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ABSTRACT.

This paper summarizes observations about net carbon erosion and re-deposition in the limiter tokamak TEXTOR, and the divertor tokamaks ASDEX Upgrade and JET. The major carbon source in TEXTOR is the toroidal graphite belt limiter. Eroded carbon is mainly re-deposited on net deposition dominated areas of that limiter, and on areas perpendicular to the magnetic field in the scrape-off layer. In ASDEX Upgrade and JET the major carbon sources are located in the main chamber. Eroded carbon is re-deposited on the divertor tiles in the inner and to a lesser extent outer divertors. Carbon migration to remote areas without direct plasma contact like the JET louvres, or the area below the divertors II and IIb of ASDEX Upgrade, are observed. Soft, hydrogen rich hydrocarbon layers with a deuterium to carbon ratio of 0.7–1.4 are formed in these areas. Precursor for this layer formation is sticking of hydrocarbon radicals like CD_3 or C_2D_x (x = 1, 3, 5) created by re-erosion of deposited hydrocarbon layers on the divertor tiles.

1. INTRODUCTION

The major disadvantage of carbon as plasma facing material is its ability to trap large amounts of hydrogen by codeposition with eroded carbon atoms [1]. Carbon is eroded at some locations in the machine, transported in the plasma edge and in the Scrape-Off Layer (SOL), and finally redeposited at a different location together with hydrogen. Tritium trapped in these codeposited layers will contain a significant amount of the total tritium inventory of a nuclear fusion reactor [2–4]. In today's machines, these layers are not only observed at plasma facing surfaces like limiters [1,5], areas perpendicular to the magnetic field in the scrape-off layer [1,6,7], or divertor plates [8], but also at areas without direct plasma contact such as the louvres in the JET Mark IIA and IIGB divertors [9], the area below the divertors II and IIb of ASDEX Upgrade [10,11], or the pump ducts in ASDEX Upgrade and TEXTOR [1,5,12]. These remote areas can be reached only by neutral particles and not by ions, because they are only accessible by traversing the magnetic field.

It was shown in low temperature plasma experiments, that neutral hydrocarbon radicals such as CH_3 and C_2H_x (x = 1, 3, 5) can contribute significantly to the growth of hydrocarbon layers [13], and it was assumed that hydro-carbon radicals are also responsible for the formation of codeposited layers in remote areas of fusion experiments [13]. Recently strong experimental evidence was reported from ASDEX Upgrade and JET, that indeed hydrocarbon radicals play a major role in the growth of these layers [14]. Hydrocarbon radicals hitting a wall may adsorb with a sticking probability s, can react to a nonreactive molecule with reaction probability γ, or can be reflected with reflection probability . The surface loss probability β is given by $\beta = s + \gamma$, with $r + s + \gamma = 1$.

For predictions of the tritium inventory in future fusion devices like ITER, the amounts of eroded carbon, the rate of carbon pump-out in form of volatile stable hydrocarbon molecules like CD_4 or C_2D_y (y = 2, 4, 6), and the hydr-gen concentrations in codeposited hydrocarbon layers have to be predicted quantitatively. Predictions about the locations of codeposited layers are also necessary in order to design deposition diagnostics and layer removal methods. This requires a detailed physical understanding of the erosion and carbon migration processes, and computer simulations.

This paper summarizes observations about carbon sources and hydrocarbon layer formation in the limiter tokamak TEXTOR and the divertor tokamaks ASDEX Upgrade and JET. By combining the different observations a comprehensive picture of carbon erosion and migration can be obtained.

2. TEXTOR

2.1 GENERAL

TEXTOR is a medium sized tokamak with toroidal limiter. The minor ra-dius is 0.46m, and the major radius is 1.7m. The total plasma exposed area is about 40m^2, of which 9.4m^2 consist of carbon: The toroidal ALT-II belt limiter, consisting of 8 blades with 228 carbon tiles and a total area of 3.4m^2, and the inner bumper limiter with 6m^2. The surface areas of other carbon components, like poloidal and antenna protection limiters, are small. The residual wall areas, the so-called liner, consist of stainless steel (Inconel) covered with 50–100 nm amorphous hydrogenated boron (a-B:D) or silicon (a-Si:D) layers created during regular boronizations or siliconizations for wall conditioning. TEXTOR wall temperatures are 150 – 350^{o}C.

2.2 CARBON SOURCES

Erosion dominated parts of the toroidal graphite belt limiter and the liner are net erosion areas. Major carbon source is the toroidal limiter. Net carbon erosion was determined by profilometry of a carbon tile before and after exposure for 7625 plasma seconds using W-coated holes as reference points [5]. About 2/3 of the tile surface were erosion dominated with a maximum observed erosion of 28μm. The net carbon erosion from the whole toroidal limiter consisting of 228 tiles is about 22 g carbon per hour [5,15]. Carbon is eroded from the limiter by physical and chemical sputtering. The limiter temperature is typically above 350^{o}C. The plasma ion temperature in front of the limiter is about ??? eV, resulting in high energies of incident ions.

The inner graphite bumper limiter is an additional source of carbon by erosion due to charge-exchange sputtering. Carbon erosion at the bumper limiter has not been quantified up to now, but is assumed to be small compared to the toroidal limiter due to its more recessed position [15]. Even a small carbon deposition was observed, see section 2.3.

