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Tungsten erosion in the baffle and outboard regions of the ITER-like ASDEX Upgrade divertor

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Abstract

Similar to the design of the next-step device ITER, ASDEX Upgrade is equipped with vertical divertor targets with adjacent baffles extending towards the main chamber. In ITER, it is intended to employ tungsten as a plasma-facing material in this baffle area. Tungsten-coated graphite tiles were installed in the divertor baffle and the outboard side regions of ASDEX Upgrade for a full experimental campaign. The erosion behavior of tungsten was investigated by scanning electron microscopy and by measuring the thickness of the tungsten coatings before and after exposure. The coatings had an initial thickness of approximately 450 nm. Two distinct erosion mechanisms were observed: in the outer baffle region a reduction of the coatings' thickness up to 100 nm was determined after about 6300 s of plasma discharge. On the roof baffle and on the inner baffle modules, no clear reduction of the film thickness was found. In the tracks of arcs, however, the tungsten coatings were completely removed. This represents an erosion of 5–10% of the tungsten-coated surface area in this region.

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1. Introduction

The choice of the plasma-facing materials in future fusion devices is governed by boundary conditions stemming from various independent objectives – lifetime considerations concerning erosion and neutron irradiation, tritium inventory and thermo-mechanical issues as well as radiative cooling and dilution of the plasma. All of these have to be met simultaneously.

Such considerations have led to the conclusion that different plasma-facing materials are required in different locations of the next-step device ITER (see [1] and references therein): It is currently intended to use beryllium in the main chamber and a combination of tungsten and CFC material for the divertor. In this arrangement, tungsten is employed for the baffle regions of the divertor and CFC for the vertical targets. A full coverage of the divertor with tungsten is, however, also under consideration after the first exploratory stage of ITER operation [2,3]. Also for the main chamber first wall, tungsten is regarded as a possible alternative candidate material [3]. This is supported by the positive results obtained from the ASDEX Upgrade tungsten program described below.

For a fusion reactor first wall, beryllium is not regarded as a possible material choice, the erosion-domi-

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nated lifetime would be much too short [3,4]. Here, a tungsten coating on the first wall is currently considered to be an attractive alternative [4].

In the light of these potential applications as a first wall material in future devices, the prospects of tungsten have been investigated at ASDEX Upgrade: after some exploratory experiments, a full tungsten divertor was installed and operated in 1995/1996 [5]. The technical performance of the plasma-sprayed coatings [6] employed in this experiment as well as plasma–wall interaction issues [7,8] were thoroughly assessed. For a large-area application in the main chamber, tests were performed and an industrial-scale method for applying micrometer tungsten coatings onto carbon-based substrates was qualified [9,10]. In a stepwise approach this type of coating was installed on subsequently larger areas of the main chamber first wall. An up-to-date description of the current status and the evolution of this process can be found in [11,12]. Detailed results on the erosion of coatings installed at the central column of ASDEX Upgrade and on the subsequent tungsten migration are given in [13,14].

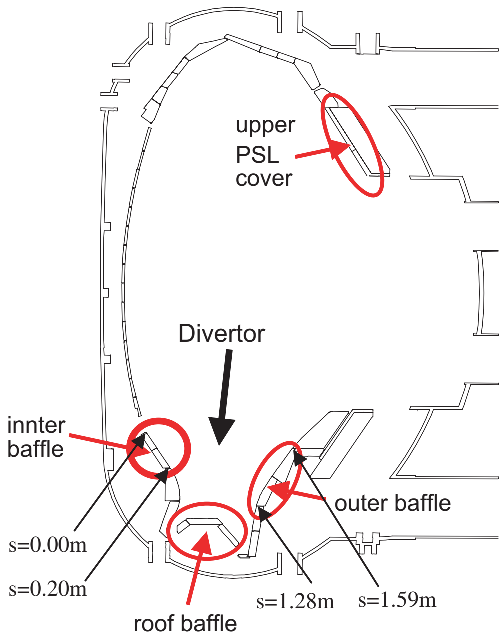

Fig. 1. A cross-section of the ASDEX Upgrade divertor IIb configuration. The locations of the W coated probe tiles are marked: upper passive stabilization loop (PSL), outer divertor baffle, roof baffle, and inner divertor baffle. Also shown is the surface contour coordinate s starting from zero at the inner baffle top and extending counter-clockwise.

