29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. ***26B****, P-2.048 (2002)*

Operation of ASDEX Upgrade with a fully tungsten coated central column – Results from experiments and modeling

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Introduction

All major design studies of future fusion devices intend the use of tungsten as plasma facing component at least in the divertor region, since in general, the erosion rate for low-Z materials seems to be far too high in a steady state power producing device. Moreover, the use of large area carbon based materials would lead to an excessive accumulation of tritium by codeposition, causing a considerable safety problem. Although W has many favourable properties such as a low sputtering yield and a high sputtering threshold, its use implies the risk of unduly high radiation losses in the central plasma and concentrations above 10^{-4} would prevent DT-burn. However, the experience with tungsten in present day fusion devices is comparatively small and ASDEX Upgrade is the only major fusion device which uses tungsten as plasma facing material on a large scale.

Starting from positive results of the W divertor experiment [1], increasingly large fractions of the central column of ASDEX Upgrade, the so called heat shield, have been covered with tungsten coated tiles starting with the two lowest tile rings (1.2 m^2) up to an almost complete cover in the present campaign 2001/2002 (7.1 m^2) which leaves out only the beam dumps of the NBI.

The W concentration in the core plasma was determined spectroscopically from a strong line at 7.94 Å of W^{46+} using a Johann spectrometer and from a quasicontinuum structure emitted by charge stages around W^{29+} at about 50 Å with a grazing incidence spectrometer. Since these charge states occur at different temperatures, the measurements also give some profile information. The information from W^{46+} is however only available for discharges with $T_{e,0} >$ 2 keV. Both instruments were cross calibrated with the bolometer after W laser blow-off. The W influx was monitored spectroscopically observing the prominent 4009 Å line of W I with a poloidal array of viewing chords across the heat shield.

Operation with W startup limiter and large area W walls

In the initial phase of the discharges at ASDEX Upgrade, the central column is used as startup limiter. During this phase generally, an increased central W concentration c_W was observed. However, after the transition to a divertor configuration, c_W drops by at least a factor of ten within a few energy confinement times ($\tau_E \approx 0.1$ s). Moreover the relatively large W concentration during start-up had almost no effect on the build-up of the plasma current and the increase of flux consumption of less than 5 % was much less than during the siliconization experiments.

In divertor configurations, the influx of W could only be measured spectroscopically in dedicated experiments, where the plasma column was shifted towards the heat shield. Here an influx of $\approx 2.5 \cdot 10^{18}$ $\mathrm{m}^{-2}\mathrm{s}^{-1}$ W atoms from only one viewing chord was observed. This suggests, that in this discharge only a very thin ring contributed significantly to the influx. The effective sputtering yield derived from comparison to the simultaneously measured deuterium flux is $Y_W^{eff} \approx 10^{-3}$, indicating a dominant contribution from light impurities.

During normal plasma operation no adverse effects of W on the plasma performance could be found. c_W mostly stayed below 10^{-5}, which still is one order of magnitude below the acceptable maximum in ASDEX Upgrade. Figure 1 shows the temporal evolution of c_W and other plasma parameters during a 'standard H-mode' discharge which is performed in the same way almost every day of operation. A peaked W profile can be observed in the low-power phase with good particle confinement. During the ICRH phase the W profile is inverted. In the following phase with intermediate beam heating at natural density, again a flat c_W profile develops. The temperature is only high enough in these three phases for the SXR line to be visible. At the end of the discharge, the density is increased and c_W drops below the detection limit of $\approx 1 \cdot 10^{-6}$.

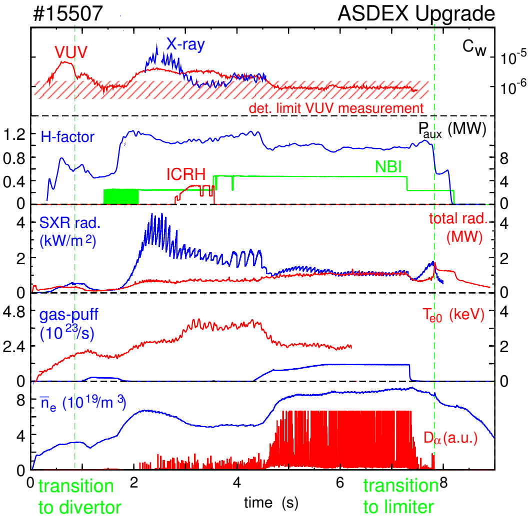

Figure 1: *Temporal behaviour of a standard-H-mode discharge ($I_p = 1$ MA, $B_t = 2.0$ T, $\delta = 0.15$).*