The chamber wall is erosion dominated by charge-exchange sputtering [12]. As it does not contain any large scale carbon components, it is not a carbon source, but a source of boron or silicon deposited during boronizations or siliconizations. Additionally metals like Ni, Fe and Cr are eroded from the liner. These elements are observed in redeposited hydrocarbon layers at a level of about 5% (boron), and metal impurities at about 1% [16].

2.3 CARBON REDEPOSITION

The observed redeposition of carbon in different parts of the machine is summarized in Table 1. As already described in section 2.2, about 22g/h carbon are eroded from erosion dominated areas of the toroidal limiter. The majority of the eroded carbon is redeposited in net deposition dominated parts of that limiter. About 1/3 of the limiter area (1.2m^2) are deposition dominated, accounting to about 10g/h carbon redeposition [5,15]. The D/C ratio in these redeposited layers is only about

0.05–0.16 D/C due to the high limiter temperatures.

Another 6g/h carbon are deposited on areas in the scrape-off layer perpendicular to the magnetic field (”obstacles”) [1]. This includes side faces of poloidal limiters, antenna protection limiters, screws, bolts etc. The D/C ratio in these layers depends strongly on the temperature history of the component and varies between 10^{-4} and 0.4. The low D/C ratios are observed for components with temperature excursions up to 1000°C.

About 1g/h carbon is deposited on the neutralizer plates below the toroidal limiter [1], and another 1g/h on the inner bumper limiter. 1–2g/h carbon are pumped out in form of stable hydrocarbon molecules like CD_4, C_2D_2, C_2D_4, C_2D_6 and higher hydrocarbons [12].

A very small redeposition of only 0.02 g/h carbon is observed in the pump ducts, where soft and hydrogen rich hydrocarbon layers with D/C ≈ 0.7 and a low diffraction index between 1.4 and 1.6 are observed [12]. The pump ducts are at room temperature. The thickest layers were observed in line-of-sight to the graphite neutralizer plates.,The layer thickness decreased strongly by more than two orders of magnitude along the pump duct with increasing distance to the neutralizer. It was assumed that the hydrocarbon layers are formed by sticking of hydrocarbon radicals to the duct wall. The radicals are created by chemical erosion of deposited carbon layers on the neutralizer plates [12]. The main deposition on surfaces in line-of-sight and the strong variation of the layer thicknesses along the pump duct is a qualitative indication that the particles responsible for hydrocarbon layer formation are not able to survive many wall collisions, i.e. the layers are formed by particles with high sticking coefficient close to unity.

In total about 18 g/h carbon are redeposited in deposition dominated areas of TEXTOR and 1–2g/h carbon are pumped out. Keeping the large errors of the accounted numbers in mind, this agrees well with the determined total carbon erosion of about 22g/h.

3. ASDEX UPGRADE

3.1 GENERAL

Plasma facing components in ASDEX Upgrade consist of carbon and tungsten. During the experimental campaign 1999/2000 1.2m^2 of the lower part of the inner heat shield were coated with tungsten (phase I). The tungsten coverage of the inner heat shield was increased to 5.5m^2 from April to July 2001 (phase II), and further increased to 7.1m^2 during the campaign 2001/2002 (phase III), covering almost the whole inner heat shield except for small regions which may be hit directly by the shine through of the neutral beam injection. During the campaign 2002/2003 the inner divertor baffle and the upper passive stabilizer loop were covered with W, increasing the W-coated surface area to 14.6m^2. Lower divertor, upper divertor, antenna protection and auxiliary limiters at the outboard side consist of carbon. Divertor II was used from 1996–2000, divertor IIb since 2000. Boronizations are regularly applied for wall conditioning. The walls are at room temperature.

3.2 CARBON SOURCES

The carbon concentration in the plasma is typically ≤1%. Possible carbon sources at ASDEX Upgrade

include inner and outer divertor, upper divertor, and antenna protection and auxiliary limiters at the outboard side.

The inner and outer sections of divertors II and IIb are net carbon deposition areas, see section 3.3. With divertor I the carbon content of the plasma was not reduced by replacing the carbon divertor tiles by tungsten coated tiles during the tungsten divertor experiment [17], despite the almost complete removal of carbon in the divertor. Strong carbon deposition was observed on the tungsten divertor plates, mainly in the inner divertor [18]. Inner and large parts of the outer divertor are therefore net carbon redeposition areas and not carbon sources. There are indications from measurements of the deuterium inventory, that the outer baffle might be a net carbon erosion area (see Section 3.3), but this is currently not well investigated.

Strong carbon in flux was observed spectroscopically from the inner heat shield before the tungsten coating was applied, and net erosion was determined with long term samples using ^{13}C, Cu and W markers [19,20]. As the inner heat shield is used as limiter during plasma start-up and ramp-down, some fraction of the observed erosion can be attributed to these phases. However, considerable erosion was also observed during divertor operation. The erosion is due to charge-exchange sputtering and additionally due to ion impact, as can be concluded from the observation of shadowed areas parallel to the magnetic field lines.

