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Operation of ASDEX Upgrade with Tungsten Tiles at the Central Column

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For a future fusion reactor the question of the most suitable wall materials is still not solved. Although carbon is the most favourable option in present machines, problems may appear in future devices, in particular due to chemical erosion and co-deposition of tritium with carbon. An alternative are high Z materials as tungsten, which have excellent thermal properties and a high threshold energy for sputtering. However, former experiments in limiter tokamaks showed that the radiation of tungsten in the core plasma was not acceptable. In the last years, however, experiments with tungsten as divertor material were performed in ASDEX Upgrade, which showed practically no influence of tungsten on the plasma performance [1]. Due to the sputtering by low-Z ions the use of tungsten at plasma wetted surfaces is restricted to regions with plasma temperatures below $\approx 20eV$ [2]. Consequently, the actual design of ITER-FEAT uses tungsten at the divertor baffle structures, where a high flux of low energy CX-particles is expected.

The inner heat shield at the central column of ASDEX Upgrade is found to be a major source of carbon. The carbon erosion is predicted to be dominated by CX neutral sputtering and chemical erosion. Due to the low average CX energy in this region tungsten is suitable as an alternative plasma facing material. To reduce the carbon content of ASDEX Upgrade and to test tungsten use as main chamber plasma facing surface, a step by step approach was chosen. As a first step the two lowest rows of the heat shield (Fig. 1) were replaced, where the CX flux reaches maximum values. In contrast to the divertor region, the probability of the eroded tungsten to enter the core plasma and degrade plasma performance by radiation is expected to be much higher. This reduces the maximum tolerable W-erosion rate further.

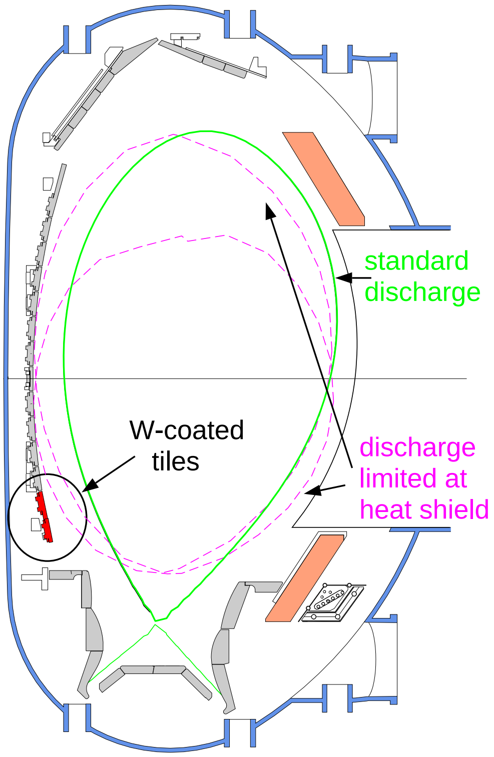

Fig.1: Position of the tungsten tiles inserted in ASDEX Upgrade. The LCFS of a standard discharge (solid) and a limiter configurations (dashed) are indicated.

Characterisation of the tungsten coating

The two lowest rows of carbon tiles at the central column of ASDEX Upgrade were replaced by tungsten coated tiles covering a total area of 1.2 m^2 (Fig. 1). To minimise the effort a coating of graphite tiles was chosen. The necessary thickness is estimated from the use of test tiles, which show a net erosion below 5 nm during one experimental campaign [3]. Interdiffusion of tungsten into carbon due to the formation of carbide is found in laboratory for temperatures above 1000 K. However, the maximum temperature of the coated tiles during plasma discharges was found below this values. Therefore no intermediate layer to prevent the carbide formation is necessary. To reduce the stress in the layer, which might result in disintegration, the thickness of the coating should be as thin as possible. Consequently a tungsten coating of about 500 nm on the graphite tiles was chosen. To prevent edge erosion, the design of the existing tiles was changed to minimise the distance of two tiles and a trapezoidal shape was used to shadow the edges. A homogeneous surface is only expected if the surface roughness of the graphite tiles is comparable to the thickness of the coating. To fulfil this condition the carbon tiles have to be polished very carefully before coating. The tungsten coating itself was fabricated by means of physical vapour deposition at a temperature of 450 K. The quality of the coating was checked using SEM. The polished tiles show a closed tungsten surface, whereas the same coating procedure on non polished graphite results in a cracked layer. The adhesive strength of the layer was tested using a scotch tape test. Several tiles were analysed using surface sensitive techniques to measure changes due to the plasma operation. Analysis using XPS revealed impurities of up to 10 % of carbon and oxygen inside the tungsten layer. These are embedded because of the not perfect smooth surface. Layer thickness was also measured to determine the total erosion during the experimental campaign from post mortem analysis.

