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Long term behaviour of material erosion and deposition on the vessel wall and remote areas of TEXTOR

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Abstract

Long term erosion/deposition at the plasma facing surfaces as well as the carbon transport to the remote areas are discussed. The erosion of the liner wall and the deposition at the inner walls of the pump ducts were quantified. A small net deposition of carbon was found also at the liner, but only in the vicinity of the toroidal belt limiter. A deposition of polymer like deuterium rich carbon films (D/C $\approx$ 0.7) took place in remote areas. Despite the minute deposition rate of $\sim$0.02 gC/h these deposits might be decisive in view of tritium retention in next step fusion devices.
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1. Introduction

Plasma facing components (PFCs) in next generation fusion devices will be subjected to massive particle and power loading. Thus, an appropriate selection of materials employed as PFCs is a key issue in fusion technology. Due to their good thermo-mechanical properties carbon-based materials are the favoured candidates for the high heat flux components in future reactors such as ITER [1,2]. In addition to erosion caused by the impact of low energy ions and by energetic CX neutrals [3], the erosion due to the high chemical reactivity with hydrogen atoms [4,5] is a critical feature of graphite or carbon fibre composites (CFCs). This all limits the lifetime of the PFCs, dilutes the plasma with impurities, and leads to high fuel inventories in layers deposited on areas less affected by the plasma [6–13]. Material removed at one location is transported in the plasma edge and in the scrape-off layer (SOL) and forms deposits whose composition and structure noticeably differs from the initial wall material. Certain fraction of eroded species may migrate over long distances and form deposits at locations difficult to access by plasma and by clean-up procedures of the vessel. In addition, these processes trigger the accumulation of fuel and are responsible for the long term tritium inventory in devices using T + D mixture.

The main contents of the presented study are (i) characterization of the wall erosion and (ii) redeposition of hydrogenated layers in remote areas of TEXTOR.

2. Experimental

Due to relatively low particle fluxes close to the vessel wall, reasonable investigation of erosion/redeposition processes is promising only by exposing samples to plasma discharges during whole experimental campaigns. A number of erosion/deposition studies were carried out during two operational campaigns between March 2000 and March 2001. Depending on interest, four kinds of long term samples (LTS) were applied. The locations of the samples are sketched in Fig. 1. (a) A 15 mm wide stripe made of Inconel 625 was joined to the TEXTOR inner wall (liner) round the entire poloidal boundary ($r = 55$ cm). The stripe had the regular wall temperature (350 °C). Though in direct line-of-sight

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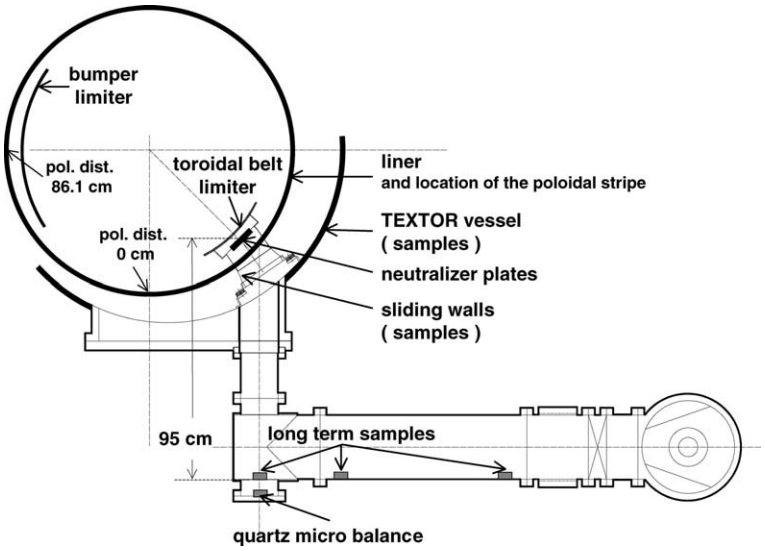

