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From carbon to tungsten: divertor plasmas in ASDEX Upgrade

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Introduction

The influence of the transition of the plasma facing components (PFC) from carbon (C) to tungsten (W) on the divertor plasma is investigated. Equivalent discharges in terms of matching global plasma parameters like plasma current I_P, toroidal magnetic field B_t, line averaged electron density $\overline{n_e}$, heating power and energy content W_{mhd} are used. The divertor plasma is characterised by flush mounted Langmuir probes in triple probe configuration [1], for the poloidal probe distribution see [2]. Strike point sweeps were applied to improve the spatial resolution of the measurements. Since the inner divertor is usually detached, this paper concentrates on the outer divertor in lower single null configuration with the ion drift towards the active divertor.

Table 1 shows the individual steps for the transition from C to W, see also [3, 4]. Divertor II was much more closed than divertor IIb and IIc which are very similar. Therefore, we discuss only measurements in div IIb and IIc. During the campaign in 2004/05 17 g of C were deposited

first shot (year)	new tungsten coverage	divertor
12754 (Nov 1999)	2 lower tile rows at inner heat shield	div II
14049 (Mar 2001)	about 10 tile rows at inner heat shield	div IIb
14609 (Oct 2001)	inner heat shield except NBI beam dump areas	div IIb
16511 (Dec 2002)	fresh tiles at inner heat shield, upper PSL, baffle at lower inner divertor	div IIb
18203 (Dec 2003)	upper divertor, baffle at lower outer divertor, 1 guard limiter	div IIb
19584 (Nov 2004)	auxiliary limiter, hor. plate lower outer divertor, 1 pol. ICRH limiter	div IIb
20670 (Dec 2005)	all poloidal limiters, roof baffle, lower PSL	div IIb
21482 (Mar 2007)	all toroidal limiters (ICRH), lower divertor, all diag. armours => full tungsten machine	div IIc
22586 (Feb 2008)	all surfaces cleaned	div IIc
23093 (Apr 2008)	first boronisation in full tungsten machine	div IIc

Table 1: *Stepwise transition from full C to full W PFCs.*

in the inner divertor and remote areas while 2005/06 the deposition was reduced to $3-5$ g and 2007 down to about 1 g [5]. The C concentration in the pedestal is reduced from peak values of 2% to $\approx 0.5\%$ in the full tungsten machine [6]. Although the C sources and concentration are strongly reduced, ASDEX Upgrade is not a C free machine since micro sources are still existing.

Impact of boronisation onto the divertor plasma

The influence of wall conditioning by boronisation has to be clarified before comparing the divertor plasmas in a tokamak with C and W PFCs. Boron getters oxygen and covers impurities at the walls. First the effect of boronisation is discussed in ohmic discharges with $B_t = -2\,\mathrm{T}$, $I_P = 0.8\,\mathrm{MA}$ with a density plateau at $\overline{n_e} \approx 2.6 \times 10^{19}\,\mathrm{m}^{-3}$. For these discharges most of the outer limiters consisted of C PFCs. W_{mhd} and $\overline{n_e}$ were matched well and also the gas fuelling was of the same size. Some variations occurred in the total radiated power P_{rad}, see table 2. In general, P_{rad} has a minimum after boronisation and increases afterwards within a few plasma discharges. Most discharges show some variation in P_{rad} during the strike point sweep. These changes are small and do not significantly affect the overall performance with exception of #20353 where a strong P_{rad} peak indicates an impurity event. In figure 1 the divertor saturation current j_{sat},

shot	# after boronisation⋆	P_{rad}, low $\overline{n_e}$	Γ_D
20256	1	0.17-0.20 MW	$0.9 \times 10^{21}\,\mathrm{s}^{-1}$
20277	18	0.21-0.34 MW	$0.6 \times 10^{21}\,\mathrm{s}^{-1}$
20292	30	0.21 MW	$1.1 \times 10^{21}\,\mathrm{s}^{-1}$
20326	55	0.25 MW	no data
20353	71	0.21-0.75 MW	$1.2 \times 10^{21}\,\mathrm{s}^{-1}$
20372	87	0.20-0.35 MW	$1.1 \times 10^{21}\,\mathrm{s}^{-1}$

⋆ counting plasma discharges with flattop.

