Overview of recent work on carbon erosion, migration and long-term fuel retention in the EU-fusion programme and conclusions for ITER

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Abstract

Recent results on carbon erosion, short and long range carbon transport and fuel retention are summarised. Existing data on carbon chemical erosion from erosion dominated areas in fusion devices and beam experiments show a consistent dependence on impact energy, target temperature and flux, indicating low carbon chemical erosion in ITER at the strike zones. The campaign averaged overall carbon deposition rates in the all carbon devices JET and DIII-D and in AUG, which is covered to a large extent with W in the main chamber, show remarkable similarities with values of 3-7x10^{20} C/s. While the inner divertor is deposition dominated in general, no uniform characteristic of the erosion/deposition behaviour of the outer divertor can be stated for AUG and JET. The majority of carbon species have a high sticking probability, leading to line of sight deposition with only a minority of the carbon with low sticking (<1%) that can travel long distances in regions shadowed from plasma. Deposition on the JET Quartz Micro Balance (QMB) occurs only for discharges with the strike point in the vicinity of the QMB location. Massive deposition (10nm/s) can occur in discharges, where the strike point was freshly moved to the vicinity of the QMB, accompanied by the simultaneous appearance of strong C_2 band emission in these shots. Be is deposited in JET mainly at the location of primary deposition at the upper part of the inner vertical tile. The deposited layer is Be-rich (Be/C ≈2/1) with a significant D inventory although these layers are heated regularly to temperatures above 1200°C, indicating the formation of a stable Be-C compound that is able to retain hydrogen up to high temperatures.

1. Introduction

The design of ITER is largely based on a robust database resulting from the collaborative work of long term fusion research but various critical questions remain which are to a large extent related to plasma wall interaction. This is due to the increased particle wall fluences in ITER (one ITER discharge is equivalent to about 4 years of JET operation), the enhanced power deposition in transients and the limited experience in general with non-graphite plasma facing materials. The most critical areas are the wall lifetime and the long term tritium inventory. The PFC lifetime will be determined largely by transient heat loads during ELMs and disruptions which may lead to target ablation, melting and melt layer loss. This will not be discussed here further.

The long term T inventory is mainly determined by material erosion, its long and short range migration and its co-deposition with eroded wall material to T-containing deposits, while direct implantation and diffusion in the bulk of the PFC is of minor importance. Experimental data on fuel retention from present devices whose wall are clad with graphite indicate strongly that the long-term tritium retention in a full graphite-wall ITER would rapidlay reach the T-retention limit.

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This is the main reason for a design aiming to avoid as much as possible graphite in ITER and to use Be on the main wall ($700m^2$), with W ($70m^2$) and C ($50m^2$) in the divertor. The hope is that this material composition mitigates significantly the T retention by reducing the codeposition of T with carbon. However, Be will be eroded as intensely as graphite in the main chamber, transported to the divertor and codeposited with the fuel forming a material mixture that is difficult to predict. One of the big challenges is to predict quantitatively the T-retention under these conditions, in the absence of experimental data from relevant tokamak experiments. The assessment of the fuel retention must, therefore, be based on the clarification and understanding of the individual processes of material erosion, its transport in the plasma edge and divertor and its codeposition. This must be supported by data on the properties of redeposited mixed layers (Be/C/O/W). The EU Task Force on plasma wall interaction tries to coordinate and focus the research towards these topics.

2. Global material erosion and deposition

Various data on carbon chemical erosion from tokamaks and lab experiments have been normalised with respect to the impact energy, particle flux and surface temperature. This results in a reasonable fit as shown in fig 1(1).

