Tungsten Migration Studies in the TEXTOR Tokamak Using Controlled Injection of Marker Gases

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1. Introduction

Application of tungsten (W) as wall material, either bulk metal or in the form of coatings calls for developing techniques enabling migration studies. One way of approaching it is to use a high-Z marker based either on a rare isotope (very expensive) or a volatile compound, e.g. tungsten hexafluoride (WF_6). Operation with tungsten plasma-facing components (PFC) requires impurity seeding for improved edge radiation, e.g. injection of nitrogen (N_2) is performed for that purpose [1]. This in turn necessities the assessment of the in-vessel residence of gas by implantation, co-deposition or by compound formation with PFC materials. The latter may become important in the case of nitrogen-tungsten combination. To address W transport and the change of PFC surface morphology in the presence of nitrogen dedicated experiments were performed in the TEXTOR tokamak by injection of WF_6 and $^{15}N_2$. The aim was to assess: (a) material balance by qualitative and quantitative determination of a global and local deposition pattern of tungsten and local of nitrogen; (b) material mixing; (c) fluorine residence in PFC.

2. Experimental

The localised WF_6 injection into TEXTOR was performed prior to the major shutdown (2011) connected with the retrieval of tiles for ex-situ analysis. Gas was puffed (1.93×10^{20} W atoms) in 13 NBI-heated discharges through the test limiter located at the bottom of the machine. Figure 1(a) shows the location of the lock with respect to the nearest blades of the toroidal belt pump limiter ALT-II (Advanced Limiter Test) which is the main PFC of TEXTOR defining the minor radius a = 46 cm. An assembly of the test limiter is shown in Fig. 1(b): a roof-shaped block with a polished plate (both made of graphite) with a hole for WF_6 puffing. It was placed the scrape-off-layer (SOL). WF6 injection was accompanied by puffing Nitrogen-15 from the toroidal inlets (3.46×10^{21} at). and $^{13}CH_4$ (1.75×10^{21} C-13 at) from the upper test limiter. Local spectroscopy measurements were focused on the test limiter where NII (451.4 nm), WI (400.8) nm, CII (426.7 nm), FII (389.8 nm) and D_ε (397.0 nm) lines were recorded. The fluxes at the SOL were estimated from the S/XB line ratio: nitrogen accounted for 5-10 % of the total flux. The exposures were followed by ion and electron beam analyses. Nuclear reaction (NRA), Rutherford backscattering spectroscopy (RBS), time-of-flight heavy ion elastic recoil detection (ToF HIERDA), electron probe microanalysis (EPMA) and/or energy dispersive X-ray spectroscopy (EDX) were done on a large number of tiles from the toroidal and inner bumper limiter (a shield for dynamic ergodig divertor, DED) and, on the plates attached to the test limiter.