Fig. 1. Sketch of the vertical cross section of the TEXTOR device; experimentally relevant components and locations of the samples are specified.

to the plasma, it was protected by the toroidal belt limiters ($r = 46$ cm). During the operational campaigns 2000/2001 the stripe was conditioned simultaneously with the inner wall by boronizations and exposed to a total of 4.7 h of plasma discharges fuelled with deuterium. (b) During the same campaign, three sets of LTS, each equipped with Si, graphite and Inconel 625 have been distributed at the bottom of the pumping duct of the toroidal belt limiter, one of them 95 cm apart from the neutralizer plates, the other two at additional distances of 22 and 92 cm respectively. (c) A second pumping duct has been employed for in situ measurements of deposition by a quartz microbalance. The system was exposed during plasma discharges 103 cm away from the neutralizer plates over 0.6 h. (d) Due to extended modifications on TEXTOR some wall material became available and the whole device was accessible for inspections. Samples were taken from the liner and from the sliding walls which are located behind the belt limiter blades, close to the neutralizers (see Fig. 1). Deposits both inside TEXTOR vessel and in pump ducts were examined visually. Material yielded during this action allows a study of the condition of the whole interior after a very long operational phase (≈24 h).

General objective was the detailed characterization of the collected material. A combination of colorimetry [14], interference fringe analysis [15] and ellipsometry was applied for the estimation of the layer thickness deposited on the poloidal stripe, liner and the walls of the pump ducts. Optical constants and thickness of deposits on substrates with a shiny target surface were set up by ellipsometry. The deposit composition was determined by electron probe microanalysis (EPMA), H and D content by elastic recoil detection analysis (ERDA) and the distribution of constituents in the layer (except H and D) by sputter Auger electron spectroscopy (AES). Thermal desorption spectroscopy (TDS) has been employed as a second method for the quantification of the hydrogenic species.

3. Results and discussion

3.1. Long term behaviour of the TEXTOR liner

The torus shaped, boronized or siliconized liner provides a minute but permanent source of boron and silicon respectively. Due to sputtering by high energetic neutral particles created in charge exchange collisions the liner is a net erosion zone [3,16]. However, surfaces located deep in the SOL, almost parallel to the field lines, as the liner is, do not seem to contribute significantly to the carbon exchange.

The poloidal stripe was firmly attached to the liner, also underneath the toroidal belt limiter 34.5 cm away from the leading edge, and at the high field site at a location not covered by the bumper tiles (Fig. 1). It had experienced six boronizations and 4.7 h of plasma exposure predominantly in deuterium (typically with n_{eo} between 1.5×10^{13} and 6×10^{13} cm^{-3}, $I_p = 350$ kA, $B_T = 2.25$ T). Fig. 2(a) and (b) shows the poloidal distribution of areal densities of boron and carbon (a) and of the layer thickness (b) after exposure described above. The initial areal densities of the layer constituents deposited by the boronizations are drawn as a dashed line

