-3} and a tungsten concentration c_W of $\simeq 10^{-5}$ in the main plasma. The particle confinement time of tungsten ions in the main plasma was determined by laser blow-off experiments to $\tau_p = 80$ ms [2]. This allows to calculate the loss rate of tungsten ions out of the plasma

$$\Gamma_W = \bar{n}_e c_w / \tau_p. \quad (1)$$

The effective net erosion yield was determined to 5×10^{-4} [1]. On the other hand, calculations for a deuterium plasma with 1% carbon impurity results in an erosion yield of 2.7×10^{-3} for the measured divertor temperature of 40 eV. If we attribute the discrepancy to prompt local redeposition, we obtain a fraction of 15% of the eroded tungsten ions reaching the divertor plasma.

Assuming significant tungsten erosion only in the outer divertor, the ratio of tungsten production in the divertor to

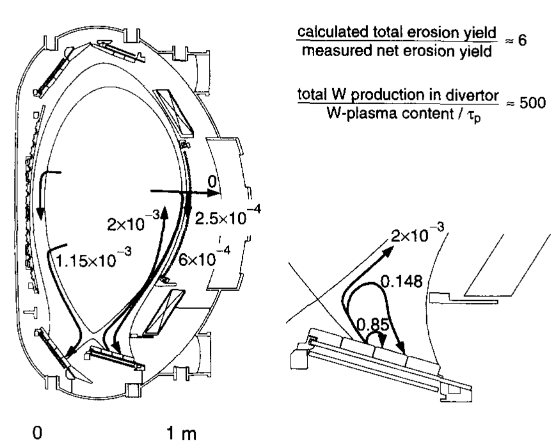

Fig. 5. Migration pattern of tungsten in the ASDEX Upgrade vessel for low density Ohmic discharges ($Y_{eff} = 5 \times 10^{-4}$).

tungsten flux out of the plasma is $\simeq 500$. Combining these values with the results for the tungsten flux to main vessel limiters and divertor plates as discussed above, we obtain finally the pattern shown in Fig. 5.

Comparing the W flow pattern for ASDEX Upgrade with a similar pattern for Cu eroded from the ASDEX divertor [6] the main difference is the very good divertor retention for tungsten. A considerable part of the high retention in the case of tungsten is, however, due to the prompt local redeposition of tungsten ions within their first gyro orbit. The value of $\simeq 1/500$ obtained in Ohmic low density discharges represents the case with the lowest divertor retention and has to be compared to $\simeq 1/7$ for low density discharges in ASDEX. This high divertor retention also results in negligible migration of W into the main vessel.

4. Summary

Tungsten migration in ASDEX Upgrade was investigated by analysis of deposition on long term sample probes and by erosion and deposition studies for single discharges using two probe manipulator systems in the midplane and the divertor respectively.

Erosion in the divertor was measured by exposure of probes covered with thin layers of tungsten. The resulting effective sputtering yields are mainly determined by the plasma temperature.

Analysis of long term samples in the divertor revealed a 2:1 ratio of tungsten deposition of inner to outer divertor, due to the lower plasma temperatures at the inner target plate compared to the outer target plate. A ratio of main vessel deposition to divertor deposition of 1:7 was obtained by analysis of tungsten deposition on midplane and divertor collector probes. Furthermore, no tungsten could be detected at the vessel walls. Both results illustrate the strong dominance of parallel tungsten transport over radial transport in the scrape-off layer and the absence of neutral tungsten flux to the walls.

For a low density Ohmic discharge scenario, a complete migration pattern for tungsten could be established. Further experiments are required to extend this pattern to other scenarios and to improve the accuracy of the present model.

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