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Carbon layers in the divertor of ASDEX Upgrade

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Abstract

One of the main disadvantages of carbon as first wall material in a fusion device is the co-deposition of hydrogen with the eroded carbon. These layers will contain a significant amount of the tritium inventory of a fusion reactor. After venting brownish layers and flakes were found under the divertor structure of ASDEX Upgrade. First investigations were made on these flakes. Due to the complicated structure beyond the divertor, shadowing effects occur indicating that the brown layers are deposited by ionised particles. The flakes were analysed using SEM and ion beam techniques. Two different types of hydrocarbon layers were found: The brownish hydrogen poor layer (D/C = 0.4) and transparent hydrogen rich layer (D/C = 1) The total amount of carbon beyond the divertor could be estimated to 1.5 g, deposited in 3000 s of plasma discharges. First measurement of the layer growth using a quartz crystal microbalance instrument is presented. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Carbon; Redeposition; Divertor

1. Introduction

The selection of first wall materials for future fusion devices is still under discussion. Nowadays most fusion experiments are using carbon for plasma facing components, because of its excellent thermal properties. One of the main disadvantages of carbon is the high erosion rate due to chemical sputtering. The carbon eroded will be deposited forming hydrocarbon layers. These layers contain a significant amount of the tritium inventory of a future fusion reactor [1,2]. Consequently the current ITER design minimises the amount of carbon in plasma facing components. In the Mark II divertor of JET massive carbon flakes were found after venting the vacuum vessel. These were located near the inner divertor at the so-called louvres. This position cannot be reached by the plasma directly [3]. The mechanism forming these flakes is not completely understood. The lyra-shaped divertor of ASDEX Upgrade consists of fine grain graphite and CFC (Fig. 1). Most of the eroded carbon are deposited on the divertor tiles and can only be detected indirectly by the co-deposited deuterium [4]. In this contribution we deal with co-deposited layers found on structures hidden below the plasma facing tiles.

2. Locations of the layers

The divertor of ASDEX Upgrade is mounted on a stainless steel structure. On this structure brownish layers are found in regions without direct contact to the plasma. In Fig. 1 these positions are marked by shaded regions. Due to the complicated structure, there are surfaces perpendicular to and collinear with the magnetic field. Thick brownish layers are mainly found on surfaces perpendicular to the magnetic field. This suggests, that the deposition of the layers is dominated by charged particles, which have to follow the magnetic field lines. This hypothesis is confirmed by shadowing of neighbouring surfaces. Most of the brownish layers are found at the inner divertor leg. On surfaces perpendicular to the magnetic field the brown layers are only found on one side. At the inner leg the layers are formed in magnetic field direction, at the other against this direction. The brownish layers are always formed at the

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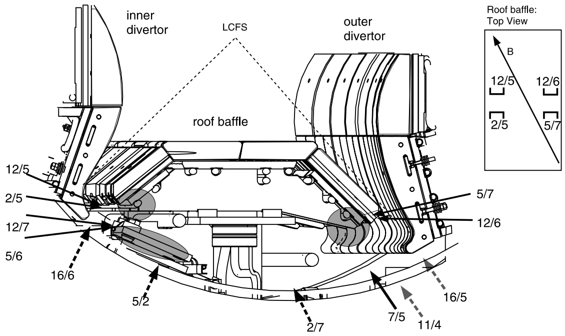

Fig. 1. Lower part of the ASDEX Upgrade vessel showing the strike point modules, the roof baffle and the corresponding support structure. The arrows indicate the locations of silicon collector probes: Dashed arrows correspond to probe surfaces parallel to the toroidal magnetic field, full arrows correspond to perpendicular surfaces (see text). The positions where the flakes are found are shaded. The insert clarifies the orientation of the probes.

surfaces next in magnetic field direction to the divertor slits.

Some days after venting the vessel, delamination of the brownish layers occurred, which results in flakes of a typical thickness of 2 μm. The flaking could be stopped by storing the components in dry air. This behaviour is similar to that observed in TFTR [5] but on a shorter time scale. An SEM picture of a flake (Fig. 2) shows a cracking pattern, which indicates stress in the layer. The sharp edges of these cracks can only be explained by formation after plasma operation. Dust particles embedded in the layers lead to shadowing effects. In the image a 'wake' is formed on the right-hand side of the particles. This confirms the formation of the layers by ionised particles, which have to follow the magnetic field lines. The composition of the layers was analysed using ion beam techniques. Typical amorphous hydrocarbon layers (a-C:H) were identified. Using 2.6 MeV proton beam RBS, a thickness of 1.5×10^{19} at./cm^2 was found. The layer consisted of approximately 60% carbon, 40% deuterium, 5% boron and 10% oxygen. An estimate on the total amount of carbon in the layers results in several grams deposited during one experimental campaign of ASDEX Upgrade (1000 discharges, 5000 s of plasma operation).