After the almost complete coverage of carbon by tungsten on the inner heat shield from 1999 to the campaign 2001/2002, the carbon concentration in the core plasma decreased by less than 30% compared to the full carbon case [21]. Still large carbon uxes originating from the inner heat shield are observed in the CII and CIII light [22]. This is shown in Fig.1, where a strong CII radiation is observed from the tungsten coated inner heat shield. The carbon originates from limiters at the outboard side, carbon radiation from the ICRH-antennae is clearly visible in Fig.1. These areas serve as primary carbon source. The carbon is then deposited at the inner heat shield, where it is further eroded and serves as secondary carbon source. Interestingly the CII radiation and hence the flux of C^+ from the tungsten coated inner heat shield even exceeds the C^+ in flux from the outboard side [22]. This paradox result is obtained because eroded carbon is deposited at the inner wall, re-eroded, deposited again, re-eroded again, etc., i.e. each carbon atom performs several attempts to penetrate into the plasma until it is finally transported into a net deposition area. Carbon in flux from the upper divertor is not well known, but assumed to be small compared to the outboard limiters.

3.3 CARBON REDEPOSITION

Deposition of thick hydrocarbon layers was observed by visible inspection of the divertor plates in the inner and outer sections of the divertors II and IIb. This observation is supported by measurements of the deuterium inventory in divertor IIb after the experimental campaign 2001/2002 by nuclear reaction analysis [23]. The whole inner divertor and large parts of the outer divertor (including inner and outer strike points) showed deuterium inventories $> 1\times10^{17}$ D-atoms/cm^2, indicating that these areas are deposition dominated. The inventories were larger in the inner than in the outer

divertor. Only the outer baffle (Bgr. 2 and 3) showed smaller inventories, which might indicate a net erosion area. More information will become available after analysis of marker tiles used in the 2002/2003 campaign.

Deposition of hydrocarbon layers below the divertors II [10] and IIb [11] was studied in more detail with silicon long term samples. Two different types of layers were observed [10]: Brownish, mechanically hard layers with a D/C ratio of 0.4–0.5, and transparent layers with a higher D/C ratio of 0.7–1.4. The transparent layers were mechanically soft and had a low diffraction index. The hard layers are observed only sporadically and are likely formed in areas with additional ion in flux or elevated temperatures, while the soft layers are formed in areas without additional ion flux. As the area below the divertor cannot be reached by ions (except the areas where hard layers are observed), they are formed by neutral particles. This is further confirmed by the observation that there is no significant difference in layer thickness on areas perpendicular and parallel to the magnetic field [11], which would be the case if ions would contribute significantly to layer formation. The deposition pattern was strongly inhomogeneous, with the thickest deposits close to the inner and outer strike points. The inner divertor samples showed thicker deposits by a factor of 2.5 than the outer divertor samples. The thicknesses of deposited layers decreased strongly by 2 orders of magnitude with increasing distance to the strike points. This is a qualitative indication that the layers are formed by sticking of particles with high sticking coefficient. In total only a small fraction of 0.3% of the total D input was trapped on the structure below the divertor IIb. Because gas balance measurements indicate a retention of 10–20% of the total D input [24], the majority of D is likely trapped at the surface of the divertor tiles. Analysis of deuterium and carbon deposition on the tile surfaces during the 2002/2003 campaign is under way.

Deposition in the ASDEX Upgrade pump ducts was studied with long term samples in sector 12 [11]. Only a very small deposition of D was observed, with a maximum inventory of 2.5×10^{15} D-atoms/cm^2 at the pump duct entrance after 1424 plasma seconds. Only 8×10^{-5} of the total D input is trapped in the pump ducts of ASDEX Upgrade. It was shown that the layers in the pump duct are formed by sticking of hydrocarbon radicals [11]. The simple geometry of the duct allowed to derive the sticking coefficient of the radicals by comparison with Monte-Carlo computer simulations. The deposition pattern could be explained by the assumption of two different hydrocarbon radical species with surface loss probabilities β of about 0.3 and $< 10^{-3}$ [11]. Because the ducts can be reached only after several wall hits, the vast majority of observed particles in the ducts belong to the small sticking species.

4. JET

4.1 GENERAL

Carbon is used at JET in the lower and upper divertors, at the inner wall (poloidal guard limiters and inner wall areas between the limiters), and for limiters at the outboard side. Beryllium evaporation is applied regularly 2–3 times per week for wall conditioning. Thick Be layers are observed at the outboard side of the main chamber [25], but Be is not observed at the inner wall due to the evaporation

characteristics of the evaporators and inner wall erosion. JET normally operates at a wall temperature of 320°C. The Mark IIGB campaign lasted from 1999–2001. For the last 12 weeks of the Mark IIGB operation the wall temperature was reduced to 200C, and of this period three weeks were with helium fuelling. The divertor structure is water cooled and reaches intermediate temperatures in the range 160–220°C with the wall at 320°C, and 80–140°C with the wall at 200°C.

4.2 CARBON SOURCES

Possible carbon sources at JET include inner and outer divertor, inner wall guard limiters, inner wall areas between the limiters, upper divertor, and outer wall limiters.

As will be shown in section 4.3, the inner divertor is a net carbon deposition area. In the outer divertor both erosion and deposition dominated areas are observed, see Fig. 2. Erosion is especially observed on the outer baffle (tile #8). But this small erosion is by far not sufficient to explain the massive deposition in the inner divertor, and additional sources must be present.