Table 2: *Parameters for ohmic discharges.*

shot	W_{mhd}	P_{rad}	Γ_D	gas puff in
18875	0.49 MJ	2.5 MW	$2.5 \times 10^{22}\,\mathrm{s}^{-1}$	midplane
19018	0.49 MJ	2.1 MW	$2.4 \times 10^{22}\,\mathrm{s}^{-1}$	midplane
19129	0.45 MJ	2.8 MW	$2.5 \times 10^{22}\,\mathrm{s}^{-1}$	midplane
20160	0.45 MJ	2.7 MW	$2.5 \times 10^{22}\,\mathrm{s}^{-1}$	midplane
20752	0.46 MJ	2.5 MW	$2.4 \times 10^{22}\,\mathrm{s}^{-1}$	midplane
22786	0.44 MJ	3.3 MW	$2.2 \times 10^{22}\,\mathrm{s}^{-1}$	mid.+div.
23097	0.48 MJ	1.7 MW	$2.7 \times 10^{22}\,\mathrm{s}^{-1}$	mid.+div.
23164	0.48 MJ	2.5 MW	$2.7 \times 10^{22}\,\mathrm{s}^{-1}$	mid.+div.

Table 3: *Parameters for H-mode discharges.*

electron density in front of the divertor target n_e and divertor electron temperature T_e are shown as a function of the distance to the separatrix. The coordinate s is following the divertor surface. The first shot after boronisation shows a 30 % higher j_{sat} than the other discharges. This results in a higher n_e although the gas puff is in the lower range of the shot series and the neutral gas flux below the divertor stays about the same for all of these discharges. T_e is slightly decreased in the first discharge after the boronisation compared to the following discharges. The peak n_e decreases over the first $18-30$ discharges after boronisation while the n_e wings almost recover over the first 18 discharges. T_e increases gradually after the boronisation reaching finally peak values of about 25 eV after $18-30$ discharges. At higher $\overline{n_e} \approx 3.6 \times 10^{19}\,\mathrm{m}^{-3}$ the same trend is found comparing #20256 and #20372. The other discharges were influenced by ICRH during this phase. The differences of fresh and old boronisation cannot be explained by P_{rad} only which recovers faster than n_e and T_e. Most likely it depends on the mixture of radiators and recycling fluxes. Measurements with a higher fraction of PFCs made from C indicated the same trends in n_e and T_e but the Langmuir measurements could not cover the T_e peak at that time.

In H-mode discharges the data are strongly smoothed by a median filter to reduce the impact of ELMs. Comparing the profiles of the first shot after boronisation (#23097) with full W PFCs with a later one (# 23164, 42 plasma plasma discharges after boronisation including a short vessel opening) the results fit to the observations in ohmic discharges. The averaged j_{sat} and n_e profiles show a maximum direct after the boronisation. There is no significant impact on T_e which was already small in ohmic discharges and might now be hidden by the remaining ELM impact. The data scatter is increased in #23164. Both discharges had the following parameters $I_P = 1.0\,\mathrm{MA}$, $B_t = -2.5\,\mathrm{T}$, $\overline{n_e} = 8.5 \times 10^{19}\,\mathrm{m}^{-3}$, gas puff $\Gamma_D = 2.7 \times 10^{22}\,\mathrm{s}^{-1}$, neutral beam injection of $P_{NBI} = 5\,\mathrm{MW}$ and energy content of 0.5 MJ. As expected the total radiation level ($P_{rad} = 1.7\,\mathrm{MW}$) is lower direct after boronisation compared to 2.5 MW in #23164.

