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Erosion and migration of tungsten employed at the central column heat shield of ASDEX Upgrade

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Abstract

In ASDEX Upgrade, tungsten was employed as plasma facing material at the central column heat shield in the plasma main chamber. The campaign averaged tungsten erosion flux was determined by measuring the difference of the W-layer thickness before and after the experimental campaign using ion beam analysis methods. The observed lateral variation and the total amount of eroded tungsten are attributed to erosion by impact of ions from the scrape-off layer plasma. Migration and redeposition of eroded tungsten were investigated by quantitative analysis of deposited tungsten on collector probes and wall samples. The obtained results, as well as the spectroscopically observed low tungsten plasma penetration probability, indicate that a major fraction of the eroded tungsten migrates predominantly through direct transport channels in the outer plasma scrape-off layer without entering the confined plasma.

1. Introduction

In most present day fusion experiments, carbon based materials are used for plasma facing components, mainly due to their good thermomechanical properties and the comparatively small radiative losses inflicted by carbon as plasma impurity. In fusion devices operating with tritium, however, codeposition with carbon will lead to formation of prohibitively high tritium inventories. In ASDEX Upgrade, tungsten has been successfully employed as an alternative plasma facing material, first in the divertor and, in recent experimental campaigns, at the central column heat shield in the plasma main chamber. Tungsten is a promising alternative to low-Z materials such as carbon and beryllium, primarily because of its high sputtering threshold energy (201 eV for deuterium impact, 136 eV for tritium impact [1]) and its low sputtering yield. One has, however, to ensure comparatively small plasma concentrations below a limit of approximately 2×10^{-5} for ignited fusion plasmas [2] to avoid excessive heat losses due to the strong specific line radiation power of tungsten [3] in the respective temperature range. In the experimental campaigns with tungsten as plasma facing material at the main chamber central column, spectroscopic measurements of the tungsten plasma concentration demonstrated that this criterion was met for all fusion reactor relevant discharge scenarios [4,5]. Consequently, no adverse effects were observed on the global plasma confinement parameters. Apart from the tungsten plasma concentration, tungsten erosion and migration processes are the main criterions to evaluate the suitability of tungsten as first wall material. Since the erosion and deposition flux are usually too small for spectroscopic analysis, these processes were mainly studied by post campaign ex situ analysis of exposed probes and of wall samples using ion beam analysis methods.

2. Experimental setup

In the experimental campaign 1999/2000 two toroidal rows of tungsten coated graphite tiles were employed at

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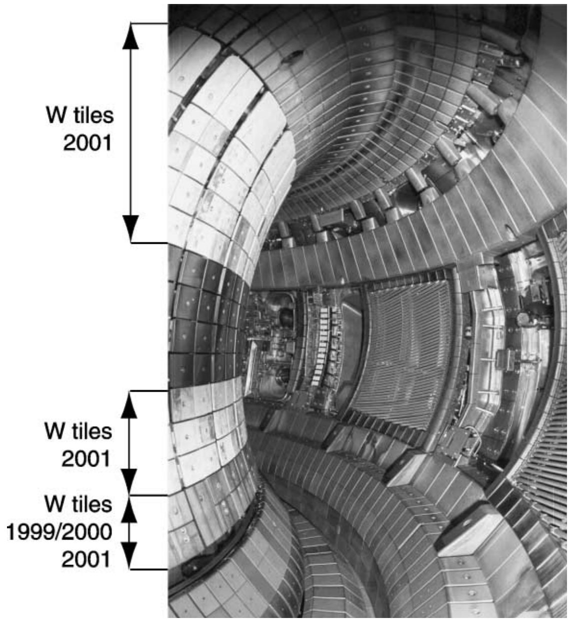

Fig. 1. Tangential view of the ASDEX Upgrade vessel before closure for experimental campaign 2001. The central column heat shield is seen at the left side of the photo. The four tile rows with graphite and CFC tiles at the vessel midplane serve as temporal limiter and neutral beam shine through dump areas and were therefore kept without W-coating.

the lower edge of the heat shield covering an area of 1.2 m^2, which accounts to ≈13% of the total heat shield surface (Fig. 1). The tungsten coating with a thickness in the range of 0.2–0.5 μm was applied in-house by physical vapour deposition [6]. During the campaign, the tiles were exposed to 919 plasma discharges with a total discharge time of 4580 s. In the subsequent campaign, 2001, the tungsten coated area was extended to cover two belts of tiles with a total area of 6.5 m^2, with graphite remaining only in the midplane region, which is used as limiter and neutral beam injection shine through dump and therefore subject to the highest plasma particle and heat loads. In addition, two columns of tungsten coated tiles were installed covering the full poloidal extent of the heat shield to allow analysis of the spatial distribution of the tungsten erosion also in the midplane limiter region. The new tiles were coated commercially by plasma arc deposition with a thickness of 1.0 μm. Uniformity of surface coverage and layer thickness were confirmed by scanning electron microscopy [6]. For one of the tungsten tile columns the thickness of the W-coating was reduced to 60 nm to increase the sensitivity of erosion measurements. To achieve a closed W-layer, the surface of the respective tiles was additionally polished. In the 2001 campaign, the tungsten coated surface was exposed to 619 plasma discharges with a total discharge time of 2800 s. As expected from thermomechanical pre-fabrication tests [6], both, the initial set of W-coated tiles, which stayed in the machine for both campaigns, as well as the second tile set for the extended area in the 2001 campaign did not show any mechanical failure, like cracking or peeling off.