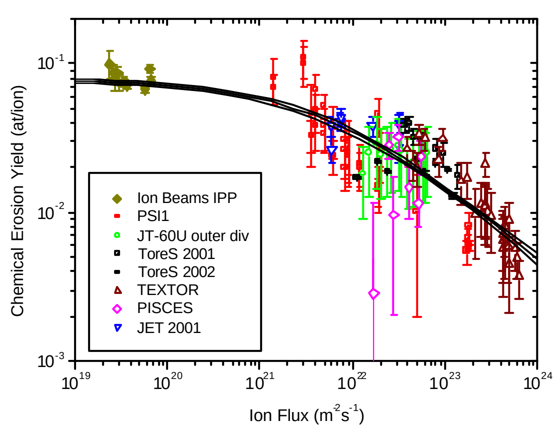

Fig 1: Normalised chemical erosion yields for various beam and tokamak experiments. (1)

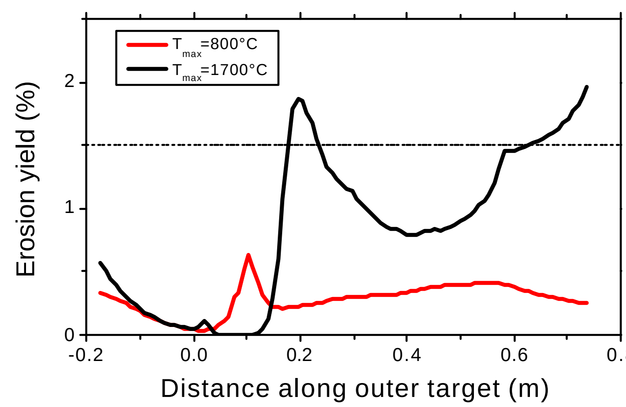

Fig 2: Chemical erosion yield along outer ITER divertor target based on normalised chemical erosion yields and impact energy, particle flux and surface temperature for the outer divertor. Data refer to two different tile surface peak temperatures. (1)

As seen in fig 2, the data indicate very low carbon net-erosion yields near the high flux areas at the ITER strike points, mainly due to the low particle impact energy and the high target temperatures. This reduces the expected carbon gross erosion significantly compared with previous assumptions. Note that this carbon erosion is estimated without taking into account a possible reduction due to Be deposition on the graphite tiles (2). A better clarification of the main chamber erosion in ITER is most crucial for the choice of wall materials and the long term T retention. In JET and AUG the main chamber walls are net sources of material, apart from local deposition regions. This general statement can be made already from the full Be (3) and the W divertor (4) experiments in JET and AUG, respectively. Recently global material balances have been attempted in JET and AUG and also in the TEXTOR limiter tokamak. In JET-MKIIGB (1999-2001,16hours of divertor plasma) operation the main chamber material source has been evaluated (5) to 450-480 g C and 20 g Be. This compares well with the material found on the wall tiles, 22 g Be and 390 g C (6). In JET, no definitive statement is possible presently about the source distribution in the main chamber but several measurements indicate an almost balanced distribution between the inside and outside first wall(7). In AUG a similar material accounting has been done for the period 2002/3 for which, however, the inner wall was coated with tungsten. Despite the tungsten coating, a strong inner wall recycling carbon source is observed by spectroscopy (8). Since no thick carbon layer is built-up, the tungsten surface seems just in balance between carbon deposition and erosion (9). The recycling carbon is most probably eroded at the outer graphite protection limiters. However, the material balance in AUG based on outer wall sources and divertor deposition does not mach quantitatively, pointing towards additional net carbon sources. This may be the outer divertor where net erosion is observed on the upper baffle tile indicating an erosion which exceeds the net main wall source(10). A possible net erosion on the outer divertor strike point in AUG is still under discussion. However, the erosion determined at the outer divertor is based on marker erosion which may be eroded faster than the target plate material and more work will be done to assess the erosion of the outer divertor in AUG. Also, the outer divertor of JT-60U is a net erosion area (11). The total divertor carbon deposition rate in AUG is estimated to about 3.5×10^{20}C/s (12). This is close to the values in JET, which are estimated to about 6.6×10^{20} and 3.5×10^{20} C/s for the MKIIA and MKIIGB divertor campaigns respectively and to values in DIII-D of 3-7 10^{20} C/s (13) (table 1). The available absolute overall carbon deposition rates are very similar showing no clear tendency to increase with machine size. Interestingly, also the total particle wall fluxes to the main chamber walls in divertor devices show very similar values, typically between 1-5 10^{22} #/s and seems also independent of machine size. (14)