With more C PFCs and gas puffing in the midplane the second shot after boronisation (#19018) showed a 20% higher j_{sat}, an enhanced peak density (the density in the wings is the same) and an slightly enhanced T_e compared to an discharge which is 37 shots after boronisation (# 18875). Even with the higher strike point position T_e was lower with C PFCs. The behaviour is quite similar to the full W case despite the fact that clear a T_e increase occurred with boronisation. The discharge parameters were $I_P = 1\,\mathrm{MA}$, $B_t = -2\,\mathrm{T}$, density about $\overline{n_e} = 8.5 - 9.0 \times 10^{19}\,\mathrm{m}^{-3}$

(see also table 3). With the gas puff in the divertor (#17883 and #17901) which requires $\Gamma_D \approx 5.4 \times 10^{22}\,\mathrm{s}^{-1}$ to reach about the same density there is no influence by the boronisation.

Divertor plasma changes with increasing W coverage

In ohmic density ramps performed in the shot range #14701 to #21857 the divertor detachment (roll over of j_{sat}) set in at $\overline{n_e} \approx 3.6 - 4.0 \times 10^{19}\,\mathrm{m}^{-3}$. The variation seems to be related to the slope of the density ramp. There is no variation when going from C to W PFCs. Either the C concentration in ASDEX Upgrade is still high enough to reach the detachment at the same $\overline{n_e}$ or C is not important for the detachment and D radiation is sufficient.

To diagnose divertor plasma changes in H-mode with increasing W coverage of the PFCs discharges with $I_P = 1\,\mathrm{MA}$, $B_t = -2.5\,\mathrm{T}$, $\overline{n_e} = 8.2 \times 10^{19}\,\mathrm{m}^{-3}$, and $P_{NBI} = 5\,\mathrm{MW}$ were investigated. All shots (see fig. 2) were performed more than 40 plasma discharges after the previous boronisation. Until #20752 the puff rate in the high density phase was slightly higher than the pump rate. Later, the pump rate was slightly higher than the puff rate. #22786 and #23164 had a lower strike point than the other discharges. Figure 2 shows, that the profiles of #22786 and #23164 scatter more than #19129 and #20160 indicating a stronger variation of the divertor plasma. The peak values of j_{sat} increase by about 20% when the LFS limiters and lower divertor were W covered. The slight shift between the peak locations is within the error bars of the equilibrium reconstruction. #22786 had a higher P_{rad} and showed a reduced peak value in j_{sat}. The j_{sat} profiles in the full W configuration (#22786, #23164) are broader than with LFS limiters made of C. The peak values of n_e stay about constant, the broadening is analogous to j_{sat}. The largest changes occur in the T_e profiles. Before all poloidal LFS limiters were W covered, T_e was about constant at 7 eV outside the separatrix. With LFS limiters made of W, T_e formed a peaked profile and maximum temperatures of 14 eV were reached. Even in case of a higher P_{rad} than in the discharges with C LFS limiters the divertor showed an increased T_e with W limiters (#22786). At the same time the C deposition was reduced when the LFS limiters were covered by tungsten and the divertor became hotter [5]. This might allow for higher T_e in the divertor at (almost) same global plasma parameters.

ITER relevant divertor conditions

In low density discharges it is possible to reach collisionalities in the SOL close to the values predicted for ITER. The global discharge parameters were $I_P = 1\,\mathrm{MA}$, $B_t = -2.5\,\mathrm{T}$, $\overline{n_e} = 10^{19}\,\mathrm{m}^{-3}$, no gas puff, $P_{ECRH} = 0.7\,\mathrm{MW}$, $P_{rad} = 1.1\,\mathrm{MW}$ and $W_{mhd} = 0.06\,\mathrm{MJ}$. The low collisionalities lead to high T_e, see figure 3. The floating potential had an extreme negative peak. This peak value could not be resolved by the Langmuir diagnostic. Due to the applied voltage the triple probes measurements of n_e and T_e worked for plasmas with $T_e < 30\,\mathrm{eV}$ only. Measurements of swept single probes were added to detect the peak temperatures of $\approx 50\,\mathrm{eV}$. It is expected that at 70 eV W erosion by D becomes significant [7].

