

HYDROGEN ISOTOPE INVENTORIES IN THE ASDEX UPGRADE TUNGSTEN COATED DIVERTOR TILES

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ABSTRACT. The total hydrogen isotope inventories in the tungsten coated divertor tiles of ASDEX Upgrade were measured by thermal desorption spectroscopy and — in the near surface region — by nuclear reaction analysis. The highest amounts of deuterium ($\lesssim 5 \times 10^{22}$ D/m²) are measured in the inner divertor region outside the separatrix due to the formation of a C:H layer on the tungsten by co-deposition of deuterium with carbon. The inventories in the outer divertor — where erosion dominates — are generally smaller by an order of magnitude.

1. INTRODUCTION

Apart from graphite and beryllium, the high-Z material tungsten is considered as plasma facing material for ITER. In order to provide an experimental data base for the ITER divertor, tungsten coated graphite tiles have been installed as divertor target plates in the tokamak ASDEX Upgrade for the experimental period December 1995 to July 1996 [1].

In order to obtain a measure and to improve the understanding of hydrogen retention in tungsten under reactor-like conditions, the total hydrogen isotope inventories of the tungsten divertor tiles of ASDEX Upgrade were measured with Thermal Desorption Spectroscopy (TDS). The near-surface deuterium inventory was measured by Nuclear Reaction Analysis (NRA).

2. EXPERIMENT

The tungsten coated carbon tiles had been installed in the ASDEX Upgrade divertor at the separatrix intersection areas (figure 1). They consist of a 500 μ m thick plasma sprayed tungsten layer on a graphite substrate. In order to avoid hot spots at the edges, the tiles were tilted in toroidal direction. Hence, a part of each tile is shadowed from the plasma by the edge of the adjacent tile, and receives much less plasma flux than the non-shadowed part of the tile. In the following, we will denote the former region as 'shadow region', whereas the region with the full plasma impact will be denoted as 'plasma region'.

About 800 discharges were performed in the tungsten experimental period. Out of these,

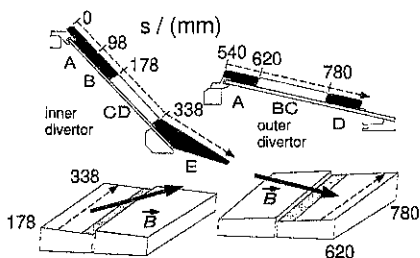


FIG. 1. Position of the tungsten coated graphite tiles (CD and BC, respectively) in the ASDEX Upgrade divertor. The tiles are tilted in toroidal direction, resulting in regions shadowed from the plasma by the edge of the adjacent tile. The arrows denote the directions of the magnetic field lines. The other graphite tiles had no tungsten coating.

about 480 discharges had been heated additionally by neutral injection. Initially, the heat load on the tungsten tiles was limited to 7 MW/m² in order to avoid damage, but during the experiments also discharges with full auxiliary heating power of 10 MW were performed, resulting in heat loads of more than 10 MW/m² [1]. Mostly, the discharges had deuterium as filling gas, and, in case of neutral injection, as well as injected atoms. Hydrogen as filling gas was used mainly in the middle of the experimental period and for the last 10 discharges. In the case of deuterium filling, hydrogen (H) is still present in the discharge. Typical values are 10% to 20%, while in the case of neutral injection with H⁰, the H background amounts to about 60% [2]. From these figures and the number of different discharges, a mean H/D ratio in the plasma core of about 0.5 can be estimated.

Thermal Desorption Spectroscopy. The experimental setup used in this work for the TDS experiments is described in ref. [3]. The samples, having a diameter of about 12 mm and a thickness of about 3 mm, are cut out of the tungsten coated tiles and are heated by electron bombardment from the rear side up to 2100 K in a ultra high vacuum chamber. The desorbed gases are monitored by means of a calibrated quadrupole mass spectrometer (QMS) by the increase of the respective partial pressures at corresponding masses during the heating of the sample. The total hydrogen isotope inventories are obtained by adding up the respective atoms in all released hydrogen containing molecules (e.g. HD, D₂ and CD₄ for deuterium).