2. Experimental

This publication deals with results on the erosion of tungsten in the divertor baffle regions of the divertor IIb configuration of ASDEX Upgrade (see Fig. 1) as well as results obtained from coated probe tiles installed on the outboard side of the vessel on the covers of the upper passive stabilization loop (PSL). The locations of the investigated probe tiles are depicted in Fig. 1. The figure also shows the vertical divertor targets below the baffle region. This geometry is similar to the ITER design. As all tungsten surfaces in ASDEX Upgrade, the erosion probe tiles consisted of PVD tungsten coatings on fine-grain graphite substrates supplied by Plansee AG. A comparative study of the fusion-relevant properties of such coatings was published in [9]. To increase the sensitivity with respect to erosion, unlike the rest of the plasma-facing tungsten coatings, the erosion probe tiles had an initial film thickness of about 450 nm as determined by Rutherford backscattering (RBS) assuming the density of bulk tungsten, which is 6.3×10^{22} atoms/cm^2 as given in Ref. [15].

Most of the tiles were mounted for a full experimental campaign consisting of 1132 successful plasma discharges with a total duration of about 6300 s and about 5400 s of divertor operation. Only the tiles from the inner baffle were removed after 623 discharges lasting about 3600 s with about 3000 s of divertor operation. After removal, the surface morphology of the probe tiles and the integrity of the coatings were determined by scanning electron microscopy (SEM). The change of coating thickness was determined by repeating the RBS analysis. Since the resulting spectra displayed some distinct distortions, most likely intermixing effects of tungsten with light chemical elements and some increase in surface roughness, a determination of the remaining film thickness in nanometers was not straightforward. Using the software package WinDF V7.0 [16], a tungsten depth profile was fitted to each spectrum. The differences of the integrals over these depth profiles for each measurement location were then taken to determine the amount of eroded tungsten. The results of this procedure were converted to nanometers employing the density of bulk tungsten (6.3×10^{22} atoms/cm^2). To direct the ion beam onto the designated measurement locations, a four-axis manipulator system was used to position the tiles with respect to the beam. To correctly calculate the eroded amount, it is necessary to retrieve these locations several months later after plasma exposure of the tiles. Employing a system of two crossing diode laser beams, the accuracy for this process was on the order of one millimeter, which is the same order as the ion beam spot size. The latter also implies that the ion beam results are to be understood as averages over a surface area of approximately one square millimeter.

3. Results and discussion

Figs. 2 and 3 show the results of the ion beam analysis of the PSL cover and of the inner and outer divertor baffle region, the respective locations within the vacuum vessel are displayed in Fig. 1. The data from the roof baffle are not shown. As an example for all the following measured data, Fig. 2(a) shows, how the measurement locations were distributed over the tiles: Measurements before and after exposure were performed in two poloidal rows about 15 mm from the toroidal edges of each tile. Analysis locations were distributed equidistantly along the poloidal length of each individual tile. The PSL cover tile has a poloidal length of about 37 cm. Outer and inner baffle regions consist of two tiles, each with a total poloidal extension of 31 cm and 20 cm, respectively. The central roof baffle consists of three tiles with a total length of approximately 30 cm. This results in a typical distance of the individual analysis locations of about 5 cm for the PSL cover and approximately 3 cm for the divertor tiles. The graphs give the eroded amount of tungsten in nanometers as an upward pointing column.

On the PSL cover, a rather homogeneous erosion pattern can be observed with maximum and minimum values of 16 nm and 30 nm, respectively. The average value amounts to approximately 20 nm. As was already observed in some of the first exposures of probe tiles in the main chamber of ASDEX Upgrade [17], this erosion exceeds the value expected from physical sputtering by charge exchange neutrals according to [18] by more than a factor of 10. With the typical electron temperatures for this radial position [19], it must be assumed that deuterium plasma ions barely exceed the threshold value for physical sputtering of tungsten. This strongly points towards multiply-charged plasma impurities as the actively sputtering species. Another explanation could be rather energetic deuterium ions expelled from the plasma by ELMs.