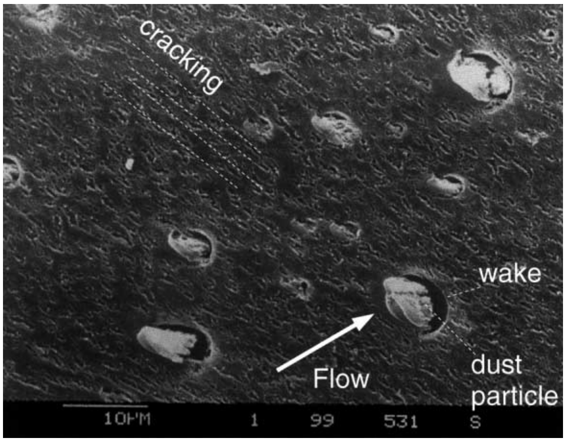

Fig. 2. SEM picture of a deposited layer observed in ASDEX Upgrade. The flow direction of charged particles, i.e. the direction of the toroidal magnetic field, is indicated. The shadowing caused by dust particles incorporated into the film results in a 'wake' of hindered film growth.

3. Classification of carbon layers

To get well-defined measurements, 12 silicon wafers were inserted and exposed during one experimental campaign. The positions of the installed probes in the divertor of ASDEX Upgrade are indicated by arrows in Fig. 1. From spectroscopic measurements we expect an asymmetric carbon deposition at the inner and outer divertor legs. To investigate this problem four probes were mounted perpendicular to the magnetic field below the roof baffle in the inner and outer divertors, i.e., almost at the same position with respect to the separatrix. Two probes are facing against the magnetic field direction. As expected only two probes show a brownish layer. The probes were analysed using again ion beam technique and ellipsometry. The results are compiled in Table 1. The amount of carbon found is almost constant for all probes. Not only brownish layers but also transparent layers are found. All layers found are typical a-C:H layer. Differences are found in the deuterium content and the density. In laboratory experiments [6] hard and soft layers are observed, depending on the deposition conditions. The hard layers are brownish with a ratio of $H/C = 0.4$ and a density of $\rho = 2$ g/cm^3. Whereas the soft layers are transparent with $H/C = 1$ and $\rho = 1$ g/cm^3. Within the error bars of the measurements our results fit to these two kinds of a-C:H layers. The brownish are hard layers, which are formed by deposition with energetic ion bombardment. The transparent layers are soft. The positions of the different layers are consistent with this interpretation: The brownish layer are only found at positions facing directly towards the divertor slits. The high energies required to form hard a-C:H layer are however not expected at these positions. From the average of both directions in the inner and outer divertors a ratio of the layer thickness for the inner and outer divertors of 3:1 for carbon and 2.4:1 for deuterium is found.

Table 1
Location and properties of the hydrocarbon layers

Position	Direction	Colour	Deuterium (at./cm^2)	Carbon (at./cm^2)	Thickness (μm)	D/C	Density (g/cm^3)
Inner	To slits	Brownish	4.0e18	1.1e19	1.0	0.38	2.4
Inner	Perpend.	Transpar.	3.5e18	8.8e18	1.9	0.73	1.0
Outer	To slits	Brownish	1.5e18	4.2e18	0.7	0.46	1.3
Outer	Perpend.	Transpar.	1.4e18	2.5e18	0.7	0.95	0.8

4. Total amount of deposited carbon

The total amount of carbon deposited on all probes installed was used to estimate the total carbon inventory deposited in the divertor region during the experimental campaign The probes mounted perpendicular to the magnetic field are representative for the structures. The total area of the structures was estimated using one section of the torus. From the probe measurements we get the layer thickness, which was extrapolated to the total surface. Summing up the whole divertor about 0.7 g carbon at the inner divertor structure and 0.2 g carbon on the outer structure are estimated. The probes oriented parallel to the magnetic field direction represent the vacuum vessel. Here only the soft kind of layers was found. The typical layer thickness is a factor of 10 lower than found at the same position for perpendicular incidence direction. This is also a strong evidence that the layers are mainly formed by charged particles, which have to follow the magnetic field lines. To get the total amount of carbon deposited, the area below the divertor was divided into strips. The amount of carbon was estimated extrapolating the probe area to that of the strips. From this we find 0.7 g carbon on the vacuum vessel. An inventory of $1.6(-1+2)$ g carbon was deposited on the divertor structure of ASDEX Upgrade during the campaign 1999 within 3000 s of plasma operation. This amount is 0.3% of the carbon eroded in the divertor as estimated from spectroscopic measurements. The deuterium inventory found in these layers is 8×10^{22} at., which corresponds to 0.4% of the total deuterium inlet during the campaign. Additional layers are found at various locations in the whole experiment. These are not included in this estimate.

