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Carbon erosion and a:C–H layer formation at ASDEX Upgrade

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Abstract

During the campaign 2002–2003 a carbon erosion and deposition experiment was performed in the lower divertor of ASDEX Upgrade. A complete divertor cross section with erosion sensitive markers, deposition monitors below the divertor and time resolved measurements by quartz mircobalance monitors (QMB) and Langmuir probes are used. The largest amount of carbon deposition was found at the inner divertor target plates. At the outer divertor, erosion was observed. However, the behaviour at the outer strike point zone is not jet fully understood. The deposition at remote areas is concentrated below the divertor. Neutrals seem to be dominant at the layer formation at remote areas. Additional erosion of deposited layers by ions reduces the layer thickness dramatically at some locations. QMB data show that at the outer divertor, deposition and erosion occur at the same location, depending on the main plasma properties. A parasitic plasma is observed below the divertor.

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1. Introduction

The use of carbon in burning fusion reactors has to be restricted due to the problem of tritium codeposition. During the last few years ASDEX Upgrade has replaced carbon plasma facing components (PFCs) with tungsten coated PFCs [1]. The former tungsten divertor experiment in ASDEX Upgrade [2] indicated, that the dominant carbon sources were located in the main chamber [3]. Consequently, the replacement of carbon in ASDEX Upgrade was started at the central column, the largest surface close to the edge SOL. Nevertheless, the central carbon content of comparable plasma discharges decreased only by a factor of 2 in comparison to results obtained with a full carbon machine [4]; this points to the fact that ASDEX Upgrade is still a carbon dominated experiment. Spectroscopy and filtered cameras had been used to study the carbon behaviour (e.g. erosion and transport)in the main chamber. The main carbon influx was found to originate from the central column [5], despite the fact that the central column was almost completely covered with tungsten coated tiles. Erosion of carbon layers deposited on the tungsten coatings could be the explanation to this finding. The largest primary carbon source in the main chamber had been observed

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at the low field side protection limiters, but they contribute only ≈20% of the secondary influx from the central column. The spectroscopic measurements had been compared with post mortem examination of the deposited layers.

Spectroscopy means measuring the influx of carbon at the plasma edge. It generally needs extensive data evaluation and is therefore usually restricted to flat top phases of typical shots. However, surface analysis methods generally provide information at the end of the experimental campaign, and account for the balance of erosion and deposition processes.

2. Primary carbon sources

Four hypotheses on the origin of the carbon influx observed at the central column will be discussed: (a) additional localised sources, such as tile edges, which are not observed by spectroscopy, (b) additional sources in the divertor, (c) erosion during some special shots or transient phases, which show strong erosion but were not monitored by spectroscopy and (d) multiple recycling of the eroded carbon at the central column.

(a) Extrapolating the spectroscopic values [3] to the whole campaign gives an erosion of 2.6 g of carbon at the limiters and 12 g at the central column [4]. However, careful inspection of the central column and the protection limiters show no hint of such an erosion. (b) The whole divertor cross section was equipped with up to 8 μm thick carbon on a Re inter layer for one experimental campaign (Fig. 1). This divertor marker experiment [6] showed an almost perfect balance between the carbon sources and sinks. The strongest deposition was found at the inner divertor (27.3 g) [6]. Additional sinks are the roof baffle (2.9 g) [6], the vessel below the divertor (2.0 g), the structure below the divertor (1.3 g), the kryo-pump LN_2 baffle (0.3 g) and the pumping system (0.6 g) [4]. The outer divertor data yields an erosion of 3.5 g of carbon at the outer divertor baffle region. The

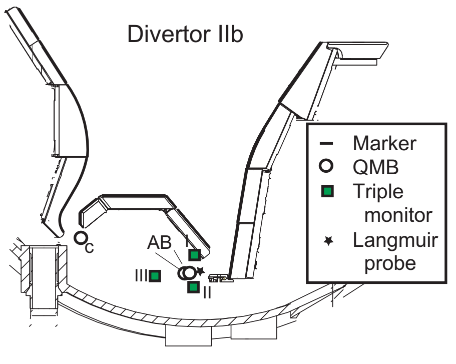

Fig. 1. Location of the various diagnostics and markers used.