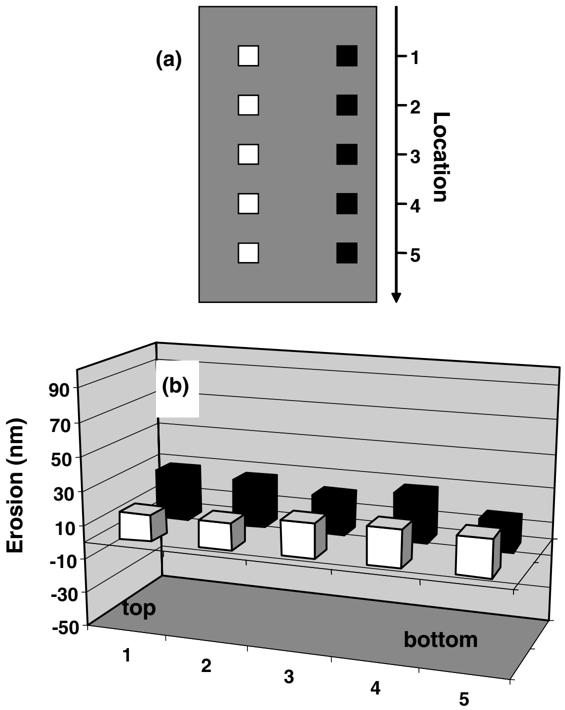

Fig. 2. Erosion data from the PSL cover: (a) is a schematic representation of the distribution of the measurement locations over the tile and (b) shows the results. Erosion was found on each analyzed spot. The average value is about 20 nm.

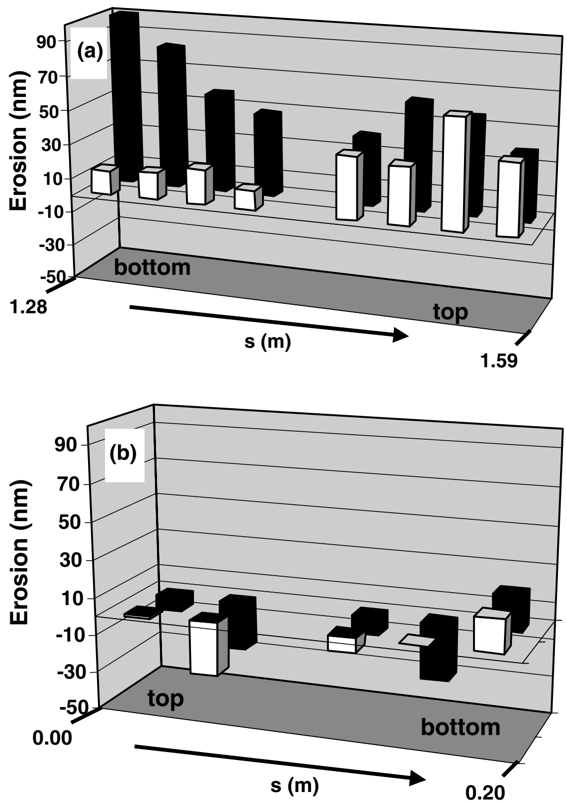

Fig. 3. Erosion data from outer (a) and inner (b) divertor baffle. The distributions of the measurement locations over the tiles are similar to Fig. 2. In the outer baffle region (a) strong erosion can be observed with a tendency to increase towards the strike point (direction bottom). On the inner baffle (b), however, most data points are close to zero and the data scatter between erosion and deposition.

Fig. 3 shows the erosion data from the outer (a) and inner (b) divertor baffle, respectively. On the outer baffle tiles, strong tungsten erosion is found amounting to a maximum of about 60 nm on the upper tile and 100 nm on the lower tile, respectively. In terms of nanometers per discharge time, this is the largest amount of tungsten erosion observed so far within the ASDEX Upgrade tungsten program. On the lower tile (bottom), a pronounced difference between the two toroidal rows can be observed. We interpret this as a shadowing effect of the row displayed in white by its upstream neighbouring tile – the tiles are flat and therefore form a polygon. This would then again demonstrate, that the observed erosion is due to energetic ions, not due to charge exchange neutrals.

It was shown in Ref. [8], that adding only one atomic percent of multiply-charged carbon ions to a deuterium plasma increases the yield for physical sputtering of tungsten by more than two orders of magnitude as compared to a pure deuterium plasma, if the electron temperature is sufficiently low. On this basis, the observed erosion of tungsten was interpreted as being caused mainly by carbon impurities eroded from the main chamber walls. Adopting the assumption of 1 at.% of C^{4+} as the plasma impurity and assuming a local electron temperature around 10 eV, the data from Ref. [8] indicate a W sputtering yield of about 10^{-4}. To erode 100 nm of W at this yield requires a total fluence of about $6 \times 10^{25}\ m^{-2}$. With the total lower divertor operation time of 5400 s given above, this results in an average necessary flux on the order of $10^{22}\ m^{-2}$. As an order of magnitude estimate, this value is in reasonable agreement with measured flux data in this area. Therefore we can conclude, that the observed erosion can be accounted for by light impurities like carbon in the plasma impinging onto the outer baffle. Erosion by D ions from the plasma can be ruled out, since it would require fluxes orders of magnitude higher than can realistically be assumed.

