Tungsten erosion and migration in ASDEX Upgrade

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1 INTRODUCTION

Tungsten erosion was investigated by observation of spectral lines in the main plasma and the divertor [1, 2] and by measuring material erosion on probes exposed to the divertor plasma [3]. Tungsten migration was investigated by measuring the tungsten deposition with midplane and divertor collector probes and by ion beam analysis of a complete poloidal set of plasma facing vessel components removed after the experimental campaign. The Monte-Carlo impurity transport code DIVIMP was employed for the interpretation of the measured data.

2 TUNGSTEN EROSION

Net tungsten erosion in the divertor was determined by exposing graphite probes covered with a thin (1–100nm) W-marker stripe oriented in radial direction and measuring the thickness of the marker before and after exposure by Rutherford backscattering analysis [3]. Further, the flux of eroded tungsten atoms was determined by spectroscopic observation of the respective line emission at 400.9 nm. For the interpretation of the results, both the particle flux to the target plates and the energy of the incident ions is required. Direct measurements of these quantities were provided by a set of flush mounted Langmuir probes.

As expected, significant tungsten erosion was only observed in operating regimes with high divertor temperatures like low density Ohmic discharges and H-mode discharges with ELMs [3, 2]. Figure 1c shows results of a divertor probe exposure in a series of such low-density Ohmic discharges. The marker erosion pattern is clearly correlated with the spatial distribution of the WI spectral line emission (Fig. 1b). The Langmuir probe results for T_e at the target plates (Fig. 1a) show that the energy of the deuterium ions is below the sputtering threshold energy of tungsten. Therefore, the observed erosion must be attributed to sputtering by low-Z impurities, in particular carbon and boron. Using sputtering yields for carbon impacting on tungsten from laboratory ion beam experiments and assuming a carbon concentration of 1% good agreement with the measured erosion fluxes can be achieved [2]. Further one observes that the erosion yields derived from the spectroscopically determined tungsten flux are generally higher than the net erosion obtained from the marker measurements. The discrepancy is attributed to redeposition of tungsten atoms from the plasma and to the effect of prompt local redeposition of W^+ ions, which occurs because of the small ratio of ionization length to gyro orbit radius of W^+ [4].

For a quantitative interpretation of the experimental results, the Monte Carlo impurity transport code DIVIMP was used to simulate the tungsten erosion and transport processes. For the discharge series described above, a two-dimensional background plasma model in the poloidal plane was created by a B2/EIRENE code simulation. In the given background plasma DIVIMP calculates the trajectories of an ensemble of tungsten atoms. The tungsten source was assumed to be due to sputtering by a 1% fraction of C^{3+} ions with an impact energy of $2T_i+3ZT_e$ (Z=3). Effects of prompt local redeposition, however, have not been included yet. The sputtered atoms move along straight lines until they become ionized. Their trajectories as ions are determined by friction, electrical and temperature gradient forces along the magnetic field, and by anomalous diffusion across the magnetic field. The code follows the ions until they finally become redeposited again at a vessel component. Apart from the spatial distribution of erosion and deposition on plasma facing surfaces, it is also possible to calculate spectral line intensities along given spectrometer viewing chords.

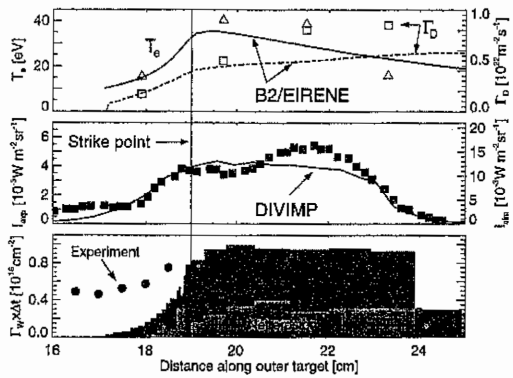

Figure 1 *a) Ion flux and electron temperature along the outer target plate for a series of low density ($\bar{n}_e = 2.5 \times 10^{19} \mathrm{m}^{-3}$) Ohmic discharges with 18.7s divertor plasma operation. The dots represent Langmuir probe measurements while the lines denote results of the respective B2/EIRENE plasma model. b) WI spectral line emission above the outer target plate. The dots represent results from the Boundary Layer Spectrometer and the solid line the result of a DIVIMP simulation. c) Radial profile of tungsten marker erosion along the outer target plate surface. The dots denote the measured tungsten marker erosion.*

The solid lines in Fig. 1a represent the electron temperature and the deuterium flux at the outer target plate as calculated in B2/EIRENE. Model and experimental results agree well within the experimental error of the Langmuir probe measurements. The spatial distribution of the WI line emission calculated for the viewing chords of the ASDEX Upgrade boundary layer spectrometer shown in Fig. 1b also agrees very well with the experimental data, whereas the absolute value of the simulation is approximately 3 times larger, which reflects the uncertainties in the ionization and emission rate coefficients of tungsten. Outside the separatrix, the measured net erosion is higher than the calculated net erosion but still below the calculated total erosion. The reason for the discrepancy are graphite tiles adjacent to the target probe which lead to a decreased tungsten flux to the probe and correspondingly to a higher net erosion.

Inside the strike point position one observes significant erosion in contrast to the code results. This reflects that the probe measurements represent time integrals, while the spectroscopic results and the code simulations represent a single time slice in the stationary plasma phase. During plasma startup, the rather hot scrape-off layer sweeps across the target plate in outward direction to it's final stationary position leading to the observed erosion in the area from 16–19cm.

