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Carbon migration at the divertor of ASDEX Upgrade

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Introduction

In present fusion experiments carbon is the most common first wall material. Graphite offers excellent thermo mechanical and electrical properties. But carbon is strongly eroded, which leads to the formation of deposition layers, which will contain a significant amount of tritium and cause safety problems. To understand the deposition processes laboratory experiments on a-C:H layers growths are not sufficient, only experiments in fusion devices match all relevant processes at the same time.

A combined experiment was realised to investigate the carbon layer formation at the complete divertor region of ASDEX Upgrade (Fig. 1). The deposition and erosion on the target plates has been measured by Re/C marker stripes. Up to 35 Si wafer and 5 cavity probes were mounted as deposition monitors at remote areas. The markers cover almost all relevant regions providing high spatial but no temporal resolution. To investigate the layer formation processes time resolved measurements using quartz microbalance monitors, $^{13}CH_4$ puffing, Langmuir probes and residual gas analysis are used. Usually, the main problem to derive a picture on the carbon migration is the lack of diagnostics. Long term probes and markers provide only campaign averaged information. But during a campaign very different plasma scenarios are used. Typically the measured layers are divided by the integrated time of the discharges to derive erosion or deposition rates. This simple approach may give rise to misleading results. For example erosion is expected at the outer divertor strike point position. From puffing experiments it is known [1] that the majority of the eroded carbon is deposited in the vicinity of the outlet. If during the next shot the strike point position is at a deposition dominated location the deposits may eroded again. Obviously time resolved measurements are needed, but they are only available through spectroscopy, residual gas analysis and Langmuir probes. These give almost no direct information on layer growth. At remote areas, where the heat flux is low, quartz microbalance monitors (QMB) can provide shot resolved information. Additionally, puffing of a marker gas ($^{13}CH_4$) give information for one scenario. In the following we will try to develop a picture of the carbon migration at ASDEX Upgrade using all available measurements. Obviously simulation calculations are needed to verify this picture.

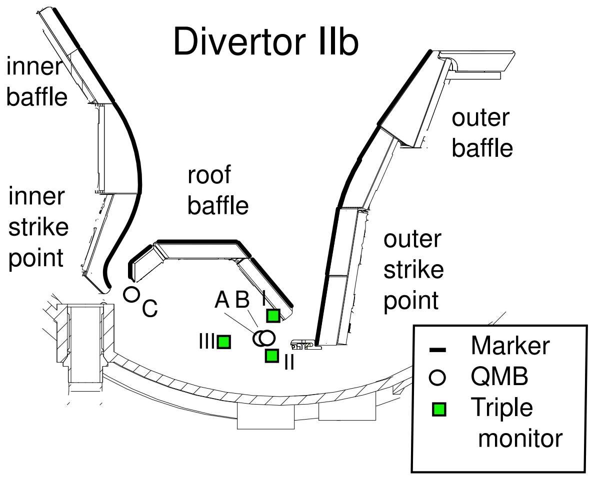

Fig.1: *Position of diagnostics used in the divertor of ASDEX Upgrade.*

$^{13}CH_4$ puffing

The primary sources of carbon in ASDEX Upgrade are the low field side limiters, the outer divertor and the roof baffle. Most of the other plasma facing components are tungsten coated. Multiple recycling is observed at the inner heat shield [2] and other main chamber components and finally the carbon will reach the divertor. To investigate the carbon transport $^{13}CH_4$ puffing experiments were done at the end of the campaign. During the flat-top phase of 10 identical H-mode discharges methane was puffed by a midplane valve. A poloidal divertor cross section was analysed post mortem using SIMS [3]. About 3.5 % of the puffed methane is deposited at the inner baffle close to the central column. Only 1.2 % is found at the inner divertor strike point module, but 5.9 % at the outer one. The inner baffle region is directly coupled via magnetic field lines with the outer most SOL field lines. Obviously the methane is ionized at the outer SOL and transported by drifts to the inner divertor without reaching the core plasma. Additional deposition is expected at the inner heat shield and the outer limiters. The deposition at the inner baffle is expected to be eroded during following shots and deposited closer to the inner strike point. Methane reaching the core plasma should be deposited close to the strike points. In contrast to long term investigations, more deposition is found at the outer than at inner divertor. The amount deposited close to the strike points (7.1 %) is in close agreement to the expected penetration [4] of 10 %.