TDS spectra of hydrogen implanted in graphite show a broad peak in the range of 900 K to 1200 K, indicating the strong C-H bonds with energies of 2 eV to 4 eV [4]. TDS spectra of hydrogen desorbed from tungsten after implantation at room temperature reveal a two peak structure [5, 6]; a first peak at about 500 K to 600 K is attributed to intrinsic traps with concentrations of the order of ≤ 0.01 traps/W-atom and binding energies of about 0.5 eV. The second peak at about 700 K to 800 K occurs only after implantation with energies sufficient to produce displacement damage (≥ 180 eV for D); hence, this peak is due to trapping at the damage sites with concentrations in the range of 0.1 to 0.2 traps/W-atom and trapping energies of about 1.5 eV. During implantation — in contrast to graphite — the solute amount of hydrogen in tungsten is of the same order as the trapped one; this solute amount is released after the implantation and can be seen in TDS spectra by an immediate rise of the released flux after the onset of the temperature ramp, when TDS is started shortly after the end of implantation. In the case of the ASDEX Upgrade samples, we can expect, that the solute amount of hydrogen in the tungsten was totally released during the storage of the samples (several months). The hydrogen isotope ions impinging the divertor plates have energies of the order of 100 eV, resulting in a mean range of less than 10 nm [5]. Hence, damage in the tungsten divertor tiles is not pro-

duced by the impinging deuterium ions, but due to the impact of multiple charged impurity ions (mainly carbon) from the plasma [1].

Surface Analysis. Thick deposited carbon containing layers on the tungsten surface were detected by means of 2 MeV H⁺ Rutherford backscattering for all samples from the inner divertor. The thickness of these layers was estimated to be several μm , without large poloidal variations. In contrast, erosion dominates in the outer divertor: these samples hardly show any carbon deposition at all. The actual surface composition (mainly boron, carbon, oxygen, and tungsten) was determined by X-ray photoelectron spectroscopy (XPS). The largest amounts of boron (40%) and oxygen (20%) were detected in the plasma region of the inner divertor. However, even for the erosion dominated outer divertor samples, boron and oxygen are still present at the very surface.

Before performing TDS, the near-surface deuterium inventory was measured by NRA using the 790 keV ³He(d, α)p reaction, resulting in an analyzing range of 0.5 μm (for pure tungsten) to 2 μm (for an amorphous co-deposited hydrocarbon layer). Hence, the analyzing depth depends on the not well known surface composition of the respective sample, leading to a relatively high uncertainty of the NRA results. Due to the larger surface roughness of the plasma-sprayed tungsten coatings, no deuterium depth profiles can be obtained. If deuterium containing layers with thicknesses exceeding the analyzing range are involved, NRA can only establish a lower limit for the results to be expected from TDS.

3. RESULTS AND DISCUSSION

As in the case of the samples from the previously installed graphite divertor [2], the release of hydrogen isotopes from the tungsten coated tiles during TDS is dominated by H. The amounts are in the range of about $(5-8) \times 10^{22}$ H/m² for all samples. The by far largest part of this H can be attributed to the water uptake both on the tungsten front surface as well as on the graphite back surface during the storage of the samples in air [2]. Hence, we will restrict the following discussion on deuterium,

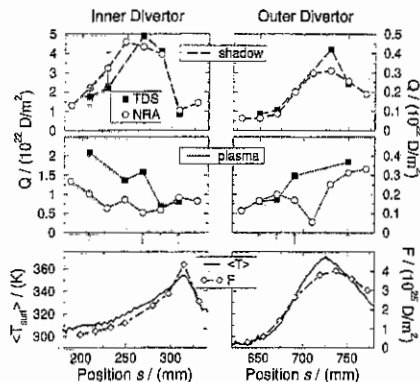


FIG. 2. Distribution of the total D inventories (Q), measured by NRA and TDS, at the shadowed and the plasma regions of the tungsten coated tiles, respectively. Also shown are the distributions of mean surface temperature ($\langle T_{\text{surr}} \rangle$), and the total incident D fluence (F). Note the different scales for the deuterium inventory plots.

Deuterium Inventories. Figure 2 shows the deuterium inventories for the different regions of the inner and outer divertor as measured by TDS and NRA. Also shown are the distributions of the mean surface temperature during the discharges with auxiliary heating by neutral injection and the incoming fluence of deuterium, as measured by thermography and Langmuir probes, respectively. The latter distributions show corresponding maxima at about 310 mm and 725 mm, roughly indicating the mean position of the separatrix during the tungsten experimental period.

The highest deuterium inventories (about 5×10^{22} D/m²) are measured in the shadowed region of the inner divertor outside the separatrix. At the position of the separatrix, the inventory shows a minimum, although the amount of deposited carbon shows only minor poloidal variations. The inventories of the outer divertor samples are generally smaller than the inner divertor inventories by a factor of 10; here the total inventories, measured by TDS, show a maximum at the separatrix position, whereas the inventories in the near surface region, measured by NRA, show a minimum at the separatrix. From this we can conclude, that deuterium

retention in the case of the ASDEX Upgrade tungsten divertor tiles in the inner divertor is governed by co-deposition of deuterium with carbon ions from the plasma, whereas implantation governs the retention in the outer divertor. Co-deposition was also found outside the separatrix in the graphite tiles of the inner divertor [2]. The co-deposited layers of the inner divertor tiles are depleted at the separatrix position as well as in the plasma region due to the increased temperature. Furthermore, the deuterium inventories in the co-deposited layers are of the same order of magnitude as those in the graphite divertor tiles ($\lesssim 2 \times 10^{23}$ D/m² [2]), taking into account the shorter exposure time of the tungsten coated tiles (about 700 compared to about 2000 discharges).