The inner wall and the inner wall guard limiters are net erosion areas, as was shown with long term samples using Al and Ni layers [26–28] and analysis of limiter tiles [28]. The erosion of Al and Ni layers at the inner wall was compatible with the assumption of sputtering by charge-exchange neutrals [26]. For the campaigns 1994/1995 an erosion of $> 3.6\times10^{19}$ carbon atoms/m^2 and JET discharge was observed at the inner wall [27]. Due to complete erosion of the carbon marker only a lower bound for the carbon erosion could be given, but the real erosion should not exceed this lower bound by a factor of more than two. In addition a carbon erosion of about 60g was deduced from the inner and outer poloidal limiters [27] between April 1994 – March 1995 in 3500 plasma pulses. Assuming identical erosion yields for the Mark IIGB divertor campaign, we can extrapolate these numbers for the whole Mark IIGB campaign of 5748 pulses to be about 60g from the inner wall and about 100g from the inner and outer limiters. This is only in very rough agreement with spectroscopic measurements using CIII light at one position at the inner wall [29], which gave a source strength of 390 g carbon for the whole Mark IIGB campaign. In any case the observed inner wall carbon erosion is much smaller than divertor carbon redeposition during the Mark IIGB campaign of 1700g, see Section 4.3.

The contribution of the upper divertor to the carbon source is unknown.

4.3 CARBON REDEPOSITION

The complete inner divertor of JET is a net redeposition area, see Fig.2. A part of the outer divertor, especially close to the corner at point #16, is also deposition dominated. The outer baffle is a net erosion area. However, this erosion is by far not sufficient to explain the massive deposition in the inner divertor.

As was shown by secondary ion mass spectrometry (SIMS) [8], redeposited layers on the tiles are enriched with Be and depleted with C. Additionally some Ni, Fe and Cr originating from the Inconel vessel wall are observed. The surface compositions of the samples are quite different to the composition deeper into the deposit, being mostly C and Be, and with a higher deuterium content. This is attributed to the different mode of operation during the last 12 weeks prior to the 2001

shutdown: The vessel wall temperature was reduced from 320°C to 200°C, and the fuelling gas was changed from deuterium to helium for the last three weeks.

Cavity samples were mounted in the inner module close to the louvres and below the septum in the inner divertor, see Fig.2. The outer faces of theses samples were covered with deposits up to 45µm (inner module) and 14µm (septum) [14]. The deposited layers consist almost entirely of carbon and deuterium, with a D/C ratio close to one. Additionally oxygen originating likely from air exposure was observed. Only minute amounts of Be and almost no Ni, Fe and Cr are observed. These areas are not hit directly by the plasma. The cavity samples allow to determine the surface loss probability of particles forming the hydrocarbon layers. The layers are mainly (> 99.8% of the layer thickness) formed by particles with in the range 0.9–1, i.e. by particles with a high sticking probability to the wall [14]. Low sticking particles are also observed, but difficult to quantify. In any case the contribution of low sticking particles to layer growth on the louvres and below the septum is negligible.

Additional deposits are observed in the areas behind the louvres. These deposits are hard to access, which makes a quantification of the total carbon re-deposition difficult. An estimate of the total carbon deposition can be obtained from the observed deposition of Be [29]: Be is redeposited only on the plasma exposed parts of the divertor tiles, and does not migrate into remote areas like the louvres and behind. The C:Be ratio in the JET plasma, as observed by spectroscopy, is 14:1. The total amount of redeposited carbon is then assumed to be 14 times larger than the amount of Be deposited on the divertor tiles, which were analyzed. This results in a total carbon re-deposition during the Mark IIGB campaign of 1700g carbon [29], which exceeds the observed carbon erosion from the inner wall (maximum 390g) by a factor of about four.

DISCUSSION

Currently TEXTOR is the only experiment where the major carbon sources, carbon redeposition and carbon pump-out as stable hydrocarbon molecules are known quantitatively. Major carbon source is the toroidal belt limiter, and 22g/h carbon are eroded from net erosion dominated areas of that limiter. 10g/h carbon are redeposited on net deposition dominated areas of that limiter, 6g/h are redeposited on 'obstacles' in the SOL, 1g/h is redeposited on the neutralizer plates below the limiter, and 1 g/h is redeposited on the inner bumper limiter, accounting to a total of 18 g/h re-deposited carbon. Additionally 1–2 g/h are pumped out as hydrocarbon molecules. Keeping the large errors of the accounted numbers in mind, there is perfect agreement between the amounts of eroded and redeposited carbon.

In TEXTOR, re-deposited hydrocarbon layers are mainly formed on plasma exposed areas. The D/C ratio of these layers is in the range 10^{-4} to 0.4, depending strongly on the temperature history of the component. Typical values for redeposited layers on the toroidal limiter are about 0.1 D/C. The growth of this type of carbon rich layers on plasma exposed surfaces with high plasma ion temperatures is relatively well understood.

A different type of layers is observed in the TEXTOR pump ducts, where soft, hydrogen rich layers with D/C ≈ 0.7 are observed. These layers are mainly observed in line of sight to the neutralizer plates and are likely formed by sticking of hydrocarbon radicals created by chemical erosion of deposited carbon layers on the plates. However, the amount of carbon redeposited in these remote areas is only 0.02 g/h, which is very small compared to carbon redeposition on plasma exposed areas in the rest of the machine.