Device (campaign)	**JET MKIIA**	**JET MKIIGB**	**AUG 2002/3**	**DIII-D 1990-2003**	**TEXTOR**
Total carbon deposition rate (C/s)	**6.6 10^{20}**	**3.5 10^{20}**	**3.5 10^{20}**	**3-7 10^{20}**	**2.5 10^{20}**
Fuel retention fraction (%)	**10.5**	**3**		**3**	**8**

Table 1

3. Long range material migration

Long range material migration is mainly determined by flows which are directed with standard magnetic field preferentially towards the inner divertor. In JET a precise determination of the stagnation point is difficult but must be located between the outer midplane and the divertor target (15). ^{13}C injection from the top of the machine resulted in a preferential ^{13}C deposition on the inside, with most deposition on the upper target tile in the SOL and no deposition on the outer divertor target (16 ,17), very well in line with the SOL flows. In reversed grad B the stagnation point moves near to the top of the machine. IR surface analysis show that under these conditions surface layers develop on the outer target which are similar to those at the inner target and disappear over time in normal field direction(18). Recently, $^{13}CH_4$ was injected also at the outer divertor SOL and a probe has been inserted at the top. First analysis shows ^{13}C on the side facing the outer divertor. Divertor tile analysis is ongoing but this result indicates the possibility of material flow from the outer SOL towards the main plasma and thus to the inner divertor. A significant net-material migration from the outer divertor to the inner would be not in line with the material balance In JET as described above. A coherent interpretation and understanding of the observed SOL flows is still missing although significant progress has been achieved (14).

4. Short range material migration

After the JET tritium campaign (DTE2) which was performed in the MKIIa divertor configuration, 35% of the injected tritium was retained immediately and 10.5% remained after several cleaning procedures (19). The vast majority (>90%) of this long term inventory was in carbon layers on the water cooled louvers at the entrance to the pump duct in the inner divertor and most of the remaining tritium was again in re-deposited C–layers on the plasma facing sides in the inner divertor (20). Tritium that had diffused deeper into the material along the porous structure of the CFC material has been detected, but represents only a small minority (20) demonstrating that T-retention by direct implantation or by diffusion inside the C-matrix is small and can be tolerated. After MKIIGB operation thick deposits are found on the inner divertor vertical and horizontal tiles, reaching about 60 µm and no clear erosion or deposition pattern in the outer divertor (21). Interestingly, Be-enriched layers with Be/C ratios of 2/1 and D/(Be+C) ratios not less then 0.1 have been found on the vertical inner tiles (22). Thick carbon layers are on the shadowed area of the horizontal tile with a D/C ratio up to unity but with much smaller Be content. This shows that the carbon can migrate further after its primary deposition while the Be stays near the site of primary deposition. Recent measurement indicate only a low carbon deposition on the septum plate inside the dome (21). Post mortem analysis provides the most robust data on material migration and long term fuel retention but represents a long term average over campaigns and allows, therefore, no identification of special plasma or wall conditions determining the deposition pattern.

Therefore, dedicated diagnostics have been implemented in JET and AUG. In the MKIIGB divertor , sticking monitors were placed in front of the inner divertor louvers and the septum plate. The vast majority of carbon species (> 99.9%) has a high sticking probability with a small minority with low sticking.(23). This result was a surprise since MKIIA data suggested the formation of low sticking hydrocarbon species that can be trapped on the water cooled areas of the louvers. A majority of high sticking species is also in line with carbon deposition in the pump ducts of AUG and TEXTOR and the AUG subdivertor region. In the post MKIIGB operation in which the septum was removed with the divertor geometry remaining as before, a Quartz Microbalance monitor (QMB) was installed in front of the louver area. Fig 3 shows the growth of the carbon layer on the QMB monitor for 307 shots lasting in total 2600s (24). The averaged C deposition rate is 2.4×10^{15} C/cm^{2}sec which extrapolates linearly to about 1.38×10^{20} C/cm^2 during the whole MKIIGB campaign (16hrs) corresponding to a layer of 18 µm amorphous carbon layer.