findings at the outer strike point section are still not completely understood. Strong erosion of the marker, leading to a source of 34.7 g of carbon and deposition (9.5 g) was also observed [6]. Simple estimations using the divertor ion flux measured by Langmuir probes and assuming a carbon content of 3%, show that about 1000 s of divertor operation are needed to build up the layer observed. In addition, there are hints that in the presence of high heat fluxes the carbon of the markers is more strongly eroded than the divertor tiles. Recent experiments with $^{13}CD_4$ puffing at the outer divertor show only local deposition [7]. For these reasons, there are some doubts that the outer divertor is the dominant gross carbon source. Carbon eroded at the outer divertor may be transported via SOL to the inner divertor. This carbon is not observed by spectroscopy, but a part of it may be responsible for the central column carbon source. (c) Spectroscopic investigations require information on the plasma temperature to get a value for S/XB. This can be done accurately only during flat top phases of the plasma. For this reason data is not routinely evaluated during all transient phases such as plasma ramp-up, ramp-down and for special shots. Extraordinary scenarios can overheat the limiters and cause strong erosion, which is not included in the balance mentioned above. (d) As the divertor is the biggest carbon sink, the total amount of carbon eroded during the campaign can be estimated from the divertor deposition (43.3 g). Remember that 12 g of carbon is eroded from the central column. As this part of the vessel is tungsten coated, the carbon has to be deposited there before it can be subsequently eroded. Assuming all eroded carbon is transported via the heat shield, a probability of ≈27 % for carbon to be deposited at the central column is required. As during flat top phases the distance from the separatrix to the surface is larger than 50 mm, a relatively high value. Alternatively manifold deposition and erosion of a smaller amount of carbon can provided high carbon influxes [4].

3. Deposition at remote areas

Carbon deposits on divertor plasma facing components represent the main sink for deuterium inside the ASDEX Upgrade vessel. However, this inventory is less severe from the viewpoint of the tritium accumulation: deposition on the plasma facing side of tiles can be remobilized by special plasma discharges. A serious problem on the tritium inventory is caused by deposition at remote areas. These can contain a non-saturating tritium inventory as observed at JET [8]. Deposition at remote areas can be separated into 3 different types: (a) deposition at the non plasma facing sides of the tiles, for example in slits between tiles: these layers are difficult to qualify and to investigate [9], (b) at the structure close to the divertor and (c) at very remote areas such as the pumping ducts. In these latter areas only a small amount of deposition was observed at ASDEX Upgrade [11] and TEXTOR [12]. At ASDEX Upgrade a comparison of the deposition at the pumping duct and below the divertor was made [10] and showed, that precursors with high surface loss probability are the dominant deposition species. Therefore, we will restrict ourselves in this paper to the deposition below the divertor.

3.1. Deposition below the divertor

The deposition below the divertor is investigated by using two techniques: (a) Quartz micro balance monitors (QMB), which are used to get time resolved data on the layer growth and (b) Si wafers, called deposition monitors, which provide good spatially resolved profiles, however they integrate over the whole campaign. Deposition monitors are analysed post mortem using ion beam techniques. The thickness of the deposited layer on the monitors below the roof baffle shows a steep decay with increasing distance to the divertor slits. This behaviour is thought to be due to species which have a very high surface loss probability (close to unity), either because they are high sticking species or due to surface activation [10]. During the last campaign, 28 deposition monitors were used. Fig. 2 shows the carbon deposition on the monitors. The monitors are located in correspondence to the lowest position of the bars. The different colours indicate the relative orientation of the mounted monitors. In former campaigns [13] the averaged deposition at the inner divertor was typically 3.5 times larger than in the outer one. For the last campaign this factor was 5. Below the roof baffle the typical spatial decay length [10] of the deposition was confirmed. The picture is completely different at the bottom of the vessel close to the outer divertor slits, where almost no deposition is found. The deposition of carbon increases for monitors more remote from the divertor slits. Whereas the deposition below the roof baffle is in line with the picture of deposition of neutrals originated at the divertor plate, additional effects are needed to explain this observation. Monitors mounted at the same poloidal position, but facing in different directions provide additional information. These triple monitors consist of a monitor facing towards the divertor plates, and two facing in and counter to the magnetic field direction (insert Fig. 3). The measured layer thicknesses are compiled in Fig. 3. Triplet I was mounted below the roof baffle. Whereas the deposition in and counter to the magnetic field direction is almost the same, the monitor facing directly towards the divertor shows 1.9 times more carbon deposition. This behaviour is, for geometrical reasons, expected if the deposition is due to neutral particles originating from the divertor plates. Triplet III shows almost the same behaviour (2.4 times more for direct view). The average carbon deposition (I:2.5e18 at cm^{-2}, III: 1.9e18 at cm^{-2}) shows only a decrease with the distance from the divertor plates. The picture for triplet II, mounted at almost the same distance as I from the divertor plates, is very different: the averaged carbon deposition is much less (I:1.6e17 at cm^{-2}). A strong asymmetry