Carbon sources and carbon redeposition are less well understood in the divertor tokamaks ASDEX Upgrade and JET. The inner main chamber wall is a net erosion area in both machines, as was shown with long term samples and by spectroscopy. However, despite the strong carbon in ux from the inner wall at least in ASDEX Upgrade the inner wall is not the primary carbon source: By replacing major parts of the inner wall carbon tiles by tungsten covered ones the carbon concentration in the plasma decreased only by less than 30%. Camera observations show a strong CII light emission from the tungsten inner wall heat shield originating from C^+ ions penetrating into the plasma. As can be seen from the camera images, the carbon originates from graphite antenna protection and auxiliary limiters at the outboard side, from where it is transported to the inner wall, deposited at the inner heat shield, and re-eroded again. The inner heat shield thus serves as secondary carbon source. At JET the primary carbon source is less clear: The inner wall consists of carbon poloidal limiters and carbon tiles. Measurements with long term samples and by spectroscopy show that the inner wall is a net carbon erosion area. However, extrapolations of several years old measurements with long term samples and spectroscopic observations at one location of the inner wall indicate a total erosion at the inner wall of 160–390g carbon for the whole Mark IIGB campaign. This is lower by factor of at least four than the estimated carbon deposition in the divertor of 1700g, indicating either additional massive carbon sources (for example from the upper divertor), or large errors in the accounted carbon deposition or erosion data. The same discrepancy by a factor of about four is also observed in the amounts of eroded and redeposited beryllium [29]. The outer divertor baffle of JET a net carbon erosion area, but the observed erosion is by far too small to explain the massive deposition in the inner divertor.

The inner divertors of JET and ASDEX Upgrade are net carbon redeposition areas. The outer divertors are partly deposition dominated, while at the outer baffle some carbon erosion is observed. Deposition on the JET divertor tiles was analyzed by thickness changes with a micrometer and by SIMS, while analysis of ASDEX Upgrade divertor tiles is not yet available. Measurements at remote areas in JET, like the inner divertor louvres, the area behind the louvres, or below the septum, are sparse. The available measurements indicate the formation of soft hydrocarbon films with a high D/C ratio close to one. The same type of soft hydrocarbon layers, but with a larger variation of the D/C ratio from 0.7–1.4, is also observed below the divertors II and IIb of ASDEX Upgrade. In both machines the layers are formed by sticking of hydro-carbon radicals with high sticking coefficient. This conclusion can be drawn qualitatively from the strong variation of deposited layer thickness below the ASDEX Upgrade divertor IIb: The thickest deposits are observed in line-of-sight to the strike points, and the layer thickness decreases by almost two orders of magnitude with increasing

distance to the strike points. More quantitative measurements are available from JET, where cavity samples yielded a surface loss probability β of the hydrocarbon radicals of about 0.9. Addition-ally low sticking hydrocarbon radicals with β of the order of 10^{-3} are observed at JET and ASDEX Upgrade. These particles are problematic, because they can form hydrocarbon layers at very remote areas like pump ducts, which are difficult to access for removal methods. The quantification of the incident flux of these particles turned out to be difficult from the JET cavities, and infor-mation from samples at very remote areas like pump ducts is not available. Long term samples in a pump duct of ASDEX Upgrade showed only very thin deposits, trapping only about 8×10^{-5} of the total deuterium fuel input. If this result could be confirmed at JET, then low sticking particles would cause much less concern.

From the observations at JET and ASDEX Upgrade the following picture of carbon erosion and migration can be drawn: The major carbon sources are located in the main chamber. Eroded carbon is ionized in the SOL and transported mainly to the inner divertor, where it is deposited at the divertor plates, forming hydrocarbon layers. These layers are then subject to further re-erosion and carbon re-deposition. It was estimated in [29], that each carbon atom is eroded and deposited about ten times in the inner divertor, before it is finally lost to a remote area. Re-erosion products of hydrocarbon layers are carbon atoms, hydrocarbon radicals, and stable hydrocarbon molecules like CD_4. Additional hydrocarbon radicals are created by cracking of hydrocarbon molecules in the cold and dense divertor plasma. These radicals then form soft hydrocarbon layers in remote areas by sticking to the surfaces. This conclusion is confirmed by the observation of carbon depleted beryllium rich layers at the divertor plates of JET, and carbon rich layers without beryllium in remote areas. Such a distribution can be only explained by assuming carbon re-erosion at the target plates.

CONCLUSIONS

Currently only the limiter tokamak TEXTOR yields a complete balance of carbon erosion and redeposition. Mayor carbon sources are erosion dominated areas on the toroidal graphite belt limiter (22g/h carbon erosion). Eroded carbon is redeposited mainly in net deposition dominated areas of that lim-iter (10g/h) and on 'obstacles' perpendicular to the magnetic field in the SOL (6g/h). 5–10% of eroded carbon is pumped out as stable hydrocarbon molecules. Only about 0.1% of the eroded carbon migrates to the pump ducts. For the transport to the pump ducts carbon deposition and re-erosion at the neutralizer plates is an important intermediate step.

