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Plasma operation with tungsten tiles at the central column of ASDEX Upgrade

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Abstract

Two rows of the graphite tiles (≈1.2 m^2) at the lower end of the central column of ASDEX Upgrade were coated with tungsten. Since no high heat fluxes are present in this region, the tiles were coated by a physical vapour deposition technique to a thickness of only 500 nm. The experimental campaign was started without wall conditioning by coating of the vacuum vessel. This allowed to measure the W-erosion and the W-concentration with an almost pure tungsten surface exposed to the plasma. The influx as well as the concentration were monitored by spectroscopic methods. The penetration probability for tungsten from the central column is deduced from direct laser ablation of the coating. The measurements were complimented by deposition probe measurements in the midplane and in the divertor. In all important discharge scenarios, which were performed already during the phase without wall conditioning, no concentrations above the detection limit of about 5×10^{-6} were found. This result is supported by the deposition probe measurements, which showed no or very small amounts of W deposited in single discharges. The concentrations are at least a factor of 10 below the acceptable concentration in ASDEX Upgrade. Consequently, no influence on the overall plasma behaviour was found and W seems also to be suited for use on larger surfaces in ASDEX Upgrade. Extrapolation to ITER conditions yields concentrations, which will not prohibit successful operation. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Tungsten; First wall materials

1. Introduction

Recent observations of high amounts of codeposited hydrogen and tritium in thick carbon layers may lead to a very fast accumulation of T (see [1] and references therein) and will restrict the use of carbon-based materials to relatively small surfaces in a future fusion device. In the search for alternative plasma facing materials (PFM), tungsten is a serious candidate because of its advantageous thermomechanical properties, its high sputtering threshold and low sputtering yields [2]. However, its high radiation potential [3], caused by the fact that even at the plasma temperatures of a fusion reactor it is not fully ionized, sets a very low margin (2×10^{-5}) for the tolerable central concentrations [4].

At ASDEX Upgrade, it could be shown under reactor relevant conditions that the use of W as a PFM in the divertor is rather promising since no adverse effects on the plasma performance were found and the W-concentrations were mostly lower than the tolerable ones [5]. Additionally, the hydrogen inventories were found to be much smaller in the tungsten-coated tiles compared to graphite tiles and were predominantly due to codeposition in C-layers [6].

In ITER, tungsten is planned to be used at the baffles surrounding the divertor strike point module [1,7]. Here the plasma flux and the flux of impurity ions are lower, however, recent model calculations for ASDEX Upgrade showed that sputtering by higher energetic charge exchange (CX) neutrals may be significant [8].

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Only few fusion devices use high-Z materials as PFM [9]. These devices either operate at high plasma currents and high plasma densities as Alcator C-Mod and FT-U or use high-Z materials only as test limiters like TEXTOR. As an overall result from these experiments, it can be stated that under high-density conditions, no limitations from the high-Z materials occur. To investigate the use of W as a PFM outside the divertor in a device operated at reactor-like densities, two rows of the graphite tiles at the lower end of the central column in ASDEX Upgrade were exchanged to tungsten-coated tiles. This is the poloidal position, where the highest sputtering flux due to CX-neutrals is predicted. However, according to the experience from siliconization [10] and from the examination of tungsten-coated test tiles [11] also, sputtering by ions seems to be significant in this region.

In this contribution, the tungsten coating will be described and first results from the plasma operation will be presented. The behaviour of tungsten was monitored by spectroscopic methods. These measurements were complimented by deposition probe measurements in the midplane and in the divertor and by direct laser ablation of the coating at the central column.

2. The tungsten coating

In the present experimental campaign, the lowest two rows of graphite tiles at the central column (heat shield) of ASDEX Upgrade were replaced by tungsten-coated ones (see Fig. 1). These represent a total area of 1.2 m^2 accounting for about 10% of the total heat-shield area.

The shape of the tiles was changed from the original rectangular design to a trapezoidal one in order to reduce edge erosion (see Fig. 2). Additionally, the tiles were polished to reduce the surface roughness to values in the range of the thickness of the coating. The W-layer was applied by PVD at 150°C with a thickness of about 500 nm, which was calculated from the weight of the deposited W on special monitor samples. This thickness minimizes the mechanical stress on the coating and is sufficiently large for the erosion expected at this position. Several tiles were additionally characterized by SEM and RBS analyses. The W-thickness extracted from the RBS measurements was quite similar to the results from the coating procedure itself, whereas the SEM analysis yielded larger values by 40%. This can be explained by the contamination with C and O, which is deduced from XPS to be about 10% C and O and from the fact that the density of the coating may be somewhat lower than that of solid W.