The total inventory in the tungsten coated divertor samples differs from the near surface inventory by only a factor of less than 2, except for the separatrix region of the outer divertor. This is in contrast to the graphite divertor samples, where the total inventory exceeds the near surface inventory by a factor of up to 100 indicating diffusion of large amounts of hydrogen out of the co-deposited/implanted layer into the graphite bulk to depths of some 100 μm [2]. This indicates, that diffusion of the co-deposited layer into the underlying tungsten layer (inner divertor) is hindered by the tungsten/carbon interface. The fact, that the total inventories in the separatrix region of the outer divertor exceed the near-surface inventories, indicates that deuterium diffuses into the bulk of tungsten with ranges of some few μm (hence exceeding the implantation range by more than a factor of 1000), as it is assumed in models describing the behaviour of hydrogen in tungsten [5]. The combination of high fluxes and high temperatures at the outer separatrix region depletes the near surface region, but also results in a large amount of deuterium which can diffuse into the tungsten bulk and in the underlying graphite substrate (see below).

TDS Spectra of Deuterium. Figure 3 shows some examples of TDS spectra of the tungsten coated divertor samples. For the different regions in the inner and outer divertor, (at least) four different peaks can be distin-

guished and attributed to different deuterium retention mechanisms: (1) a small peak (shoulder) at about 500 K, as in the case of the outer divertor samples, due to trapping at intrinsic trapping sites in the tungsten layer; (2) a broader peak at about 900 K in the case of the samples from the outer divertor, due to trapping at ion induced damage sites in the tungsten layer; (3) a broad and large peak at 1000 K to 1100 K in the case of the samples from the inner divertor, due to C-H bonds in the co-deposited a:C-H layer — in agreement with the peak temperature of the D_2 release from the graphite divertor samples [2]; and (4) a sharp peak at about 1400 K in the case of the samples from the outer divertor, which might be due to trapping of deuterium in the underlying graphite substrate after diffusion through the tungsten layer. The latter retention mechanism is pronounced in the case of the samples from the separatrix region ($s = 690$ mm, 748 mm), where due to high temperatures and fluxes a relatively large amount of deuterium can diffuse through the tungsten layer. Generally, the peak positions are shifted to higher temperatures compared to laboratory results, indicating the diffusion of some deuterium out of deep regions of the samples.

4. SUMMARY

The total hydrogen isotope inventories of the tungsten coated divertor tiles of ASDEX Upgrade — consisting of a 500 μm thick plasma sprayed tungsten layer on a graphite substrate — were measured with quantitative TDS. The near surface deuterium inventory ($\approx 1 \mu\text{m}$) was measured by nuclear reaction analysis (NRA) using the 790 keV $^3\text{He}(d,\alpha)p$ reaction.

The total hydrogen isotope inventory measured 'in' the tungsten divertor tiles of ASDEX Upgrade is dominated in the case of the inner divertor by the build-up of thick co-deposited C-H layers (several μm) onto the tungsten surface outside the separatrix. The inventories in these co-deposited layers are of the same order of magnitude as the total hydrogen inventory measured in the previously installed graphite tiles. Increased temperatures, as in the separatrix region, deplete the co-deposited layer,

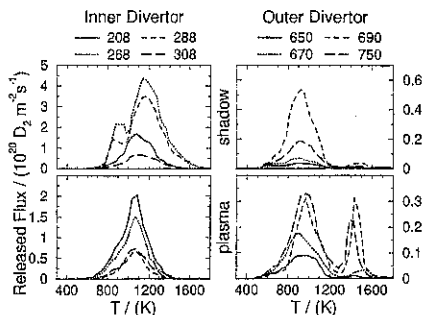


FIG. 3. Released fluxes of D_2 during the heating of the samples for the shadowed and plasma regions of inner and outer divertor tiles. Heating ramps are of the order of 10 K/s. The legend numbers denote the sample positions, as indicated by the arrows in figure 2.

reducing the deuterium inventory by a factor of 5. Diffusion of hydrogen out of the co-deposited C-H layer into the underlying tungsten layer is hindered by the tungsten/carbon interface. The inventories in the outer divertor samples are generally smaller by a factor of 10 than the inner divertor inventories; here the retention is governed by implantation and diffusion out of the implantation zone into the tungsten bulk. In the case of high fluences and high temperatures (separatrix), some hydrogen seems to diffuse into the graphite substrate.

Co-deposition with carbon from the plasma is the by far most effective hydrogen isotope retention mechanism for the tungsten coated divertor tiles installed in ASDEX Upgrade. This also will be the case in future fusion devices, as long as carbon is the main plasma impurity.

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