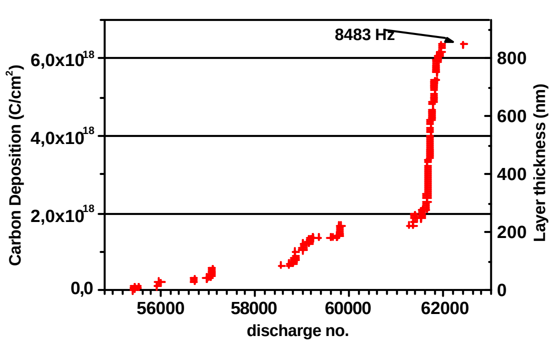

Fig 3: Accumulated carbon deposition on the QMB during 307 shots

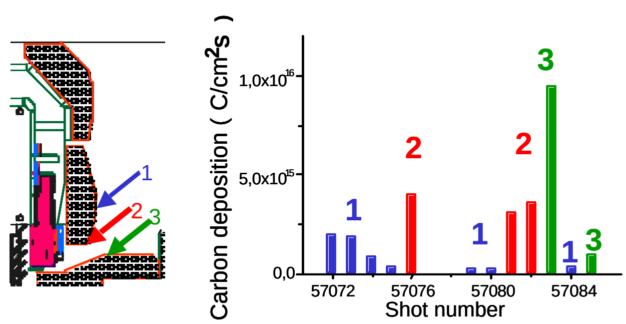

Fig 4: Carbon deposition rate in reproducible L mode discharges for different strike point positions as indicated by the left insert.

About 21 gC is deduced for the whole entrance area of the inner louver using a total area of 0.81 m^2. The averaged C deposition rate on this area is $1.9 \; 10^{19}$C/s and thus only about 5% of the overall C-deposition rate in the inner divertor (table 1). In general the QMB monitor shows a strongly varying deposition from shot to shot, with also a number of shots showing net erosion. The most obvious parameter determining the deposition is the position of the strike point with respect to the louver entrance: all measured shots with the strike point at the upper vertical target (so called DOC-U configuration) show no measurable deposition (sensitivity about one carbon monolayer). With the strike point at a constant position near the QMB entrance, the deposition is significant but with a significant scatter from shot to shot indicating the influence of other parameters. High power low density ELMy H-mode shots tends for more deposition compared with the same shots at higher density resulting in smaller ELMs. The largest deposition is observed for shots for which the strike point was positioned for the first time onto the horizontal target with preceding operation on the vertical target. An example of this is shown in figure 4. Evidently,freshly deposited carbon layers at the horizontal target are more strongly eroded compared with surfaces that have been exposed already to the plasma. This is consistent with the observation of enhanced C_2 -molecular line emission observed by spectroscopy for such types of shots (25). The carbon transport towards the louver seems, thus, to be a stepwise process of erosion at the vessel walls and vertical target leading to deposition on the horizontal target followed by strong erosion of the layer in a horizontal target shot. Erosion on the QMB is observed sometimes after preceding shots with strong deposition indicating the formation of a soft C-layer which is eroded by the impact of neutral atomic hydrogen. Also in AUG dedicated observations have been done on carbon deposition in the subdivertor region by probes and 3 QMB systems in the inner and outer leg. Deposition rates are typically between 0.3 and 0.8 nm/shot and show a strong dependence on the plasma scenarios, similar to JET. While the inner divertor shows always deposition, significant erosion is observed in the outer divertor in special shot scenarios. A parasitic plasma is created in the remote areas viewing the plasma which can contribute to erosion.

During the MKIIA divertor and the DTE2 tritium campaign the plasma strike zones were situated mainly on the horizontal targets that open a direct line of view to the louver area while during MKIIGB the plasma were mostly on the vertical targets. This is considered as a main reason for the strong carbon deposition in MKIIA on the louver area.

The $^{13}CH4$ that was injected at the end of the MKIIGB operation from the top of JET was found on the upper part of the inner vertical target but not on the horizontal tile where, however a large part of the total amount of carbon was found. This is consistent with the QMB results, that the C transport to this region is not promoted under quiescent L mode plasma conditions.