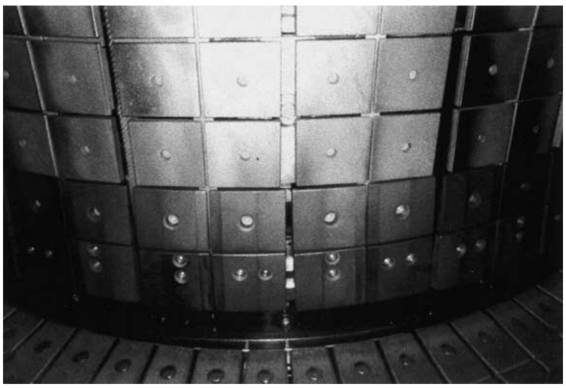

Fig. 1. Lower part of the central column in ASDEX Upgrade showing the two rows of tungsten-coated tiles.

Fig. 2. Optimized tile with trapezoidal shape to reduce the edge power load. The size of a tile is approximately 80×80 mm^2.

During the plasma operation no signs of peeling off of the W-layer were observed. These findings were confirmed by an optical inspection during an intermediate opening of the machine after about two months of operation.

3. Spectroscopic investigations

The experimental campaign was started with the standard conditioning procedure by baking the machine at 150° for 65 h and by He glow discharge for 8 h but without wall conditioning by coating of the vacuum vessel. This allowed to measure the W-erosion and the W-concentration with an almost pure tungsten surface exposed to the plasma. During this period, discharges in all major plasma regimes were performed. Moreover, specially dedicated limiter discharges were produced in which the closest possible distance to the W-tiles was realized (see Fig. 3). After about 60 discharges, siliconization of the vessel walls was performed, and to date about 600 discharges with heating powers up to 15 MW were made.

The behaviour of tungsten in plasma discharges was mainly monitored by spectroscopical means. For the

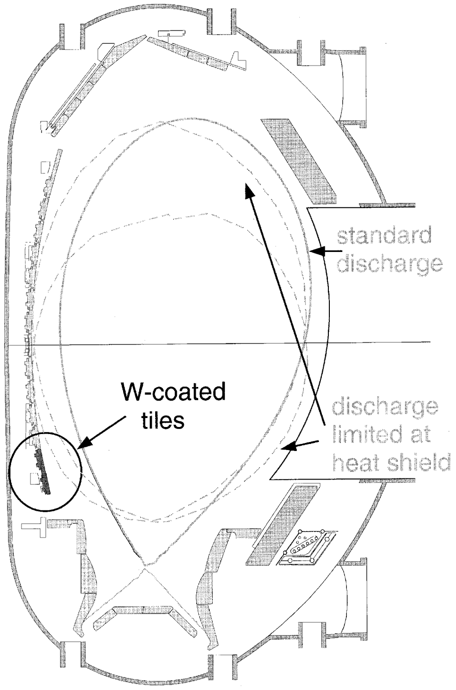

Fig. 3. Poloidal cross-section of the ASDEX Upgrade together with the positions of the last closed flux surfaces in a standard divertor configuration and during a vertical scan of a limiter discharge.

influx measurement, the intensity of the WI line at 400.8 nm was used. The observation was made employing both, a spectrometer system with a movable mirror, which allows one to scan the whole central column (see [12]), and a fixed fiber optics which was specially dedicated to the long-term observation of the W-tiles. In none of the discharges, even in those which were in limiter configuration, a significant signal for the WI line was found. Therefore, only an upper limit for the influx can be estimated. Using the S/XB from [13], one gets the value of 1.2×10^{18} m^{-2} s^{-1}.

Besides the W-influx, also the C-influx from the W-tiles was monitored. In Fig. 4, the intensity of a CIII spectral line at 465 nm is plotted against the intensity of the OVIII Lyman-α spectral line (1.897 nm), which is a measure for the oxygen edge density. Already starting with the first discharge, a strong CIII signal was visible. With an increasing number of discharges, the CIII influx decreased and rose again after a venting of the vacuum vessel. Finally, it dropped by a factor of 2 after siliconization. This behaviour implies that a thin carbon layer is built up rather quickly which is in a dynamical equilibrium with the impurity content in the plasma as already observed from metallic surfaces in ASDEX Upgrade and TEXTOR [13,14]. As no surface coating was performed at the start of the campaign, high levels

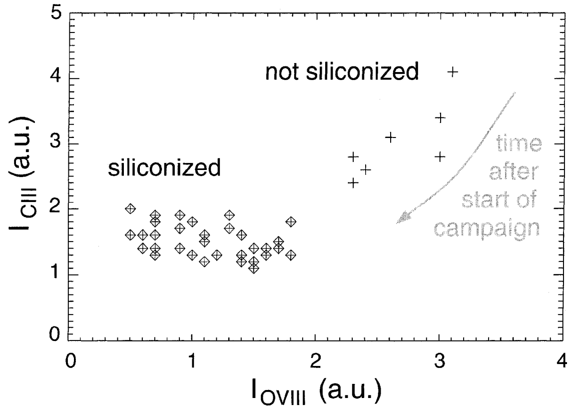

Fig. 4. Carbon influx (CIII line intensity) from the tungsten tiles in discharges with $I_P = 1$ MA, $\bar{n}_e \approx 6 \times 10^{19}$ m^{-3} and $P_{NBI} = 5$ MW, plotted versus the oxygen edge density (OVIII line intensity). For high levels of O, a strong correlation of both signals is found.