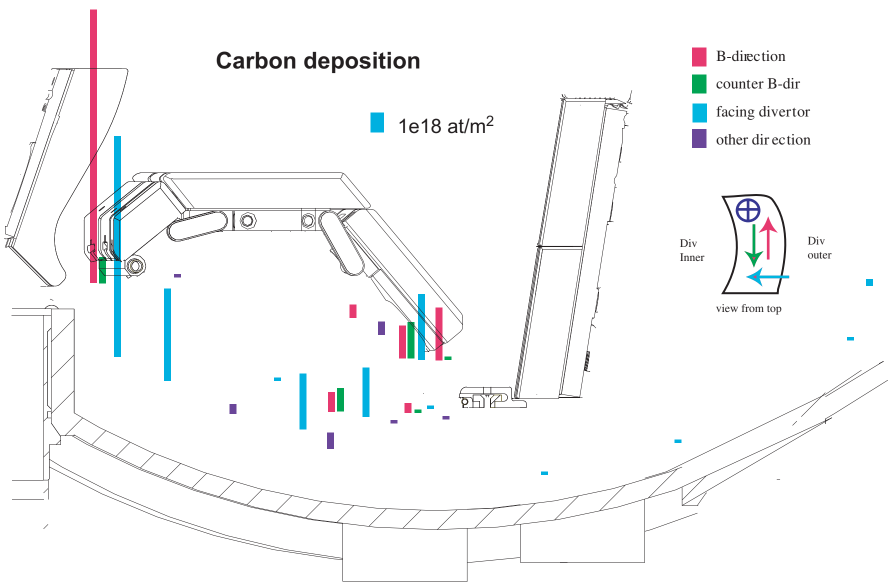

Fig. 2. Deposition below the divertor of ASDEX Upgrade measured by deposition monitors during the campaign 2002–2003. Different colours indicate the orientation of the monitors (see insert). Additionally the position of the QMB (A, B, C) and Langmuir probe (LP) are indicated.

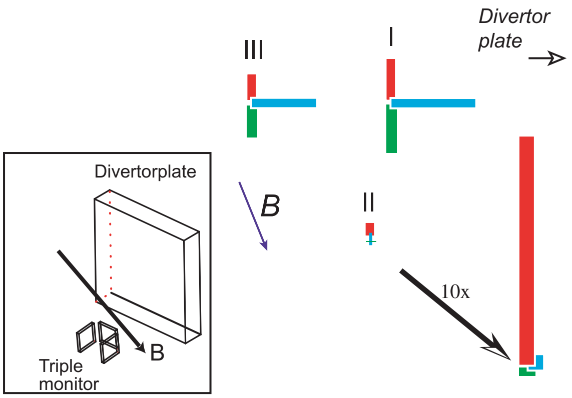

Fig. 3. Deposition pattern for three triple monitors. The data for monitor II is also shown enhanced by a factor of 10. The inset clarifies the orientation of the triple monitor.

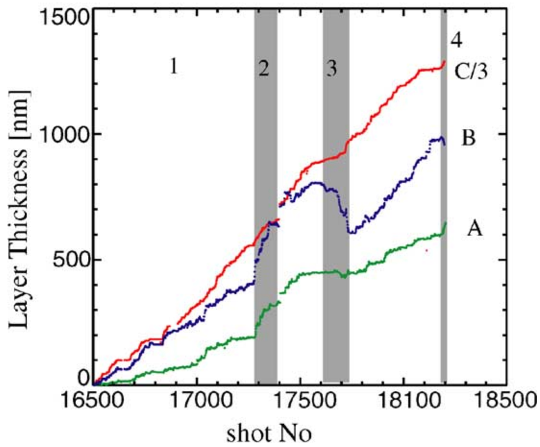

Fig. 4. Deposition measured by the QMB during the campaign 2002–2003. The data of QMB C is divided by a factor of 3. The four periods, which are discussed in the text are also indicated.

is observed for the different orientations relative to the magnetic field direction: The monitors in and counter to the magnetic field direction differ by a factor of 29. The direct viewing monitors show a factor of 7 times less deposition than the monitor looking in the magnetic field direction. Assuming a deposition by neutral particles, an additional erosion process is required. The strong asymmetry of the measured layers supports the picture of erosion due to ions. All monitors, which show low deposition are mounted in line of sight to the typical divertor strike point position. In this region a parasitic plasma is observed [14], which might cause the erosion.

3.2. Time resolved measurements

Quartz microbalance monitors are offering additional shot to shot resolved information on the growth of the layers. Two QMB monitors were mounted at the outer divertor in ASDEX Upgrade, facing into the magnetic field direction and towards the divertor plates. One QMB facing towards the divertor plate was mounted at the inner divertor. The crystals are affected by thermal heat load, which restricts the data evaluation to a shot to shot base [13]. The deposited layer thickness measured by the QMBs during the 2002–2003 campaign is shown in Fig. 4. At the inner divertor, the deposition rate is much higher, and the data in the figure have been divided by a factor of 3. An almost constant growth of the layer thickness is observed.