In the divertor tokamaks ASDEX Upgrade and JET the major carbon sources are located in the main chamber, additionally the outer divertor baffle is a net carbon erosion area. Primary carbon sources at ASDEX Upgrade are graphite antenna protection and auxiliary limiters at the outboard side. The carbon is then redeposited at the tungsten covered inner heat shield, which serves as secondary carbon source. At JET the inner wall consists of carbon and is a net carbon erosion area. However, the determined erosion is by a factor of at least four smaller than the observed carbon deposition, indicating either additional carbon sources or large errors for the accounted amounts of eroded or redeposited carbon.

Carbon re-deposition is observed on the tiles in the inner and to a lesser amount in the outer divertors of JET and ASDEX Upgrade. Additional re-deposition of soft hydrocarbon layers in remote areas without direct plasma contact is observed, like the JET louvres, areas behind the louvres, the area below the divertor IIb of ASDEX Upgrade, or the ASDEX Upgrade pump ducts. These layers are formed by sticking of hydrocarbon radicals. Two diffferent types of radicals are observed: One species with high sticking coefficient ($\beta = 0.9$), and a second species with low sticking coefficient (β of the order 10^{-3}). Hydrocarbon layers in line-of-sight to the divertor are formed mainly by the high sticking species, while layer formation in very remote areas like pump ducts, which are only accessible after many wall collisions, is mainly due to the low sticking radical species. While there is no information available from JET about deposition in these very remote areas, in ASDEX Upgrade the trapping of deuterium in the pump ducts is only 8×10^{-5} of the deuterium fuel input.

New information about carbon erosion and migration in ASDEX Upgrade and JET became available during the last few years, resulting in new insights into the physical mechanisms of carbon migration. But there is still a lack of quantitative information about carbon sources and carbon redeposition. These gaps have to be filled within the next years.

REFERENCES

[1]. M. Mayer, V. Philipps, P. Wienhold, H. Esser, J. von Seggern, M. Rubel, Hydrogen inventories in nuclear fusion devices, J. Nucl. Mater. **290-293** (2001) 381.

[2]. G. Federici, R. Anderl, J.N.Brooks, R. Causey, J. Coad, D. Cowgill, R. Doerner, A. A. Haasz, G. Longhurst, S. Luckhardt, D. Mueller, A. Peacock, M. Pick, C. Skinner, W. Wampler, K. Wilson, C. Wong, C. Wu, D. Youchison, Tritium inventory in the ITER PFC's: Predictions, uncertainties, R&D status and priority needs, Fusion Eng. Des. **39-40** (1998) 445.

[3]. G. Federici, R. Anderl, P. Andrew, J. Brooks, R. Causey, J. Coad, D. Cowgill, R. Doerner, A. Haasz, G. Janeschitz, W. Jacob, G. Longhurst, R. Nygren, A. Peacock, M. Pick, V. Philipps, J. Roth, C. Skinner, W. Wampler, In-vessel tritium retention and removal in ITER, J. Nucl. Mater. **266-269** (1998) 14.

[4]. G. Federici, J. Brooks, D. Coster, G. Janeschitz, A. Kukuskhin, A. Loarte, H. Pacher, J. Stober, C. Wu, Assessment of erosion and tritium codeposition in ITER-FEAT, J. Nucl. Mater. 290-**293** (2001) 260.

[5]. M. Mayer, P. Wienhold, D. Hildebrandt, W. Schneider, Erosion and deposition at the ALT-II limiter of TEXTOR, J. Nucl. Mater. **313-316** (2003) 377.

[6]. M. Rubel, J. von Seggern, P. Karduck, V. Philipps, A. Vevecka-Priftaj, Analysis and oxidation of thick deposits on TEXTOR plasma facing components, J. Nucl. Mater. **266-269** (1999) 1185.

[7]. J. von Seggern, M. Rubel, P. Karduck, V. Philipps, H. Esser, P. Wienhold, Properties of thick layers deposited on plasma facing wall components of textor-94, Phys. Scripta T81 (1999) 31.

[8]. J. Coad, P. Andrew, D. Hole, S. Lehto, J. Likonen, G. Matthews, M. Rubel, Contributors to the EFDA-JET work-programme, Erosion/deposition in JET during the period 1999–2001, J. Nucl. Mater. 313-316 (2003) 419.

[9]. J. Coad, N. Bekris, J. Elder, S. Erents, D. Hole, K. Lawson, G. Matthews, R.-D. Penzhorn, P. Stangeby, Erosion/deposition issues at JET, J. Nucl. Mater. **290-293** (2001) 224.

[10]. V. Rohde, H. Maier, K. Krieger, R. Neu, J. Perchermaier, ASDEX Upgrade Team, Carbon layers in the divertor of ASDEX Upgrade, J. Nucl. Mater. **290-293** (2001) 317.

[11]. M. Mayer, V. Rohde, A. von Keudell, the ASDEX Upgrade Team, Characterisation of deposited hydrocarbon layers below the divertor and in the pumping ducts of ASDEX Upgrade, J. Nucl. Mater. **313-316** (2003) 429.

[12]. J. von Seggern, P. Wienhold, T. Hirai, V. Philipps, Long term behaviour of material erosion and deposition on the vessel wall and remote areas of TEXTOR, J. Nucl. Mater. **313-316** (2003) 439.