of O were observed, which slowly decreased from discharge to discharge and finally reached very low levels after the siliconization. The correlation with the oxygen density for high levels of O clearly demonstrates the role of oxygen in the C recycling by the production of CO. For lower O-density, as after the siliconization, other effects, such as chemical erosion and local redeposition may take over at a reduced level.

The W-concentrations were extracted from the so-called W-quasicontinuum at about 5 nm following the procedure described in [15] and from W-lines observed in the soft X-ray (≈0.7 nm) spectral region [16]. The detection limit was established by injection of W by laser ablation. This kind of cross-calibration was performed in several discharges and the result of this procedure is presented in Fig. 5. From this, one can nicely judge the reliability of this method and also, a detection limit of at

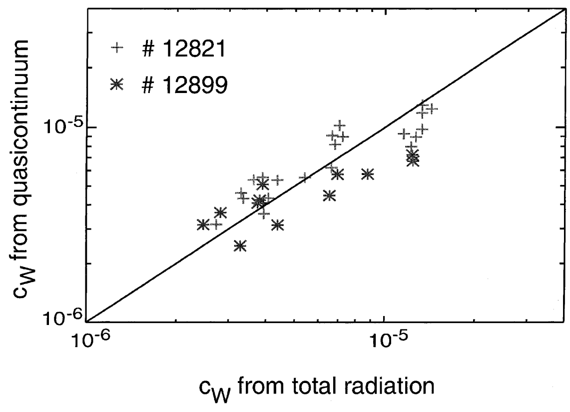

Fig. 5. Cross-calibration of the concentration evaluated from the quasicontinuum radiation and the total radiation in two discharges with repetitive W-injection.

least 5×10^{-6} for discharges with intermediate densities can be extracted. In the case of the soft X-ray spectra, the concentration was calculated directly from the absolute intensity of the spectral lines by comparison with intensities from a collisional radiative model. Both diagnostics did not show significant signs of tungsten in any discharge. Neither in low-density H-mode discharges, where the sputtering yield by the CX-neutrals is assumed to be highest, nor in plasmas with smaller distance to the inner column, where the sputtering by plasma particles may play a role, enhanced concentrations were observed. Only recently, a focusing X-ray spectrometer (Johann type) was commissioned to measure the intensity of a spectral line at 0.793 nm from Ni-like W. With this instrument we were able to detect W non-ambiguously in a few low-density H-mode discharges with concentrations of a few times 10^{-6}.

An experimental investigation was performed to get an estimate for the particle confinement time τ_p for W originating from the central column. For this purpose, the laser of the laser blow off (LBO) system at ASDEX Upgrade [17] was focused on the W-coating at the central column in an H-mode discharge with $\bar{n}_e = 6 \times 10^{19}$ m^{-3}, $T_{e0} = 3.0$ keV and 5 MW neutral beam heating. The layer could be ablated with one single laser pulse and the number of ablated particles was calculated from the thickness of the coating and the spot-size. The tungsten penetrating into the plasma was analyzed with the spectroscopic means described above. For non-recycling impurities, the particle confinement time τ_p can be separated (at least formally) in a penetration probability, that means the probability to reach the confined plasma and the transport time within the confined plasma. This penetration probability depends on the impurity species and its energy when it interacts with the SOL as well as on the local properties of the SOL, which can vary for different discharge types but also for different spatial locations inside the tokamak. From the comparison of the total amount of ablated W-atoms and the maximum number of W-ions in the plasma, a penetration factor of 0.04 is calculated. Performing the same experiment with a W-target of comparable thickness at the low field side of the the torus (classical laser ablation), a value of 0.03 is found for the penetration of the W. This result is illustrated in Fig. 6 where the temporal evolution of the W-density is shown.

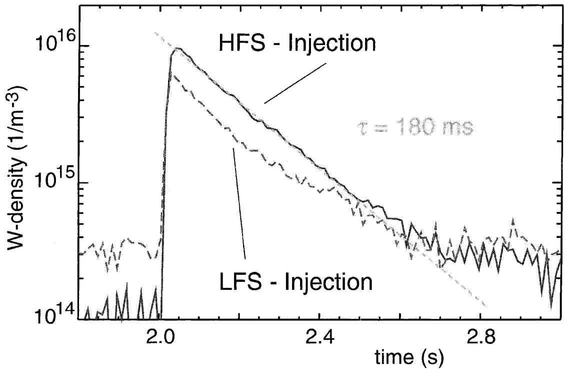

Fig. 6. Temporal evolution of the tungsten density after W-ablation from central column (solid line) and from a W-target at the low field side (dashed line, scaled to the same amount of ablated W). The values for the W-densities before the injection are below the detection limit.