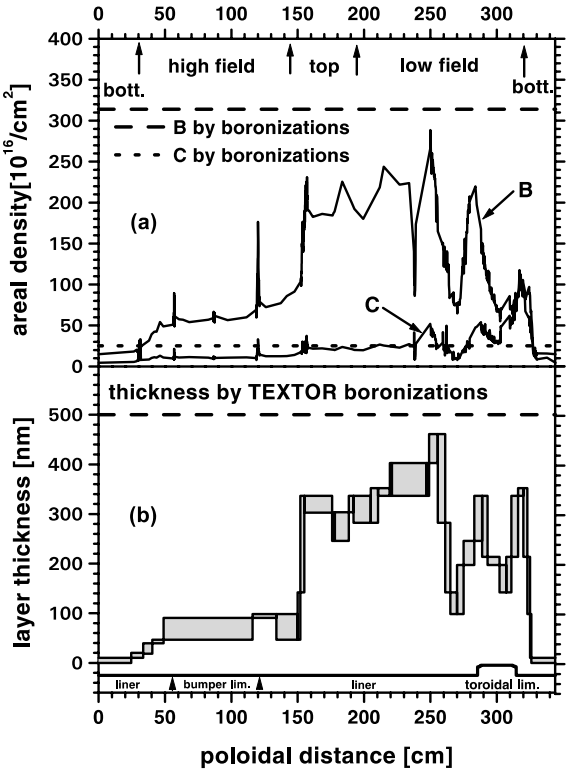

Fig. 2. Long term exposure of the poloidal stripe attached to the liner wall of TEXTOR (4.7 h plasma operation including six boronizations). (a) Poloidal distribution of areal densities of boron and (b) poloidal distribution of the thickness after exposure.

(boron) and a dotted line (carbon) (Fig. 2(a)). The initial thickness of the deposit is illustrated as dashed line (Fig. 2(b)). Strong erosion of boron ($>6 \times 10^{17}$ B/cm^2 h) and carbon ($>3.7 \times 10^{16}$ C/cm^2 h) took place at the bottom of the device. At the high field side, boron is eroded with $\sim 5.4 \times 10^{17}$ B/cm^2 h and carbon with $\sim 5 \times 10^{16}$ C/cm^2 h. The lowest boron erosion rate is found at the top and at the low field side ($\sim 4.3 \times 10^{17}$ B/cm^2 h). The asymmetry in erosion of the vessel wall along the poloidal direction is not yet clarified. The poloidal distribution of the D^0 flux along the liner, calculated by the B2-EIRENE code [17], does not describe this behaviour. Obviously, erosion by the impact of not confined fast ions contributes to the erosion at the bottom of the device. Examination of samples assembled from the liner material after about 24 h of plasma operation (Fig. 3(a) and (b)) confirmed the observation made on the poloidal stripe.

In the vicinity of the toroidal belt limiter (graphite) a moderate net carbon deposition occurs (mean deposition rate $\approx 5 \times 10^{16}$ C/cm^2 h). Due to physical and chemical erosion of the limiter edges by D^+ ions and by charge exchange (CX) neutrals an enhanced penetration of carbon neutrals through the SOL seems to be likely. The B2-EIRENE code calculates for a typical TEXTOR ohmic discharge ($I_p = 350$ kA, $n_{eo} = 3.5 \times 10^{13}$ cm^{-3}, $B_T = 2.25$ T) a D^0 flux of about 3×10^{21}/cm^2 h at poloidal edges of the belt limiter which erodes about 8×10^{19} C/cm^2 h [16–19]. Only a small portion of carbon eroded at the limiter edges remains at the liner (<0.1%). The majority of the eroded carbon seems to be transported over short distances and directly redeposited [12] or enters the plasma and is transported in the form of carbon ions to various locations outside the LFCS. A part of it is directed at leading edges of the belt limiters together with D^+ plasma behind the limiter blades (2–4% of the Γ_{D^+} [20]).

3.2. Deposition of hydrogen rich films in remote areas

As mentioned above a fraction of the initial carbon ion flux is transported behind the blades of the belt limiter and redeposited at the neutralizer plates [13], and at the inner areas of the pump ducts. At this stage, the neutralizer plates seem to be the main source of hydrocarbon radicals creating films in areas remote from the plasma.

Inspection after the last shutdown revealed little but clear formation of soft films along all inner areas of the pump ducts. The thickness of these deposits have been estimated by interference fringe analysis [13,14]. Sliding walls, since located close to neutralizer plates, are the only wall elements inside the hot vacuum vessel ($\leqslant 150$ °C) which can be easily dismantled and analysed post mortem. Deposits observed in this region possess a slightly higher refraction index ($n \approx 1.7$) and a fairly low D/C < 0.1. Beside carbon and deuterium they also include an evident quantity of boron and silicon mainly originating from the neutralizer plates [13].