To reduce excessive erosion at leading edges, the graphite tiles were shaped trapezoidally and mounted in pairs with opposite toroidal alignment (see cross-sections at bottom of Fig. 2).

3. Tungsten erosion

Tungsten erosion was studied by ex situ ion beam analysis of the W-coated tiles using Rutherford back-

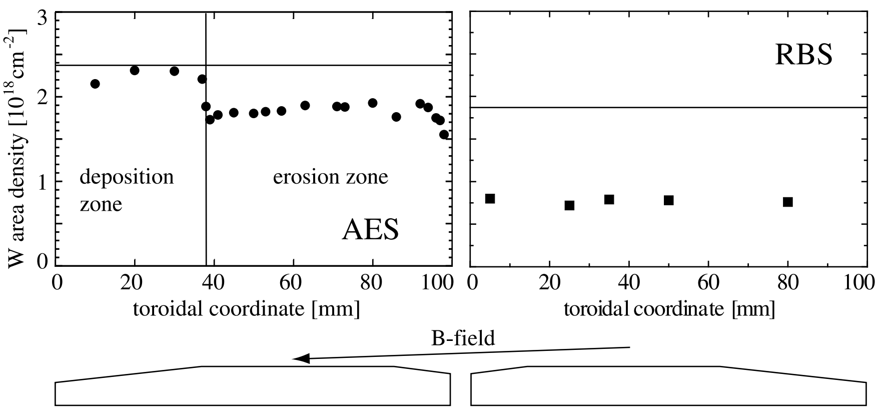

Fig. 2. Toroidal variation of tungsten erosion along a tile pair at the lower edge of the inner column heat shield in campaign 1999/2000. The outlines show the trapezoidal cross-section of the tiles, which was introduced to avoid excessive erosion at the tile edges due to perpendicular incidence of *B*-field lines. The downstream tile (left) was analysed using sputter AES analysis, while the upstream tile (right) was analysed using RBS analysis.

scattering analysis (RBS) and sputter Auger electron spectroscopy (AES). The campaign integrated tungsten erosion fluence was derived from the difference between the tungsten areal density of the virgin tiles and the areal density of the remaining W-layer after the campaign.

For RBS analysis 2.6 MeV He^+ ions were used, which allowed quantitative determination of the tungsten areal density as well as determination of the depth distribution of tungsten and other layer constituents such as oxygen and carbon. The layer thickness of the virgin tiles for campaign 1999/2000 derived from the RBS analysis agreed well with respective values obtained from the weight gain of the tiles during the in-house coating procedure [6]. In addition, X-ray photoelectron spectroscopy (XPS) was used for chemical analysis of the virgin W-layer and revealed a 10–15% fraction of carbon and oxygen [6].

After the campaign, one pair of tiles from each toroidal row was removed for surface analysis. Fig. 2 shows the results for the tile row at the lower edge of the heat shield. Due to the trapezoidal cross-section of the tiles, there are areas, which are shadowed from the incident field lines as illustrated in the lower part of Fig. 2. The downstream tile (left) was analysed using sputter Auger analysis [7]. At the shadowed downstream surface facet of the tile, the thickness of the remaining layer is significantly higher than on the upstream facets. Since the tile was not analysed before exposure, the tungsten erosion fluence can only be estimated with limited accuracy. In the shadowed area, the AES analysis revealed, however, a deposited layer consisting mainly of carbon oxygen and silicon with a thickness of 20–30 nm on top of the tungsten layer [7]. It is assumed that the thickness of the tungsten layer in this deposition dominated area approximately reflects the thickness of the virgin layer. With this assumption, one obtains a tungsten erosion fluence of 5.5×10^{17} cm^{-2}, and taking into account the total plasma exposure time of 4580 s, one obtains a campaign averaged W-erosion flux of 1.2×10^{14} cm^{-2} s^{-1}. The upstream tile (right) was analysed before and after the campaign by RBS. In this case the W-layer has been eroded uniformly across the tile surface. The total erosion fluence was determined to $\approx 10^{18}$ cm^{-2}. This is almost two times larger than the maximum erosion estimate from the AES analysis of the adjacent tile. Detailed analysis of the RBS energy spectra obtained after the experimental campaign show, however, a significant increase in the roughness and low-Z impurity content of the W-layer. These parameters have a strong influence on the evaluation of the tungsten areal density and might cause significant systematic errors. To investigate these effects, the tile analysis facility will be extended by an X-ray detector for proton induced X-ray emission analysis, which allows to determine directly the total areal density of the respective materials.