3 TUNGSTEN DIVERTOR RETENTION

For divertor retention, i.e. the capability of a divertor configuration to keep impurities from escaping to the upstream scrape-off layer (SOL) region and to the confined plasma, there is no unique definition in literature. In the following we use the ratio of the tungsten density in the midplane SOL to the tungsten density at the target plates to characterize the retention capability. We determine the retention directly from measurements in the edge plasma and at the target plates. The often used method of correlation analysis of target erosion flux and central tungsten concentration suffers from large uncertainties about the cross field transport in the confined plasma [1]. Unfortunately, it is not possible to determine the tungsten density in the edge region directly. Instead, the tungsten flux in the midplane SOL was measured by deposition probes exposed in the shadow of the ICRH antenna limiters. The tungsten deposition corresponds to the radial flux of tungsten into the shadowed region. Assuming a simple model of purely diffusive radial transport, it is possible to extrapolate the measured tungsten deposition flux from the shadowed region towards the SOL. The target flux was derived from the WI line emission as described in section 2.

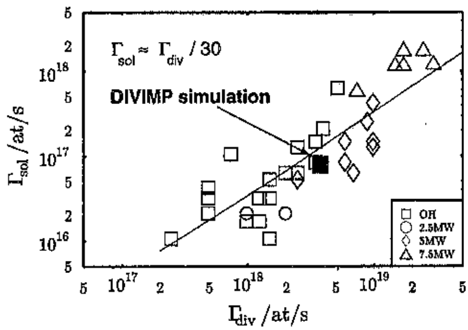

Figure 2 *Correlation of the tungsten flux at the midplane scrape-off layer derived from deposition measurements to the tungsten erosion flux measured spectroscopically at the outer target plate.*

As shown in Fig. 2 the midplane tungsten flux turned out to be proportional to the target erosion flux independent of the discharge conditions with an approximate ratio of 1/30 between mid plane and divertor. This yields a first estimate of the divertor retention capability for tungsten. For a more detailed analyis, the target and SOL tungsten density was determined by DIVIMP code simulations with the code results validated by the measured fluxes. From this analysis one obtains for the low density Ohmic discharges described above a divertor retention factor of $\simeq 0.01$. A fraction of 0.002 of the eroded tungsten atoms actually penetrates the confined plasma resulting in a core contamination of $\lesssim 2 \times 10^{-5}$ in good agreement with the measured central W-concentration.

With the successful demonstration of DIVIMP as a tool for the interpretation of the tungsten experimental results, further studies will concentrate on the properties of tungsten in reactor relevant discharge scenarios.

4 TUNGSTEN REDEPOSITION

The long term migration of tungsten eroded at the divertor target plates was investigated by measuring the amount of deposited tungsten on a complete poloidal set of plasma facing surface components removed after the experimental campaign. The samples were analyzed by Particle Induced X-ray Emission (PIXE) using a 1.5MeV Proton beam and the amount of deposited tungsten was derived from the intensity of the tungsten L_β doublet line at 9.68/9.96 keV.

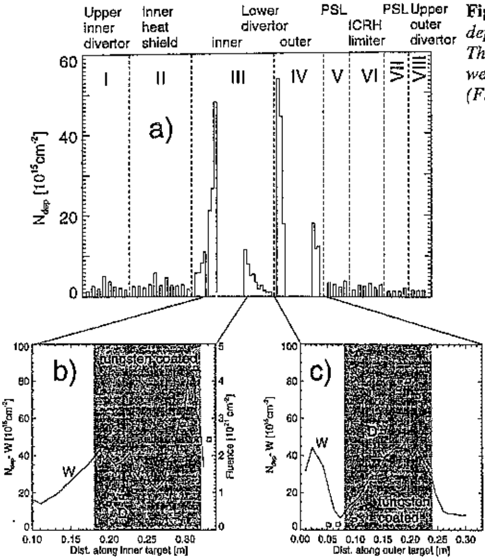

Figure 3 *a) Poloidal distribution of tungsten deposition on plasma facing vessel components. The data in the tungsten coated target area were obtained from graphite thermography tiles (Fig. 3b - inner target, 3c - outer target).*

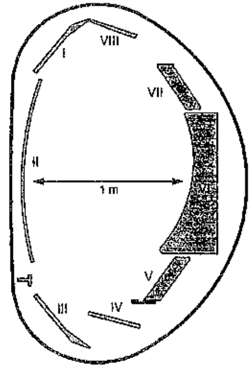

Fig. 3a shows the tungsten surface density along a poloidal set of plasma facing vessel components. All surfaces in the main chamber exhibit a roughly constant tungsten contamination, which is several times lower than the respective values for copper and iron. Comparison with results of the previous experimental campaigns yields an upper limit of $10^{15}/\mathrm{cm}^2$ W-atoms deposited within $\simeq 3000\,\mathrm{s}$ plasma discharge time. On the other hand, in the lower divertor, we find up to one order of magnitude higher contamination level with the peak value near the average strike point location on the deposition dominated inner target plate (Fig. 3b) and a less pronounced broader maximum in the strike point region of the erosion dominated outer target plate. Both of these features coincide very well with the average particle flux in these areas [5]. However, a high level of tungsten deposition extends onto the graphite tiles adjacent to the W-coated area, which cannot be accounted for by changes of the strike point position alone.

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