Divertor plates

C/Re marker tiles are used to measure the erosion / deposition pattern at the end of the campaign [5]. In general three different areas could be distinguished: Thick a-C:H layers are found at the inner divertor strike point and baffle tiles. An averaged carbon deposition up to $7.4 \cdot 10^{19} at/cm^2$ is observed. The outer baffle region is erosion dominated probably by chemical processes ($-3.0 \cdot 10^{18} at/cm^2$), whereas at the outer divertor strike point module erosion and deposition is measured at the same time. Using the different intrinsic impurities some additional information could be gathered. Assuming that for typical divertor conditions deposited Fe and W are almost not reeroded, the deposition pattern should reflect the integrated strike point position during the whole campaign. This simple picture fits almost perfect to the deposition pattern observed at the outer divertor. The most dynamic behaviour is expected for the D-inventory at the outer divertor. Here, the total ion flux can be determined by summing up the ion saturation current of the divertor Langmuir probes. The observed D inventory is by orders of magnitude less than the flux for one shot. A significant D inventory is found only inside the private flux

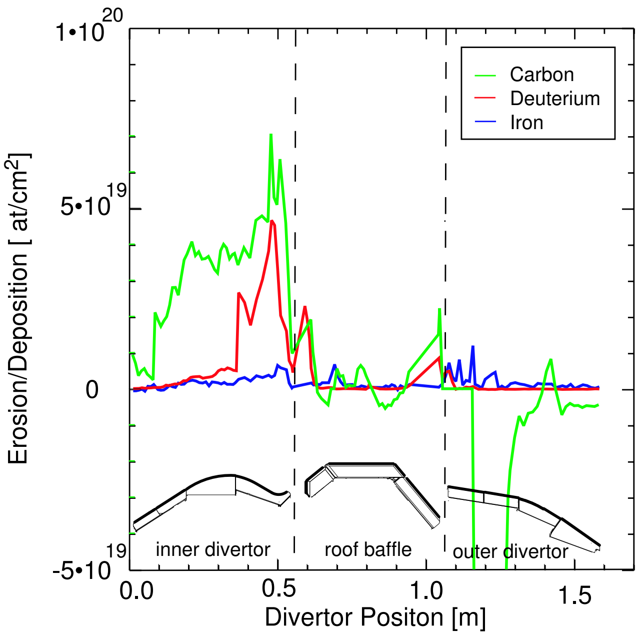

Fig.2: *Deposition of C,D and Fe found on the poloidal divertor cross section.*

region. During the shots surface temperatures of 1200 K are measured by thermography at the outer divertor target tiles. This is sufficient for the outgasing of the deuterium inventory of the a-C:H layers within one discharge. So the D inventory of the outer divertor target plate is determined by less than one discharge. For carbon the picture at the strike point plates is more complex. On the one hand the C layer ($7.5 \cdot 10^{19} at/cm^2$) is completely removed, on the other side deposits ($5.0 \cdot 10^{19} at/cm^2$) are found. The reason for this behaviour can be a preferential erosion of the marker carbon due to the high thermal flux. A glowing of the carbon layer at the strike point position is observed, which may be due to the poor thermal conductivity at the c markers, which leads to significant higher temperatures. This higher temperature can lead to a preferential erosion of the layers.

The carbon deposits at the divertor plates are forming a-C:H layers. As the ion flux is highest close to the magnetic strike point position, strong deposits are formed there. It is known from laboratory investigations [6], that a-C:H layers have a much higher chemical erosion rate than carbon. The material is eroded again during the plasma discharge forming C-H radicals, pre-cursors for the build up of new a-C:H layers. Eroded neutrals will spread from the divertor plates and cross the SOL plasma. If they are ionised they will be deposited at the target plates again. Otherwise they will be deposited at the first wall and the structure. Depending on their sticking probability, they will stick on the surface forming new a-C:H layer. If these new layers can be hit by ions or atomic hydrogen they will be eroded again. Only at the inner divertor, which is almost detached, and at remote areas these layers will grow, forming an nonsaturating sink for C and D, which will cause problems for the T inventory of a future fusion reactor.