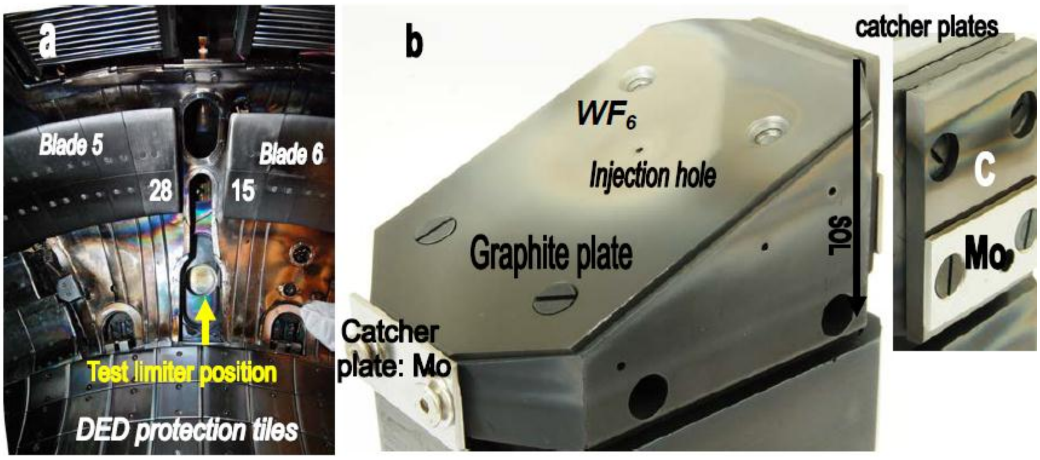


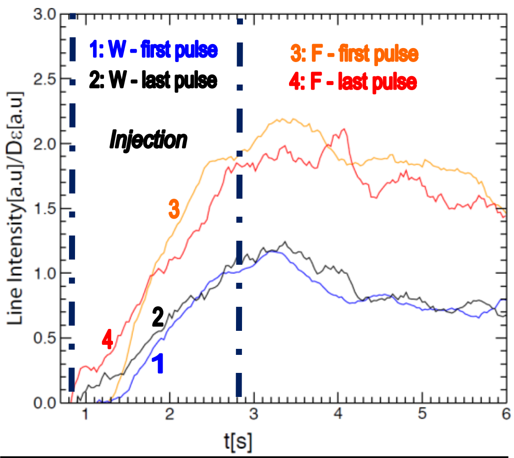
Figure 1. Top view into the TEXTOR vacuum vessel showing the location of the test limiter with respect to ALT-II limiter blades with marked position of corner tiles (a); test limiter assembly with marked components of the set-up (b and c).

3. Results and discussion

Spectroscopy Temporal evolution of tungsten and fluorine fluxes at the test limiter is plotted in Fig. 2 for the first and the last shot with WF_6 injection. The data are normalized with respect to the intensity of the D_ε line. The main message is that for a given species the shape and intensity of the signals are fairly similar. Some differences observed, as expected, at the beginning of the discharge level already after 0.7 s into the gas puff. This weak "memory" effect may indicate that fluorine retention on the test limiter is not pronounced, i.e. species is effectively transported to other PFC or to pumps.

Deposition profiles The injection of WF_6 lead to the formation of a co-deposit on the graphite plate in the vicinity of the gas inlet, as seen in Fig. 1(b) taken after the limiter exposure to plasma. The deposited layer contains a mixture of light and heavy species: H, D, He, ^{10}B, ^{11}B, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, F and W accompanied by small quantities of Inconel components (Ni, Cr, Fe). The greatest amounts are found near the gas inlet: up to $1x10^{18}$ W cm^{-2}, N-15 ($3x10^{16}$ cm^{-2}), F ($2x10^{16}$ cm^{-2}) and He ($1x10^{17}$ cm^{-2}). Only a small quantity of F is detected in comparison to other species, especially to tungsten. They also prove and confirm nitrogen retention in deposits [2-4]. Helium originating from regular glow discharge wall conditioning and He-beam diagnostics is identified again [3] in TEXTOR deposits in fairly high concentration with respect to other gaseous elements in the layer.

In analyses of the ALT-II tiles the emphasis was on differences between tungsten deposition patterns on plasma-wetted areas (erosion zone) and in the deposition zone where the eroded species are eventually resting. The standard pattern for deuterium and impurity atoms on ALT-II after entire campaigns has been shown previously [5]: tiny amount of species in the erosion zone and a sharp increase (by orders of magnitude) in the deposition region. The profile in Fig. 3(a) measured on tiles retrieved just after the experiment reveal irregular behaviour. There is an increase into the deposition zone and then sharp decrease. The graph in Fig. 3(b) reflects the deposition in the area nearest to the injection point: corner Tile 28 marked in Fig. 1(a). The profile is wave-shaped with a concentration maximum at the in the central part of the tile, i.e. in the area known as the erosion zone on ALT-II. The same shape of the tungsten distribution has been found on the other corner plate (Tile 15) from the adjacent ALT-II blade, see Fig. 1(a). The W content on these two corner tiles is greater than measured on other plates from various toroidal locations.