Sets of samples located in one of the cold pump ducts (room temperature) in increasing distance to the neutralizer had been characterized after a total exposure time of 4.7 h by various analysis methods. Soft polymer like carbon films were found. They have a diffraction index n between 1.6 and 1.4, decreasing with increasing distance to the source, but a constant D/C ratio of $\sim$0.7. They also store a significant quantity of hydrogen (H/D varies between 1 and 3) which may originate from water uptake. Except carbon and hydrogen isotopes they do not contain any other elements existing in the device. Deposition rates established in the duct are extremely low, about 1×10^{17} C/cm^2 h in line-of-sight, and only about 0.03×10^{17} C/cm^2 h at the second position; deposit at samples located close to the pump was not detectable. Film deposited at the cold inner walls of the pump ducts ($T \approx 25$ °C) corresponded to layers identified at the LTS. The source of the hydrocarbons is apparently the nearby neutralizer which is re-eroded by deuterium ions with energy of several

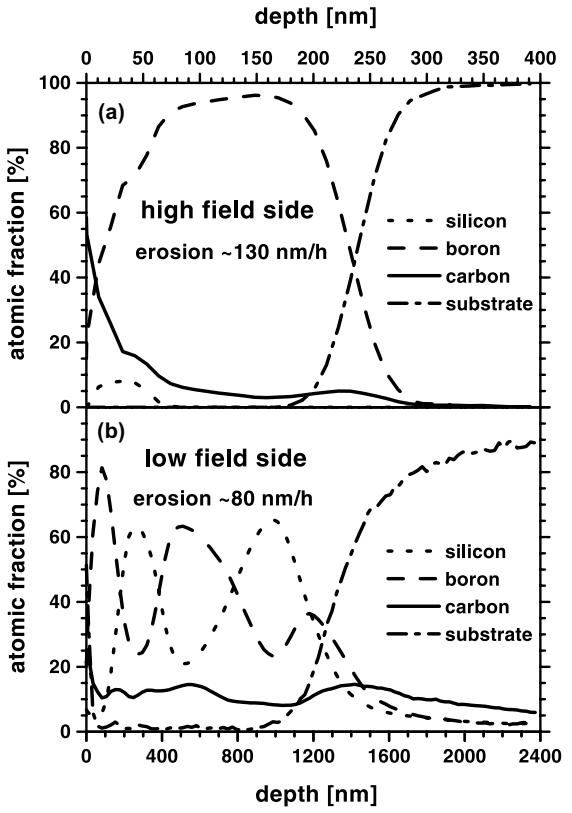

Fig. 3. Depth distribution of the deposit constituents of eroded liner surface after about 24 h plasma exposure containing 38 conditioning procedures. (a) AES depth profile taken at the low field side and (b) AES depth profile taken at the high field side.

hundred electronvolts. In this, from the plasma isolated region, physical and chemical erosion leads to formation of volatile, unsaturated hydrocarbon radicals and of CD_4 molecules. Observations made by a sniffer probe [20] suggest a rate of 1–2 gC/h leaving the system in gaseous form. Radicals impinging the duct walls and finally sticking there continuously form polymer like deuterated carbon films. Under the existing conditions, they have a free mean path of several metres, thus they may reach, collision free, quite long distances. The thickness of the deposits declines corresponding to the dilution of the system with growing distance to the source.

Carbon deposition in remote areas was also measured in situ by a commercial quartz microbalance (for operation see *Instruction manual*, Thickness monitor IL 150, Intellemetrics Ltd, Glasgow, UK) located in line-of-sight to the neutralizer at the bottom of another pump duct. Fig. 4 shows the frequency variation of the microbalance system ΔF (reference frequency – frequency of the quartz crystal) during the plasma operation and the fairly constant ΔF during night and weekend breaks respectively. Increasing ΔF points to a rising deposit. Using calibrated values, direct determination of the layer thickness is possible. A deposition rate of ≈30 nm/h has been found at this location. Characterization of the deposit has shown a similar, deuterium-rich film as deposited on long term samples described above.