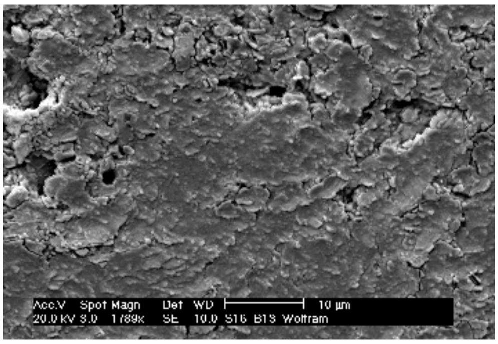

Fig.2: SEM picture of the tungsten surface after exposition to the plasma.

Experimental investigations

After venting the vacuum vessel, the experiment is usually baked out and a wall coating by boronisation is performed to remove oxygen, which disturbs the start up of the plasma. The tungsten tiles would be covered by this coating, which complicates the measurement the erosion rate of the pure tungsten. Based on the good experience using silicon as wall conditioning [4] a siliconisation was applied just before opening of the vessel, which was reactivated after the shut down period using He glow discharges. A special program of all relevant plasma regimes was performed to test the influence of the tungsten tiles on discharge performance. Additionally limiter discharges were performed to maximise the plasma flux on the tungsten tiles (Fig.1). No influence of tungsten on the global plasma performance was observed. Because of an accidental venting of the vacuum vessel the tiles could be examined after 1500 s of plasma operation. By optical inspection no significant change on the tungsten coating, especially no flaking, was found. Some tiles were replaced and analysed by RBS and SEM. No significant change of the tungsten layer thickness was observed. This confirms the erosion as expected from earlier experiments [3]. A SEM picture of a tile is shown in Fig. 3. The layer is almost not affected by the plasma. No local melting is observed. The surface shows mainly pure tungsten with some silicon at shadowed regions, which originates from previous siliconisations.

Tungsten deposition

The eroded tungsten is deposited from the plasma on the divertor and limiter structures. Two manipulator systems were used to expose deposition probes at the outer midplane and the outer divertor region near the strike point. The probes were analysed using RBS, which is very sensitive for high Z materials. The midplane measurements, representing the W-flux to limiters, were always below the sensitivity limit of $\approx 1 * 10^{16}\ at/m^2/s$. Tungsten deposition was found 1-4 cm outside the separatrix. From the divertor probes a W-flux to the outer divertor of $0.5 * 10^{17}\ at/m^2/s$ for high density and $1.6 * 10^{17}\ at/m^2/s$ for low density H-mode discharges can be derived (Fig. 3). The higher fluxes for the low density discharges coincide with the higher temperature in the SOL. The correspondingly higher erosion may be caused by CX neutrals with energy above the sputter threshold for tungsten or by impurity ions like carbon. Investigations of the erosion pattern on the tiles experimental campaign will be done to resolve this question. The divertor measurements were extrapolated to the amount of tungsten eroded. Assuming a direct transport of the tungsten along the SOL to the divertor and a deposition ratio of the inner to outer divertor of 2:1 an influx of $1.5 * 10^{17} at/m^2/s$ for the low density case is estimated. This value is about a factor of 8 higher than calculated for pure CX erosion[3]. The erosion of tungsten during these low density H-mode discharges cannot be explained by the calculated CX fluxes. However, additional effects as ion sputtering or higher neutral density because of the changed ASDEX Upgrade divertor might contribute significantly to the measurements.