Remote areas

The layers at the remote areas are investigated using deposition monitors [9]. Typically 4 % of the total deuterium inlet during an experimental campaign is found in these remote regions. Typical a-C:H layers with D/C = 0.4 to 1.0 are observed. After venting the vessel the layers can form flakes. The thickest (up to $1.1 \cdot 10^{19} at/cm^2$) layers are again found at the inner divertor. Depositions close to the divertor plates are expected to be formed by high sticking species. Low sticking species, which will be lost on average within 1000 wall contacts, will produce a homogeneous layer. The e-folding decay lengths of the amount of deposition from 10 mm show that high sticking species are forming the deposits. A more quantitative sticking factor is measured using cavity probes [7]. A value of 0.65 to 0.75 is found. To estimate the absolute value of low sticking and high sticking species, deposition probes at the pumping duct are used. Here only low sticking species can contribute to the layer formation. Due to the simple geometry of the pumping duct the deposition can be simulated as a big cavity probe [5]. From these data it is clear that in ASDEX Upgrade almost only high sticking pre-cursors are contributing to the layer formation [8]. Further away from the divertor significant deposits are only found at the LN2 shield of the in vessel cryo pump.

Probes were also mounted at the same position facing into different directions (triple probes). If only deposition of neutral species is responsible of the layer formation, the deposition on probes facing in and inverse magnetic field direction should be the same. Probes facing towards the divertor plates should show thicker layers. These expectations are found at some locations, whereas at other location the picture is quite different. A triple probe mounted at Position I and III (Fig.1) shows the expected behaviour: The deposition parallel and antiparallel to the magnetic field directions are identical. The probe facing towards the divertor plate shows a thicker deposition. This behaviour fits perfectly to a layer formation by neutral precursors with a surface loss probability close to one. At the location II the picture is quite different: Much less deposition is found. A significant deposition is only on the probe facing in magnetic field direction. Obviously the deposited layers are eroded again. The direction dependence of this erosion points to ion sputtering as erosion process. As reported earlier [9] parasitic plasma is observed at this region, which causes the erosion.

Quartz mircrobalance monitors

Three QMBs, which provided time resolved information on the layer growth, are operated below the roof baffle [10]. Typically a continuous layer growth is found at the inner divertor. The behaviour at the outer divertor is variable. The layer growth rate depends strongly on the strike point position. This is in line with the dominance of very high sticking pre-cursors: They will contribute to a layer growth at the position of the QMBs only, if they reach them without without wall contact. The strike point position must be almost in line of sight with the QMB. For identical strike point positions the layer growth rate was checked against different other measurements. A simple correlation was only found with the divertor neutral density. In contrast to JET measurements, no conditioning is observed, i.e. for a series of identical shots identical deposition is measured. For high power, low density discharges even erosion is detected by the QMB at the outer divertor.

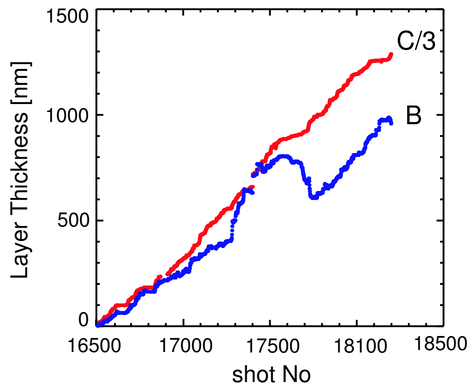

Fig.3: *Layer Thickness measured by the QMB at outer (A) and inner (C) divertor*

Synthesis

A consistent data set on the carbon migration at the divertor of ASDEX Upgrade was gathered. Depending on the plasma scenarios, deposition or erosion are found at the same location. Carbon seems undergo manifold recycling processes. Time resolved measurements are needed to characterize these processes.

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