[13]. A. von Keudell, C. Hopf, T. Schwarz-Selinger, W. Jacob, Surface loss probabilities of hydrocarbon radicals on amorphous hydrogenated carbon film surfaces: Consequences for the formation of re-deposited layers in fusion experiments, Nucl. Fusion 39 (10) (1999) 1451.

[14]. M. Mayer, A. von Keudell, V. Rohde, P. Coad, JET-EFDA contributors, Mechanism of hydrocarbon layer formation in remote areas of fusion devices, in: 30th EPS Conference on Controlled Fusion and Plasma Physics, europhysics conference abstracts, 2003.

[15]. P. Wienhold, V. Philipps, A. Kirschner, A. Huber, J. von Seggern, H. Esser, D. Hildebrandt, M. Mayer, M. Rubel, W. Schneider, Short and long range transport of materials eroded from wall components in fusion devices, J. Nucl. Mater. **313-316** (2003) 311.

[16] P. Wienhold, H. Esser, D. Hildebrandt, A. Kirschner, K. Ohya, V. Philipps, M. Rubel, J. von Seggern, Investigation of erosion and deposition on wall components of TEXTOR-94, Physica Scripta T81 (1999) 19.

[17]. R. Neu, K. Asmussen, K. Krieger, A. Thoma, H.-S. Bosch, S. Deschka, R. Dux, W. Engelhardt, C. García-Rosales, O. Gruber, A. Herrmann, A. Kallenbach, M. Kaufmann, V. Mertens, F. Ryter, V. Rohde, J. Roth, M. Sokoll, A. Stäbler, W. Suttrop, M. Weinlich, H. Zohm, M. Alexander, G. Becker, K. Behler, K. Behringer, R. Behrisch, A. Bergmann, M. Bessenrodt-Weberpals, M. Brambilla, H. Brinkschulte, K. Büchl, A. Carlson, R. Chodura, D. Coster, L. Cupido, H. de Blank, S. de Peña Hempel, R. Drube, H.-U. Fahrbach, J.-H. Feist, W. Feneberg, S. Fiedler, P. Franzen, J. Fuchs, G. F. mann, J. Gafert, O. Gehre, J. Gernhardt, G. Haas, G. Herppich, W. Herrmann, S. Hirsch, M. Hoek, F. Hoenen, F. Hofmeister, H. Hohen¨ocker, D. Jacobi, W. Junker, O. Kardaun, T. Kass, H. Kollotzek, W. Köppendörfer, B. Kurzan, K. Lackner, P. Lang, R. Lang, M. Laux, L. Lengyel, F. Leuterer, M. Manso, M. Maraschek, K.-F. Mast, P. McCarthy, D. Meisel, R. Merkel, H. Müller, M. Münich, H. Murmann, B. Napiontek, G. Neu, J. Neuhauser, M. Niethammer, J.-M. Noterdaeme, E. Pasch, G. Pautasso, A. Peeters, G. Pereverzev, C. Pitcher, W. Poschenrieder, G. Raupp, K. Reinmuller, R. Riedl, H. Röhr, H. Salzmann, W. Sandmann, H.-B. Schilling, D. Schlögl, H. Schneider, R. Schneider, W. Schneider, G. Schramm, J. Schweinzer, B. Scott, U. Seidel, F. Serra, E. Speth, A. Silva, K.-H. Steuer, J. Stober, B. Streibl, W. Treutterer, M. Troppmann, N. Tsois, M. Ulrich, P. Varela, H. Verbeek, P. Verplancke, O. Vollmer, H. Wedler, U. Wenzel, F. Wesner, R. Wolf, R. Wunderlich,

D. Zasche, T. Zehetbauer, H.-P. Zehrfeld, The tungsten divertor experiment at ASDEX Upgrade, Plasma Phys. Controlled Fusion **38** (1996) A165.

[18]. H. Maier, K. Krieger, M. Balden, J. Roth, the ASDEX Upgrade-Team, Erosion and deposition in the ASDEX Upgrade tungsten divertor experiment, J. Nucl. Mater. **266-269** (1999) 1003.

[19]. A. Tabasso, H. Maier, J. Roth, K. Krieger, ASDEX Upgrade Team, Studies of tungsten erosion at the inner and outer main chamber wall of the ASDEX Upgrade tokamak, J. Nucl. Mater. **290-293** (2001) 326.

[20]. K. Krieger, A. Geier, X. Gong, H. Maier, R. Neu, V. Rohde, ASDEX Upgrade Team, Erosion and migration of tungsten employed at the main chamber first wall of ASDEX Upgrade, J. Nucl. Mater. **313-316** (2003) 327.

[21]. R. Neu, R. Pugno, V. Rohde, R. Dux, T. Eich, H. U. Fahrbach, A. Geier, A. Herrmann, D. Hildebrandt, A. Kallenbach, P. Lang, C. Maggi, T. Pütterich, F. Ryter, W. Schneider, U. Seidel, the ASDEX Upgrade Team, Assessment of intrinsic impurity behaviour in ASDEX Upgrade, in: 30th EPS Conference on Controlled Fusion and Plasma Physics, europhysics conference abstracts, 2003, p. P1.123.