Summary

In ohmic discharges the divertor plasma seems not to be affected by the transition from C to W. Changes occur in H-mode discharges, especially with the W coverage of the poloidal LFS limiters. The reduction of C affected the edge cooling. While the total P_{rad} stayed unchanged

W is a weaker radiator in the edge than C. Obviously, especially in additionally heated plasmas, C is an important radiator where it can be partly replaced by boron. In plasmas with low collisionalities the outer divertor in ASDEX Upgrade became hot (up to 50 eV).

References

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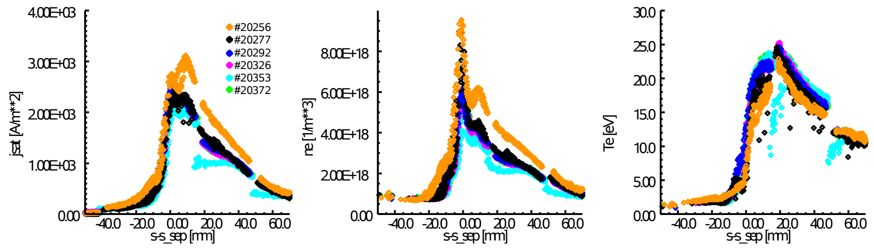

Figure 1: *Influence of boronisation onto the divertor plasma at* $\overline{n_e} \approx 2.6 \times 10^{19}\,m^{-3}$

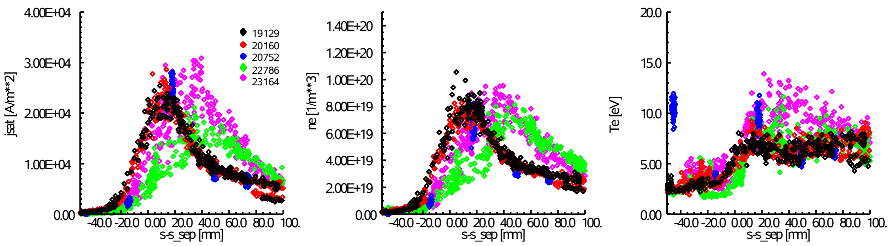

Figure 2: *Divertor plasma parameter in H-mode for different levels of PFC W coating.*

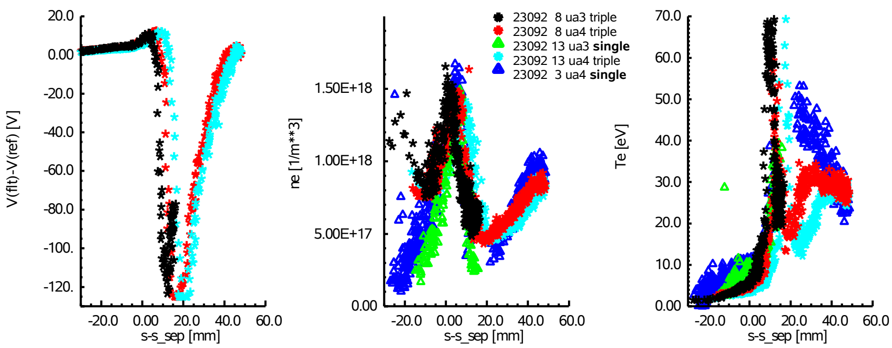

Figure 3: *Divertor plasma parameters for ITER relevant conditions. Measurements of triple and single probes are shown.* n_e *and* T_e *measurements of triple probes are reliably for* $T_e \leq 30\,eV$ *only. The* T_e *peak of the triple probes at* $s - s_{sep} \approx 15\,mm$ *is an artefact.*