In the experimental campaign 2001, the poloidal variation of the tungsten erosion flux was determined by analysis before and after the campaign of a complete vertical column of W-coated tiles with reduced coating thickness of ≈ 60 nm. Fig. 3 shows the remaining layer thickness along the poloidal coordinate. The maximum W-erosion fluence of $\approx 2.6 \times 10^{17}$ cm^{-2} is found above the midplane. Taking into account the total plasma exposure time of 2800 s, one obtains a maximum campaign averaged erosion flux of 0.9×10^{14} cm^{-2} s^{-1}, which agrees approximately with the corresponding erosion flux in the previous campaign.

The W-erosion flux from both experimental campaigns exceeds the corresponding result from the analysis of the initial test experiments (0.8×10^{13} cm^{-2} s^{-1}) [8] by an order of magnitude. Further analysis of the tiles by scanning electron microscopy showed that the residual amounts of tungsten, which were initially misinterpreted as a closed layer, remained only in grooves of the machined tile surface protected from further erosion. Therefore the much thinner W-layer of the test tiles (4.3×10^{16} cm^{-2}) was almost completely eroded long before the end of the respective experimental campaign. Consequently, the total plasma exposure time used for the calculation of the campaign averaged W-erosion flux must be greatly reduced and the reported results must be taken as a lower limit for the erosion flux.

Considering the observed lateral variation and the magnitude of the tungsten erosion flux, it is clear that the predominant erosion channel is due to ion impact. The W-erosion flux due to impact of charge exchange neutral atoms is much too small to account for the measured erosion rate [8]. This is further supported by results from scanning electron microscope (SEM) analysis of the tiles exposed in campaign 1999/2000.

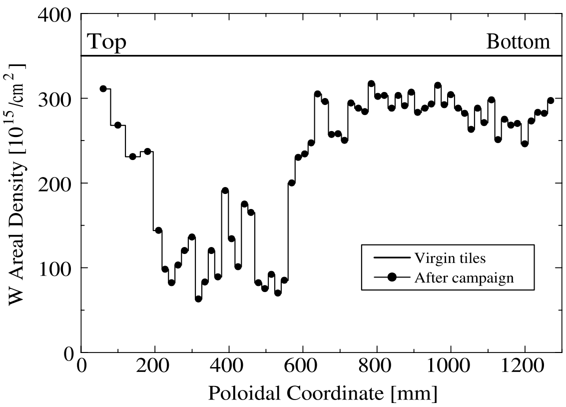

Fig. 3. Erosion of the tungsten coating along a complete vertical column of heat shield tiles in the campaign 2001. The poloidal coordinate denotes the distance along the tile surfaces from the top edge of the heat shield. The post campaign data were measured at a distance of from the left edge of the tiles.

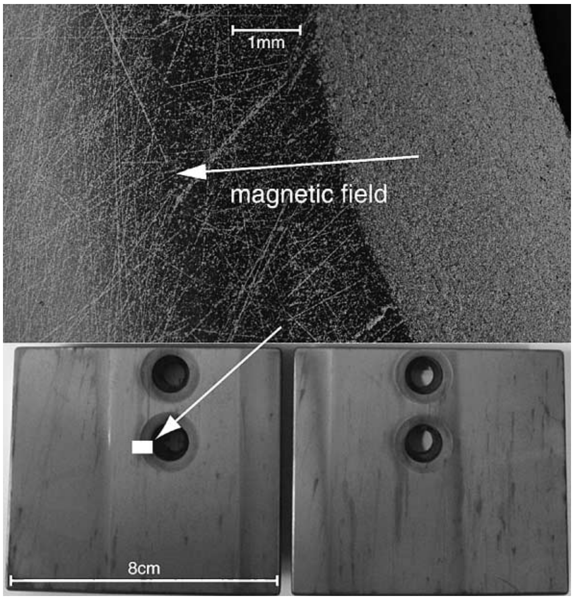

Fig. 4. SEM image of the area around the edge of a mounting bore of a W-coated tile from the lower edge of the heat shield in campaign 1999/2000. The photographic image of a tile pair shows the approximate location where the SEM image was taken. The brighter areas in the SEM image indicate higher electron backscattering caused by the presence of tungsten. The darker areas correspond to a carbon surface.