[22]. T. Pütterich, R. Dux, J. Gafert, A. Kallenbach, R. Neu, R. Pugno, S. Yoon, ASDEX Upgrade Team, Carbon in ux studies in the main chamber of ASDEX Upgrade, Plasma Phys. Controlled Fusion Submitted.

[23]. K. Krieger, Deuterium inventory in the divertor IIb of ASDEX Upgrade, private communication (2003).

[24]. V. Mertens, G. Haas, V. Rohde, ASDEX Upgrade Team, Hydrogen gas balance in asdex upgrade with div iib, in: 30th EPS Conference on Controlled Fusion and Plasma Physics, europhysics conference abstracts, 2003.

[25]. M. Mayer, R. Behrisch, V. Prozesky, P. Andrew, A. Peacock, Surface layer composition of the JET vessel walls, material transport and hydrogen trapping in the vessel walls, in: 22nd EPS Conference on Controlled Fusion and Plasma Physics, Vol. 19C of europhysics conference abstracts, 1995, p. 301.

[26]. M. Mayer, R. Behrisch, P. Andrew, A. Peacock, Erosion at the vessel walls of JET, J. Nucl. Mater. **241-243** (1997) 469.

[27]. M. Mayer, R. Behrisch, K. Plamann, P. Coad, P. Andrew, A. Peacock, Wall erosion and material transport to the Mark I carbon divertor of JET, J. Nucl. Mater. **266-269** (1999) 604.

[28]. M. Mayer, R. Behrisch, P. Andrew, P. Coad, A. Peacock, Transport and redeposition of eroded material in JET, Physica Scripta T81 (1999) 13.

[29]. G. Matthews, M. Stamp, P. Coad, J. Likonen, V. Philipps, M. Rubel, J. Strachan, JET EFDA Contributors, Material migration in JET, in: 30th EPS Conference on Controlled Fusion and Plasma Physics, europhysics conference abstracts, 2003.

	Area (m^2)	Carbon deposition (g/h)
Toroidal limiter	1.2	10
"Obstacles" in SOL	0.2	6
Bumper limiter	6	1
Neutralizer plates	0.08	1
Pump ducts	1.4	0.02
Pumped out		1–2
Total		**19–20**

Table 1: Carbon deposition in TEXTOR. The carbon source from the toroidal limiter is 22 g/h. From [12].

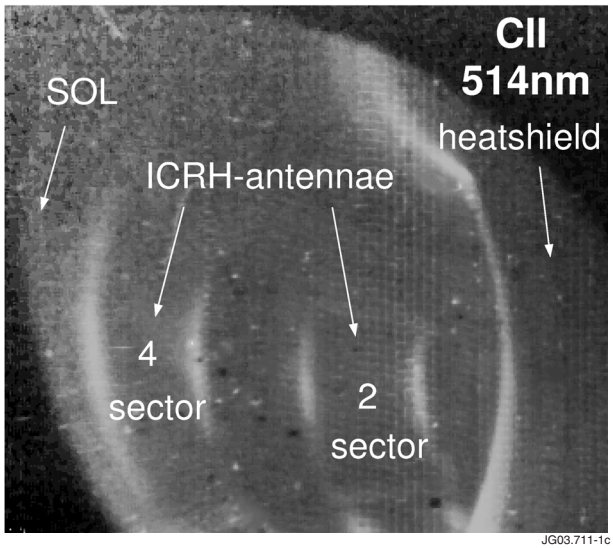

Figure 1: Camera picture of the main chamber of ASDEX Upgrade for CII light at 514 nm. Pulse No: 15236. The camera is located at sector 6. The inner heat shield is coated with tungsten. From [22].

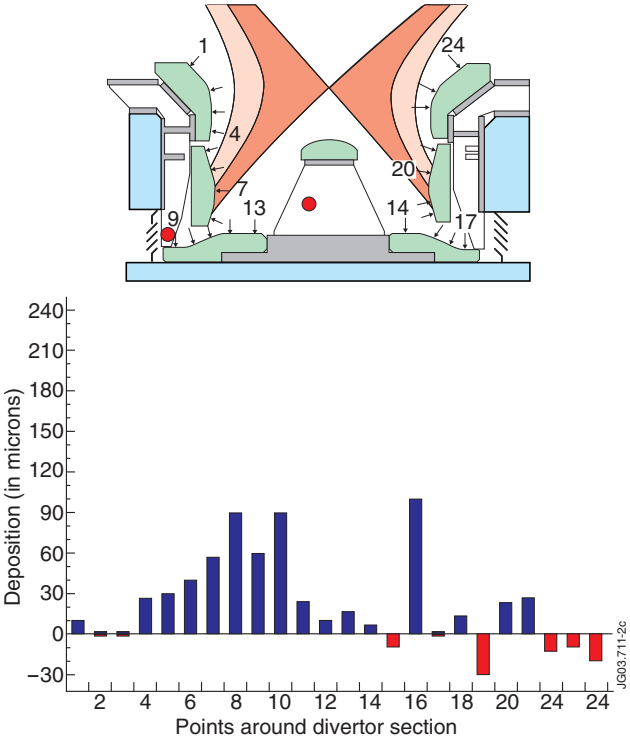

Figure 2: Erosion/deposition in the JET Mark IIGB divertor during the period 1999–2001, measured with a micrometer. Positions of cavity samples close to the louvres and below the septum are marked with dots. From [8].