None of the major discharge scenarios at ASDEX Upgrade are hampered by the W coated wall. Discharges with a higher triangularity showed an up to five times higher c_W which can be attributed to the generally better particle confinement. These discharges also show a slight density peaking, which makes them prone to neoclassical impurity accumulation. Advanced scenarios, especially improved H-modes showed a similar behaviour with maximum W concentrations of about $5 \cdot 10^{-5}$. High-β and electron ITB discharges were completely unaffected and c_W mostly stayed below the detection limit.

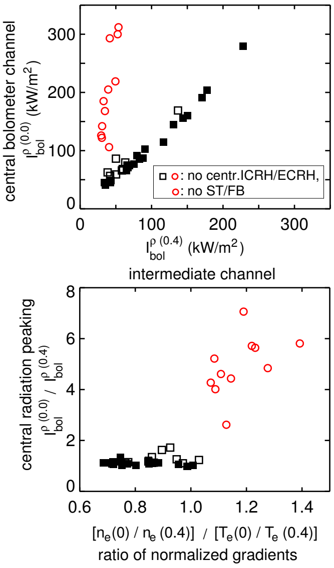

Figure 2: *Comparison of radiation profiles for discharges with and without impurity accumulation.*

The accumulation of W can be explained neoclassically from the equation

$$\frac{\partial \ln n_Z}{\partial r} = \frac{\partial \ln n_i}{\partial r} \frac{Z}{1+\frac{D_{an}}{D_{neo}}} \left(1 - H \frac{\partial \ln T_i}{\partial \ln n_i}\right)$$

describing the impurity density profile n_Z [2]. $H \approx 0.2-0.5$ is the so called neoclassical impurity screening, Z is the charge of the impurities. D_{neo} and D_{an} are the neoclassical and anomal diffusion coefficients respectively, n_i and T_i are the ion density and temperature. The prerequisite for accumulation is a peaked density profile $\partial \ln n_i / \partial r$ which is usually caused by a small anomal diffusion. A large Z also reinforces this behaviour. Impurity accumulation can be avoided by making the ratio of normalized temperature and density gradients as large as possible. The radiation level, which is an indicator of the total impurity content, was rather low (40 %) for all discharges and strongly dominated by the edge. Peaked radiation profiles only occur, if the driving therm $(\partial \ln T_i / \partial r)/(\partial \ln n_i / \partial r)$ gets small, which generally coincides with a loss or at least a strong reduction of sawtooth/fishbone activity. The peaking itself only affects the very plasma center within $\rho = 0.2$.

In these cases, central wave heating can strongly reduce the central impurity content without affecting global confinement [3]. The mechanism is an enhanced anomalous transport due to the coupling of particle and thermal transport [4] and a decrease of neoclassical drifts, leading to a flattening of the density profile.

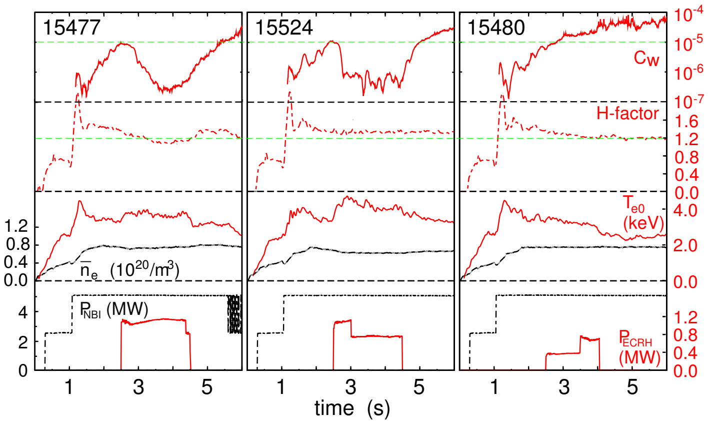

Figure 3: *Threshold of reduction of central impurity content by taylored on-axis ECRH.*

The behaviour of peaking radiation profiles in cases with and without central wave heating and sawtooth/fishbone activity respectively is illustrated in figure 2. As shown in figure 3, the power dependence of the mentioned impurity reduction by central wave heating shows a threshold behaviour with the value of the threshold depending on the actual central accumulation.