The SEM image in Fig. 4 shows the area around the edge of a mounting bore of a W-coated tile. At the bevelled edge of the mounting bore the original tungsten layer was shadowed from direct plasma contact and is therefore still intact. In the area just outside the hole, the W-layer is almost completely eroded due to direct plasma contact. The erosion pattern is clearly associated to the direction of the magnetic field lines. Similar to the initial test tile results, residual tungsten is only found in surface grooves from the machining of the tiles. The strong short scale variations and the dependencies from the field line geometry show clearly that the observed erosion is caused by impact of ions as opposed to sputtering by charge exchange atoms or possible erosion effects by glow discharge cleaning, which would lead to a much more uniform distribution of the erosion.

4. Tungsten migration and redeposition

Migration and redeposition of eroded tungsten were investigated mainly by post-campaign analysis of tungsten deposition on a complete poloidal cross-section of graphite and carbon fibre composite divertor and baffle tiles, which were removed after campaign 1999/2000. Fig. 5(a) shows the geometry of the ASDEX Upgrade divertor II configuration during this campaign. Poloidal positions at the tile surfaces are given in terms of a coordinate S, which represents the distance from the inboard divertor throat along the tile surfaces as indicated in Fig. 5(a). The amount of redeposited tungsten was determined by RBS using 1.5 and 3.0 MeV protons. Fig. 5(b) shows the tungsten areal density along the poloidal contour of the divertor and baffle tiles. Only minute amounts of tungsten are found at the plasma wetted strike point modules of the divertor. The tungsten deposition increases strongly towards the divertor throat baffle modules with the deposition maximum at the inboard horizontal closure tiles. This pattern with the deposition maximum at surfaces, which are in contact only with the outer region of the edge plasma, indicates that a major fraction of the eroded tungsten migrates directly through the plasma scrape-off layer without entering the confined plasma. This is presumably a result of the comparatively short ionisation length of eroded tungsten atoms, which leads to a good shielding by the edge plasma and is in agreement with spectroscopic measurements of a W-penetration probability in the range of 1% [4].

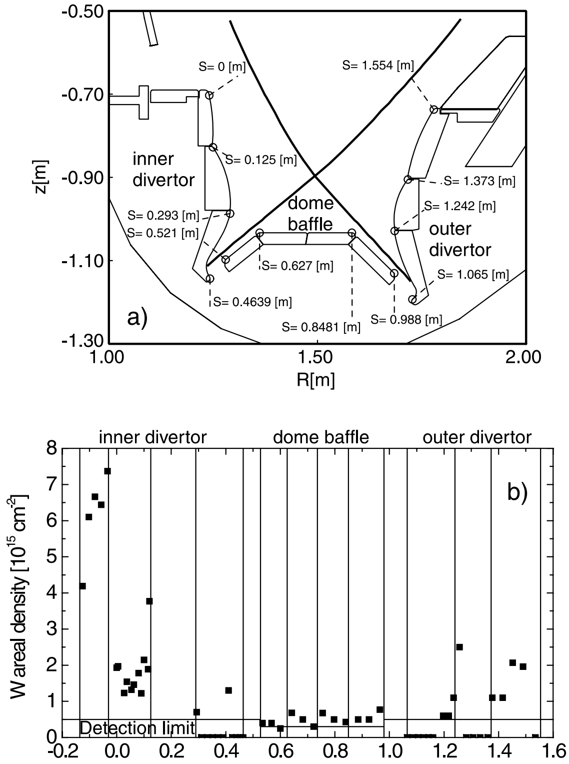

Fig. 5. (a) Poloidal cross-section of the ASDEX Upgrade divertor II during experimental campaign 1999/2000 and (b) area density of deposited tungsten at divertor II plasma facing components plotted along the poloidal contour coordinate S as shown in (a).

5. Summary

In subsequent experimental campaigns ASDEX Upgrade has been operated with large areal tungsten plasma facing components in the main chamber. Tungsten coated graphite were introduced at the central column heat shield with the area increasing in two steps from initially 1.2–6.5 m^2.

Tungsten erosion was studied by ion beam analysis of the tungsten coatings before and after the experimental campaigns. From the spatial distribution and the magnitude of the measured tungsten erosion flux the predominant erosion mechanism has been identified as erosion by impact of ions from the scrape-off layer plasma. Tungsten migration and redeposition was investigated by determination of the spatial distribution of deposited tungsten at divertor and baffle wall tiles. Tungsten redeposition increases from the plasma wetted strike point zone in the divertor towards baffle surfaces in contact with outer edge plasma regions. This observation and the low tungsten plasma penetration probability demonstrate the good shielding of eroded tungsten from the confined plasma.

Consequently, tungsten plasma concentrations in fusion relevant discharge scenarios have so far remained far below the maximum tolerable limit despite the increased tungsten source term. Due to the positive results obtained so far, the tungsten covered area has been increased further to almost full coverage of the inner column heat shield.

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