5. Quartz crystal microbalance measurement

Probe measurements yield only averaged information for a whole experimental campaign. Due to the different scenarios, which are performed during this time, it is hardly possible to identify the mechanism forming the layers. The need for time resolved or, at least, shot-to-shot resolved measurements is evident. The positions where the layers are found are not accessible with existing manipulators. Therefore two quartz crystal microbalance (QCM) sensors were installed near the inner divertor of ASDEX Upgrade. Positions expected to be deposition dominated are chosen. Both sensors are at the same poloidal position mounted back to back. The technique is based on the resonance frequency of a quartz wafer. This is changed by material deposited on it according to

$$\Delta f = f^2/\rho(t) \; * \; \Delta m/A \tag{1}$$

with Δf the change of the resonance frequency, Δm the mass of the deposited material, A the area of the sensor, f the resonance frequency of the crystal and $\rho(t)$ is the density of the quartz [7]. Due to the distance of 2 m from the flanges to the sensor head the oscillator has to be integrated into the sensor. A commercial available instrument is used.

It allows measurements with a time resolution of 0.2 s. As shown in Eq. (1) the shift of the resonance frequency depends also on the density of the quartz, which is temperature sensitive. Although the location is not directly exposed to the plasma, there is nevertheless a thermal load on the sensor, which is changing the resonance frequency, which inhibits direct measurements of the deposition during the discharge. Calculations to include this effect are under investigation. Here

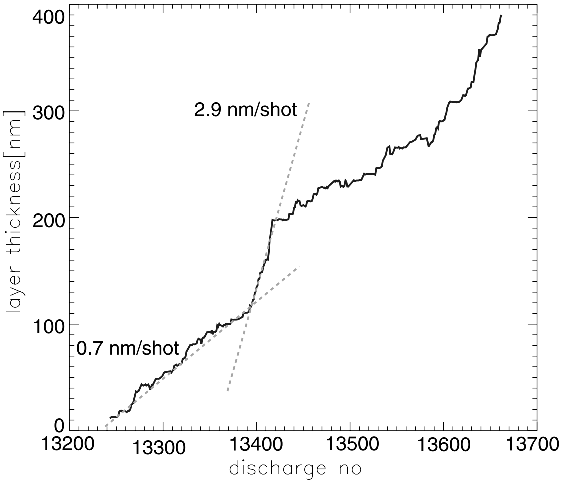

Fig. 3. Film growth on a microbalance sensor plotted versus discharge number.

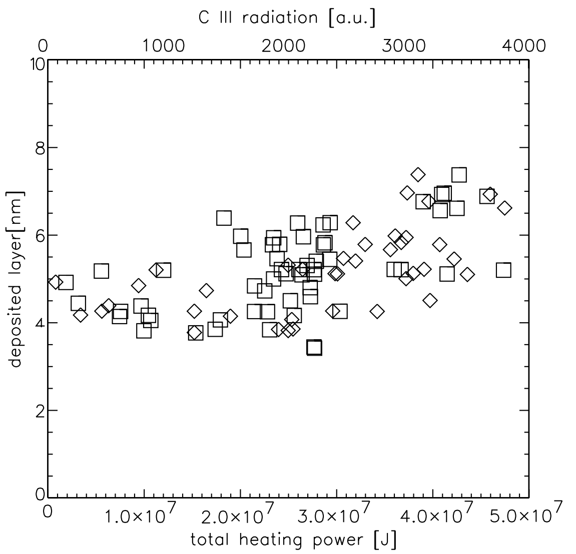

Fig. 4. Growth rate versus total heating power (square) and SOL carbon density (cross).

we restrict the analysis to measurement on a shot-to-shot base.

In Fig. 3 the growth of the layer thickness during 400 discharges is shown. The layer thickness is rising continuously. An average rise of 1 nm per plasma discharge is found in good agreement with the probe measurement. In some discharges a decrease of the layer thickness is observed. This can be explained by elevated temperatures due to a short time between successive discharges. From the differences in the thickness measurement before the discharge the amount of deposited material during the discharge can be calculated. The maximal deposition is about 7 nm during one discharge. The strong increase of the layer thickness during the discharges 13 390–13 416 can be identified due to scenarios with high divertor neutral densities.

For first investigations we compare this data with shot integrated measurements of global plasma parameters. Only measurements with deposited amounts larger than 3 nm are used. As shown in Fig. 4 significant correlation with the heating power and the carbon content in the scrape-off layer is found. A detailed analysis of this measurement is currently being worked out.

6. Summary and conclusions

Carbon layers in the divertor of ASDEX Upgrade are observed. Two kinds, deuterium poor brownish and deuterium rich transparent layers are identified. The brownish layers are deposited by charged particles. A ratio for the layer thickness for the inner and outer divertors of 1:3 is found. During the experimental campaign 1 mg of carbon is deposited at the divertor structure each second of plasma discharge. First measurement using a quartz crystal microbalance sensor is presented.

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