Layers deposited in the remote areas contribute altogether with only 1×10^{21} C/h to the carbon balance in the machine. Table 1 summarizes the carbon balance and the retention of deuterium in TEXTOR. Assuming a carbon flux of ~22 g/h a remainder of 2–3 g/h in the balance is missing. The discrepancy in the source–sink balance is not surprising. The uncertainties of the implemented extrapolations might settle this difference.

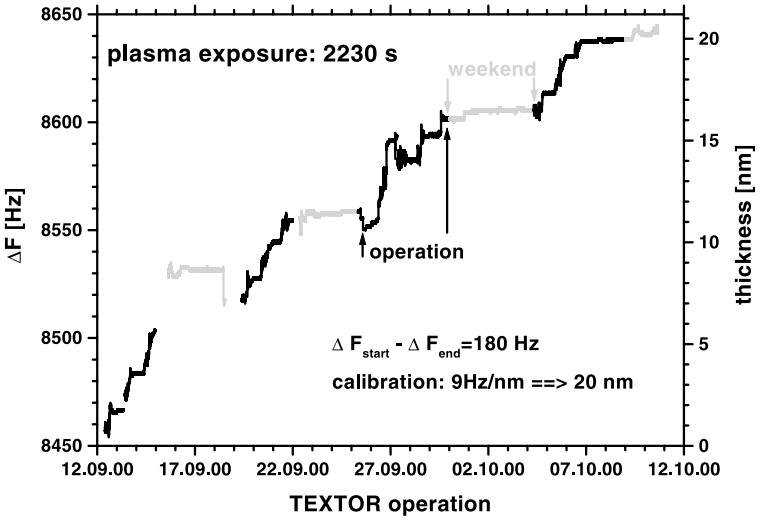

Fig. 4. In situ determination of film deposition in remote areas by calibrated quartz microbalance.

Table 1
Estimated carbon balance and retention of deuterium in TEXTOR (Source: toroidal limiter – 22 gC/h)

Sink	Deposited area (m^2)	Average temperature (°C)	Deposited carbon (g/h)	Deuterium content D/C	Co-deposited deuterium (10^{20}/h)
Toroidal limiter	1.1	350	10	0.1	500
Obstacles	0.2	Excursions	6	4×10^{-4}	1.2
Liner	32	150–350	$<4 \times 10^{-4}$	0.1	Negligible
Bumper limiter	6	150–350	1	0.1	50
Neutralizer plates	0.08	150–350	1	5×10^{-3}	2.5
Ducts	1.4	25	0.02	0.7	7
Pumps		25	1–2	–	–
Total content			19–20		561

4. Conclusions

Long term erosion/deposition upon plasma facing regions as well as material transport to the remote areas of TEXTOR had been studied in detail. Surfaces located deep in the SOL almost parallel to the field line, like the liner wall, are predominantly erosion zones. The surface of an in situ boronized metallic stripe mounted to the liner along the whole poloidal boundary had been eroded asymmetrically. A distinct net erosion rate at the bottom and the high field side (~100 nm/h and higher) less at the top and the low field side (~80 nm/h) was established. This poloidal dependency is not yet interpreted; further investigations are needed. A minor fraction of carbon eroded from the toroidal belt limiter (<0.1%) had been deposited at the liner in the vicinity of this limiter. A low D/C ratio of the deposit ($\leqslant 0.1$) might not significantly influence the tritium inventory.

The rest of the carbon eroded from the graphite belt limiter but not found inside the torus escaped the torus via the pump ducts. However, carbon deposited on the neutralizer plates, from where it is partly re-eroded by deuterium ions, serves as source for a soft polymer like deuterated carbon film found at inner areas of cold pump ducts. Though their contribution to the carbon balance is negligible (0.02 gC/h) these layers are rich in deuterium (D/C $\approx$ 0.7). They could, because of their accumulation in partly inaccessible areas, severely increase tritium content in future fusion devices.

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