Here we will discuss only 4 different periods of the campaign: (1) #16513–17284: normal operation at the start of the campaign, (2) #17285–17404: occurrence of damage at the outer divertor plates which caused higher carbon erosion in the outer divertor, (3) #17570–17722: a period of reversed field and plasma current to investigate low density plasmas, and (4) #18190–18202: identical high density discharges for ^{13}C puffing experiments. During these 4 phases different plasma scenarios and discharge duration are used. To compare the observed deposition behaviour, the deposition for the outer divertor QMBs are normalised to the inner one, which shows almost constant layer growth. The normalised deposition and averaged measurements of divertor relevant diagnostics are summarised in Table 1. At the beginning of the campaign (1) the measurements agree with the former ones [14]: the layers are continuously growing, the deposition at the inner divertor is by a factor of four stronger than at the outer one. QMB B, facing towards the divertor plates, shows twice as much deposition as QMB A, orientated perpendicular to the divertor plates.

Table 1
Growth on QMB A and B normalised to QMB C for discrete periods of the experimental campaign 2002–2003

Period	Layer growth		Neutral flux $*10^{21}$ at/s	Radiation $W m^{-3}$	Parasitic plasma	
	QMB A	QMB B			$n_e *10^{14} m^{-3}$	T_e eV
1	0.12	0.25	38	63 300	12	9
2	0.45	0.72	124	116 300	54	14
3	−0.11	−0.98	16	62 700	20	18
4	0.57	−0.39	230	246 100	>45	23

Additionally averaged measurements for relevant diagnostics are shown.

This ratio is expected for the deposition of neutrals originating from the divertor plates, and agrees with the long term samples below the roof baffle. During phase 2 an additional carbon source at the outer divertor occurred. The deposition at QMB C remains almost constant, but both QMBs at the outer divertor show by a factor of 3 stronger layer growth. This reflects the higher carbon content at the outer divertor and the low transportation rate of carbon from the outer towards the inner divertor. A direct comparison with the data of phase 1 is hindered by different divertor conditions: neutral flux, radiation and ion flux are higher. However, this data suggests that erosion at the outer divertor is not directly responsible for the layer formation at the inner divertor. Divertor ^{13}C puff experiments, which also show only local carbon deposition [7], confirm these findings. After removal of the additional carbon source a low density, high power experimental programme was started. This programme causes low densities, but strong radiation in the divertor (3). At the inner divertor less deposition is measured and the region below the outer divertor turns to be erosion dominated under these conditions. The erosion on both outer divertor QMBs differs by a factor of 9. This asymmetry reflects that direction sensitive processes, as erosion due to ions, are dominant. A Langmuir probe installed close to the QMBs (Fig. 1) is measuring a parasitic plasma, with an electron temperature twice as high as for the phase 1. This parasitic plasma erodes the a:C–D layers. Period (4) offers the most relevant plasma scenario: H-mode and high density. Additional $^{13}CD_4$ was puffed to study the carbon migration [15]. This series of 12 identical shots shows a constant rate for all QMB instruments. In the outer divertor deposition is observed at QMB A and erosion at QMB B. Unfortunately, the Langmuir probe measuring the parasitic plasma was installed at a different position during (4), so only a lower limit for n_e could be derived. The discharges shows high neutral densities, radiation and ion fluxes in the divertor. A dense and hot parasitic plasma leads to erosion. Positions which are not hit by this plasma show strong deposition. Consequently, the QMB data demonstrate that even at remote areas erosion processes are involved at the layer formation. Simultaneously, the deposition and erosion varies strongly depending on the experimental programme.

4. Conclusion

The dedicated divertor carbon erosion and deposition experiment offered a unique data set for evaluating the carbon erosion and deposition in the lower divertor of ASDEX Upgrade. New information has been gathered by the simultaneous use of marker tiles, deposition monitors, cavity probes, quartz microbalance monitors, divertor plasma diagnostics, and $^{13}CH_4$ puffing. Neutrals seem to be responsible for the deposition at remote areas but the observed high surface loss probability is still not understood. The parasitic plasma in remote areas below the roof baffle seems to play an important role in the formation and erosion of layers. A numerical model describing the layer formation at remote areas should include erosion at the target plates, transport by neutrals, and surface activation and erosion by the parasitic plasma, which is generated by photoionisation of hydrocarbons. In the future, the temperature dependence of the layer growth will be studied by heated deposition monitors. The further enhancement of tungsten will help to identify the dominant carbon source and the divertor marker experiment will be repeated.

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