5. Long term fuel retention

Campaign averaged long term fuel retention rates are deduced from post mortem tile analysis or from T balance in the DTE2 campaign. The long term T-retention fraction in DTE2 was 10.5%, obtained after intensive cleaning . In MKIIGB the total injected fuel was about 766g D and the total amount of D found in the divertor about 22g (21) corresponding to a retention fraction of 3%.This compares with a value of about 3%-5% in DIID-D (26) and 8% in TEXTOR (27). Thus the T-retention in the JET DTE2 campaign is at to the upper limit of these values (although this value is measured after long term cleaning which was not done after MKIIGB operation), probably due to a combination of unfavourable plasma configuration and plasma parameters driving the eroded carbon to the inner divertor louvers as described above. New attempts have been made to measure the fuel retention by gas balance in JET and AUG (28, 29). In JET reproducible high fuelled H-mode shots over a full day of operation showed no long term retention while low density limiter shots in Tore Supra reached retention fractions of 50% (30). This demonstrates that care must be given to use single results on long term fuel retention for the assessment of long term fuel retention. The reasons for these discrepancies might be the long wall saturation equilibrium times, in particular on low flux areas, the importance of special plasma events for the long term retention, as indicated by the QMB results, or the preferential release of particles from the walls in special events like disruptions.

6. Outlook and summary

A remarkable consistency is seen in the available data on the campaign averaged carbon deposition rates in different JET divertor campaigns, AUG, DIII-D and TEXTOR with values between 3 and $7x10^{20}$C/s. The reason for this is not very clear but may indicate machine independent overall carbon net erosion rates as seen also for the overall wall fluxes in different machines.
Recent data from JET and AUG and TEXTOR (31, 32) show that redeposited C layers in ITER will undergo further transport along the plasma wetted surfaces. The strong transport may be either due to high chemical re-erosion of redeposited carbon due to the amorphous structure of the deposit, the synergistic action of the ion impact enhancing the chemical erosion of the hydrogen atoms or the ablation or thermal decomposition of weakly bounded C layers under thermal impact (33). The carbon can migrate until it will be deposited finally to a large extent on shadowed areas with a direct view to the plasma wetted areas but not migrate much further. This behaviour may help to concentrate the redeposited carbon on areas where the possibility for cleaning is more favourable.
JET shows that the Be transport in ITER will be much more short ranged compared with that of carbon. However Be layers will form on the plasma facing sides with the incorporation of carbon and oxygen impurities, the amount of which is highly unclear. The fuel retention in these layers is a crucial for the T-retention in ITER. JET shows the formation of mixed Be/C/O layers on the inboard divertor tiles which have survived many temperature excursions up to high temperatures (>2000K) during ELMs but contain still significant amount of fuel, while recent Pisces experiments (34) show the formation of redeposited Be layers with D/C ratios below 10^{-2} at temperatures above 500K. Thus, data on D retention in Be and mixed Be layers show a large scatter and more work is needed here.
A concern for ITER is the possible migration of carbon into the gaps of the targets. The JET MKI divertor had a castellated structure reminding to the ITER design and reanalysis shows that about twice as much D is retained in the gaps of the C-target compared with the surface (35). Preliminary analysis of the D retention in the Be MKI divertor indicates a reduced retention fraction of D in these gaps but this needs further confirmation. Experiments in TEXTOR with ITER-like castellated Mo-limiters have been started showing a significant C and D deposition in gaps (about 30%), also on the erosion dominated plasma facing areas where no carbon deposition had been found within the sensitivity of the measurement (few 10^{15}C/cm2 (36).
While the database from carbon cladded devices strongly indicate that the T limit in ITER would be reached soon, the impact conditions on the ITER graphite target together with the wall material composition will certainly lead to a significant reduction of the T retention compared with a full C-device. However, a more precise prediction about the reduction and the absolute amount of retention remains still largely uncertain. This makes a strong case for a relevant tokamak experiment with an ITER like material composition.

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