Edge modeling activities

In order to interpret the measured erosion and migration patterns [5], modeling with the 2D Monte-Carlo impurity transport code DIVIMP [6] has been performed. DIVIMP treats trace impurities in front of a background plasma which was taken from the B2/EIRENE modeling of a hydrogen L-mode discharge, which was diagnosed very thoroughly and thus presently represents the best background plasma available. Since the area of direct plasma - wall interaction in DIVIMP is restricted to the divertor, a simple model for the plasma in front of the heat shield was implemented in the code where the plasma parameters are extrapolated from the outermost grid ring to corresponding points on the wall. The sputtering was modeled taking into account the important contribution of light impurities. The sputtered tungsten is then fed back into the appropriate outer grid cells.

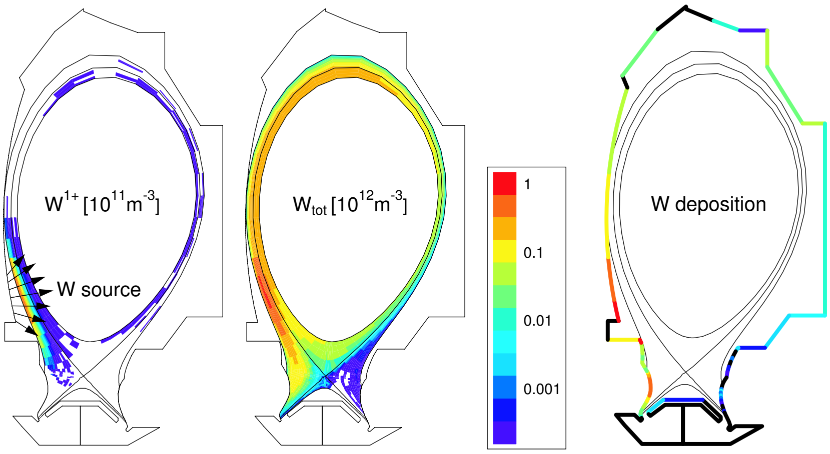

Figure 4: *Modeling of W migration with DIVIMP for a constant source at the lower heat shield*

The results obtained with DIVIMP can be compared to spectroscopic influx measurements and post mortem erosion and deposition surface analysis measurements. Figure 4 shows the poloidal distribution of W for a constant source on the two lowest tile rings, corresponding to the first stage of the tungsten covered heat shield. Generally, the lower ionization states are concentrated around the source and in the divertor, whereas the higher ionisation states are located more at the top of the plasma and, of course, inside the separatrix. The colour of the wall contour in figure 4 corresponds to the relative amount of deposited W.

Most of the tungsten is deposited in the direct vicinity of the source on the heat shield, the inner baffle and the inner strike point region. Keeping in mind the problem of the campaign integrated deposition measurement and the rather simple background plasma in the computations, the qualitative agreement between modeling and measurement [5] is quite satisfactory although not all measured features, such as the deposited W found in the outer divertor can be reproduced. The measured erosion patterns can be fitted in the code by an appropriate selection of the extrapolation function, however more input is needed from Langmuir probe measurements which should become available in the near future.

Conclusions and outlook

In the latest stage of W coated tiles at the central column of ASDEX Upgrade the positive results prevail as in earlier campaigns. Even the behaviour during the ramp-up with a W limiter turned out to be very benign. In all relevant discharge scenarios, the central W concentration c_W stayed below $1 \cdot 10^{-5}$ and thus one order of magnitude lower than the acceptable maximum for ASDEX Upgrade. As already found in earlier campaigns, c_W was confirmed to be dominated by transport. The discharges that were prone to a peaking of c_W had a low central transport and also showed density peaking of the background plasma. It was further demonstrated, that tailored central heating can effectively suppress accumulation of W with only a very modest degradation of the overall confinement.

For the understanding of W transport in the plasma boundary modeling calculations with the 2D impurity transport code DIVIMP have been performed. Preliminary results on comparisons between experimental and computational migration studies already show satisfactory agreement.

In the next campaign, the W covered surface in the main chamber of ASDEX Upgrade will be renewed and extended further by a coating of the upper phase stabilizing loop and the inner baffle of the lower divertor to 15 m^2.

References

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