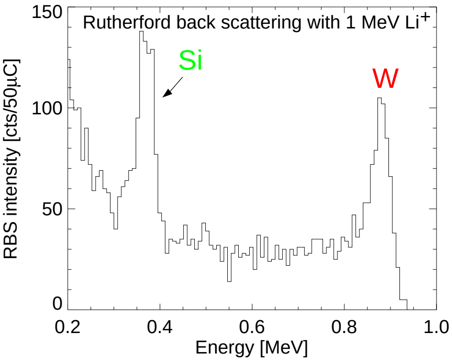

Fig.3: W/Si deposition in the divertor determined using RBS.

Central tungsten concentration

The tungsten influx into the plasma and the core concentration are measured using spectroscopic methods. Based on the experience of the divertor tungsten campaign the WI line at 400.8 nm was used to determine the tungsten erosion [4]. The central tungsten concentration was extracted from the quasi W-continuum at 5 nm. Absolute calibration of these measurements was done by tungsten laser blow off. Typical spectra measuring the W-influx with and without W-injection are shown in Fig. 4. An optical fibre and a spectrometer system with a scanning mirror are used to collect data from the tungsten covered region of the central column. In both measurements no significant influx of tungsten was detected. From the calibration we can therefore conclude that the W-flux, measured at the coated tiles, was always below the detection limit of $\Gamma_w = 10^{18}\ at/m^2/s$, which is an order of magnitude higher inferred from the deposition probe results. The central tungsten concentration was always below $5 * 10^{-6}$ and also mostly below the detection limit. Further, no accumulation of tungsten was observed. As mentioned above, the penetration probability for eroded tungsten from the inner heat shield into the core plasma is a critical issue. Because no data are available from plasma operation, experiments using LBO ablation from the tungsten coating were performed [6]. A penetration probability of $P_f = 0.04$ and a decay time of $\tau = 180\ msec$ was found. This value coincides with the probability of $P_f = 0.03$ for low field side LBO found before. Using the penetration factor and transport time a tungsten core density of 10^{-6} could be estimated. This value fits the concentrations measured spectroscopically. The concentration found are a factor of ten below the value tolerable for ASDEX Upgrade, which shows that, even in the worst case of low density H-mode discharges, a complete tungsten inner heat shield ($10\ m^2$) is tolerable for ASDEX Upgrade

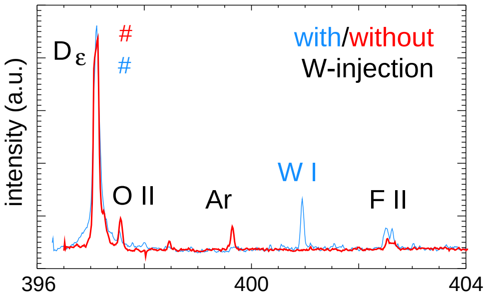

Fig.4: Typical spectrum during W injection used for calibration of the spectrometer.

Summary and Outlook

To test the capability of tungsten as a plasma facing material in a future fusion device $1.2\ m^2$ of tungsten coated carbon tiles were installed at the inner heat shield of ASDEX Upgrade. The operation was not influenced in any way by tungsten radiation. No significant erosion or destruction of the tungsten coating was observed. The tungsten deposition in the outer divertor cannot be explained by the calculated CX erosion alone. Even in specially designed limiter discharges and low density H-mode discharges with heating power up to 15 MW the eroded tungsten flux was below $\Gamma_w = 10^{18}\ m/s^2$. The central tungsten concentration was always below $5 * 10^{-6}$. These experiments demonstrate the suitability of tungsten as a first wall material not only at the divertor but also in the main chamber. An extrapolation to ITER requires modeling efforts to estimate the SOL temperature and the CX fluxes. For high density regions, which suffer from carbon erosion, tungsten seems to be a good alternative to carbon. For ASDEX Upgrade it was decided to follow the step-by-step approach and cover about 70% of the inner heat shield by tungsten for the next experimental campaign.

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