If we assume this as an explanation for the erosion reported in this publication, we obtain a qualitatively consistent picture and the increase of the observed erosion towards the strike point can be interpreted as an increasing plasma fluence. In this case, however, a similar situation would have to be expected for the ITER divertor baffles, since erosion of the beryllium main chamber first wall would represent a source for multiply-charged ions impinging onto the divertor baffle areas.

In contrast to the above findings, the inner divertor baffle tiles do not display significant erosion. Most of the data are close to zero and in addition there is a large scatter, even with a change of sign, between −30 nm and +20 nm of erosion. There is, however, a feature which does not exist on the outer divertor baffle tiles: on the tiles of the inner baffle, a large areal density of arc tracks is observed. Fig. 4 shows one example for such a track. As a detailed investigation using back-scattered electrons and energy-dispersive X-ray analysis shows, the arc completely removed all tungsten from its track. In addition, Fig. 4 also shows, that along the arc track molten material is produced and redistributed. A combination of microscopy and ion beam analysis was not employed in this investigation. Therefore the arcing situation on the investigated ion beam spot areas with a diameter of only one mm is unknown. This is a tentative explanation for the large scatter observed in the data of Fig. 3(b). In summary, it can be concluded that the inner divertor baffle does not exhibit any distinct erosion pattern by ion impact. In this respect, this area rather seems to be deposition-dominated. The large number of arc tracks, however, represents an erosion of the tungsten coating by about 5–10% of its surface area, removing the coating completely in its full thickness of 450 nm. A similar picture was observed for the roof baffle tiles.

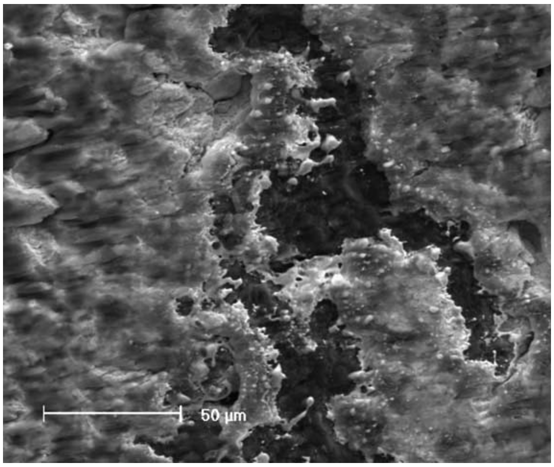

Fig. 4. SEM image of an arc track from the inner divertor baffle region. Detailed analysis shows, that the arc removed the complete thickness of the tungsten coating. On the edges of the track, traces of molten tungsten can be identified. From vacuum arcs it is well known, that their cathode spots generate a spray of droplets [20].

The cathode spots of vacuum arcs are known to generally generate a spray of liquid droplets [20]. As Fig. 4 shows, the same must be expected from the arcs observed here. When these droplets cool and resolidify, this is a mechanism for the production of dust particles with sizes in the micrometers range [21]. It is stated in [20], that an older investigation [22] found, that an arc discharge on a massive tungsten surface even produces macroparticles with no signs of melting. For these reasons, the observed erosion of tungsten by arcing would represent a possible safety concern in a fusion reactor via the formation of radioactive dust particles [3] which may accumulate in the plasma vessel and possibly be liberated during accidents.

4. Summary and conclusion

By installing fine-grain graphite tiles coated with 450 nm of tungsten, the erosion of tungsten was investigated on the outboard main chamber wall and in the divertor baffle area of ASDEX Upgrade for an experimental campaign comprising 1132 successful discharges with a total duration of about 6300 s.

Two distinctively different mechanisms of tungsten erosion were found: On the outbard side, smooth erosion patterns were observed. The eroded amount scaled to about 20 nm on the cover of the upper passive stabilization loop; on the outer divertor baffles, it showed a peak value of 100 nm. This erosion is obviously caused by impact of multiply charged light impurity ions. In the ITER device, the beryllium main chamber first wall could be a source for such ions. The tiles from the inner divertor baffle, in contrast, did not show significant erosion by ions. Instead, here the erosion of the tungsten coatings was found to be generated by arcing. In a future fusion device, such arcing on tungsten surfaces may represent a safety concern, because the spray of liquid droplets and macroparticles generated by the cathode spot of an arc can be regarded as a source of radioactive dust.

Finally, it must be mentioned, that plasma–wall interaction is a topic, which is very sensitive to the peculiarities of a particular device as well as to specific discharge conditions, especially when statements on erosion processes are drawn from a whole experimental campaign. Therefore, discharge-resolved data accompanied by numerical simulations are required for an extrapolation of the observed phenomena to a next-step device.

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