4. Migration

To complement the spectroscopic measurements, deposition probes were exposed to special discharge series in the first phase of the campaign. Since W is by far the heaviest element existing in the tokamak, the sensitivity of the surface analysis methods, especially that of RBS, is very high. The probes were exposed both in the outer midplane and in the divertor.

The evaluation of the divertor probes showed averaged W-fluxes from 0.5 to 2.8×10^{17} atoms m^{-2} s^{-1}. The W-fluxes are largest in H-mode discharges with very low electron densities, which is expected because of the higher erosion by CX-particles [8].

The midplane probe showed no W-deposition above the detection limit of 10^{17} atoms m^{-2}. This observation is consistent with the observations in the divertor, since the W-deposition is concentrated in the small strike-point region in the divertor because of the much faster parallel transport in the scrape-off layer. Additionally, this also leads to a larger integral deposition in the divertor as already shown in [18].

5. Discussion

To check whether the different W-measurements are consistent with each other, one can use the numbers for the W-penetration ($P = 0.04$) and the transport time ($\tau = 180$ ms) extracted from the ablation of W from the central column. Taking the detection limit for the W-influx and the W-surface area, one gets a maximum influx of about 10^{18} W-atoms s^{-1}. This would lead to a discharge with intermediate density (6×10^{19} m^{-3}) to concentrations below 10^{-5}, which is true for all discharges. The comparison of the probe measurements with the spectroscopic measurements is much more complicated since a model for the transport is needed. Under the likely assumption that there is no direct W-flux in the SOL across the X-point or the upper stagnation point, the eroded tungsten can only reach the outer midplane or the outer strike point through the main plasma. However, this would lead to erosion fluxes, which were up to a factor of 10 higher than the spectroscopic detection limit. But allowing also a direct transport channel not involving the bulk plasma, all observations are consistent. In this context, post mortem analyses of the W-deposition on the inner divertor tiles will be of major interest to pin down the migration pattern.

Comparing the actual measurements to the long-term erosion measurements of Tabasso et al. [11] and their calculations for D-discharges following the simulations of [8], total W-fluxes below $5 \times 10^{16}\ s^{-1}$ are expected from sputtering by CX particles. This value is lower than the one extracted from the measured W-deposition fluxes in the divertor and may be explained by W-ion sputtering observed in [11].

The extrapolation of our results to ITER clearly requires modeling efforts employing self-consistent calculations on SOL and the central transport. Nevertheless, an estimation can be made combining our observations and the numbers for hydrogen fluxes, their mean energies, the W-area in the main chamber, the particle content and confinement time from [1,19] as well as the CX sputtering yield from the simulations of [8] and the measurements of [11]. This yields W-concentrations in ITER of $1–10 \times 10^{-6}$ (range given by the uncertainty of D-fluxes) resulting solely from the W-surfaces in the main chamber. However, it should be kept in mind that the penetration factor in ITER may be lower, but also that the CX sputtering yield is a strong function of energy. This will restrict the use of W in ITER clearly to the high-density domain.

6. Summary and outlook

Two rows of the graphite tiles ($\approx 1.2\ m^2$) at the lower end of the central column of ASDEX Upgrade were coated with tungsten to a thickness of about 500 nm. The influx as well as the concentration were monitored by spectroscopic methods and the penetration probability for tungsten from the central column was deduced from direct laser ablation of the coating. The spectroscopic measurements were complimented by deposition probe measurements. In all discharge scenarios, which were performed already during the phase without wall conditioning, no concentrations above $\approx 5 \times 10^{-6}$ were found. This result is supported by the deposition probe measurements, which showed no or very small amounts of W deposited in single discharges. Consequently, no influence on the overall plasma behaviour was observed. Extrapolation to ITER conditions yields concentrations which will not prohibit successful operation.

In the future, direct laser ablation from the heat shield will be further used for the in situ characterization of (deposited) surface layers and for transport investigations and the focusing crystal X-ray spectrometer will allow to extract routinely W-concentrations down to 10^{-6}.

One of the current aims at ASDEX Upgrade is the reduction of carbon surfaces. In this context, the ongoing campaign was a benchmark for the use of larger W-surfaces. Motivated by the presented results, it was decided to cover two-thirds of the heat-shield area ($\approx 6\ m^2$) with tungsten during the next campaign. From this, further information about the general use of tungsten in a fusion device should be gained and the configuration will also allow to perform tests with direct plasma contact.

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