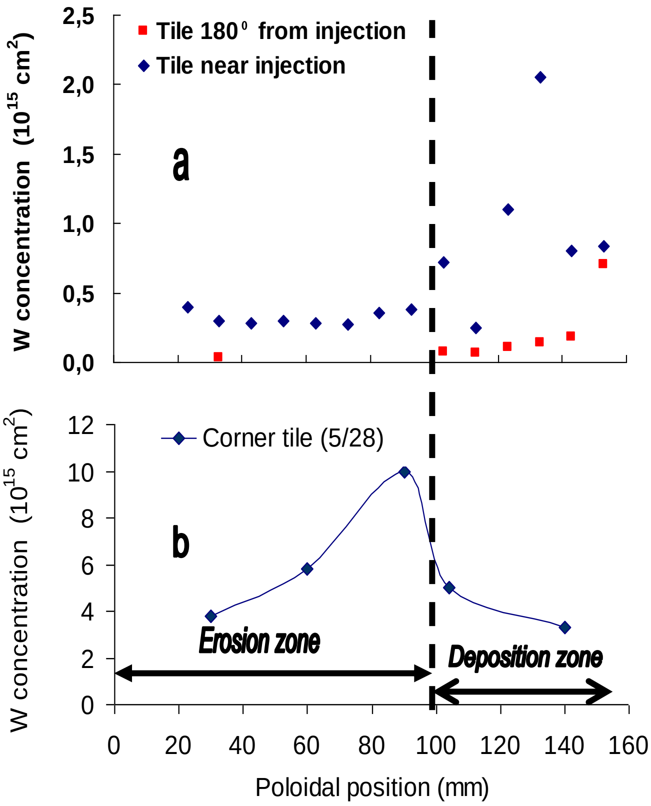


Fig. 2. Normalized spectroscopy signals of WI and FII lines for the first and the last discharge with the WF_6 injection.

Fig. 3. Deposition profiles of tungsten on the ALT-II toroidal limiter tiles detected in areas located at different positions with respect to the gas puff: (a)on standard tiles;(b) on the corner tile next to the gas injection point.

This complex deposition pattern in Fig. 3(b) is a net result of global and local transport phenomena. It reflects the migration of tungsten from the net erosion area where it is originally deposited by plasma flux to areas where it rests: deposition – re-erosion – ionisation – re-deposition cycle. Erosion of tungsten occurs predominantly via physical sputtering. At the edge temperature T_e of about 60 eV it is eroded mainly by plasma impurity ions (carbon, oxygen and boron), but the contribution of deuterium to the overall process is not excluded. The majority of sputtered species are neutrals with mean energy of 5-7 eV. At the edge density n_e ~5 x 10^{18} m^{-3} their mean free path is 2-3 mm (normal to the limiter surface) before they get ionized [6]. As predicted by Naujoks [7], species ionized close to the limiter surface may promptly be re-deposited within the first gyro orbit (Larmor radius is about 2.0 mm under the experimental conditions). The results of surface analysis explain gradual tungsten migration on ALT-II. They also clearly demonstrate the agreement with the model. The process leads to the "spill over" of tungsten on graphite until the equilibrium between the re-erosion and re-deposition is reached. As determined with EDX, tungsten in the erosion zone resides in small pits acting as local shadowed regions. This is in agreement with previous studies on micro-distribution of fuel and plasma impurities on PFC [8].

Tungsten balance The integrated quantity of tungsten found on the graphite plate near the gas inlet corresponds to 2-3% of the injected amount. Also the integrated W content on the ALT-II tiles amounts to 10.5% thus showing that only approx. 13% of the injected species could be identified on surfaces of the the test and toroidal pump limiters. In the search for tungsten several DED tiles from various locations were studied for the first time. The W content ranges from 1 to 25×10^{15} cm^{-2}. Taking 3×10^{15} cm^{-2} as a mean value, the integrated amount on DED is approximately 2×10^{20} W atoms, i.e. exceeding the amount puffed in the experiment described her. It is impossible to assess accurately the amount originating from the last experiment because the tiles were in TEXTOR for eight years. The results lead to a conclusion that the inner bumper is a major residence place for high-Z metals eroded from the TEXTOR liner, various test limiters, and those introduced by injection. Also the deuterium content on the DED tiles is significant: $3\text{-}4 \times 10^{18}$ cm^{-2} leading to the integrated amount in the range $2.0–2.5 \times 10^{23}$ D atoms accumulated in that region.

4. Concluding notes

Surface studies performed for the first time on the DED tiles allowed for the identification of a major deposition area for high-Z species eroded from the wall or introduced by injection. Volatile WF_6 can be used as a high-Z transport marker without a major risk of leaving large quantities of fluorine sticking (co-deposited) to PFC and then released to plasma during subsequent pulses. The statement is justified by two facts: (i) the memory effect is not pronounced, as proven by spectroscopy and (ii) small quantities of F (maximum 2×10^{16} cm^{-2} *versus* 1×10^{18} cm^{-2}) are found even near the injection point. The application of the ^{15}N tracer and a not standard analysis method, i.e. HIERDA, has allowed for conclusive identification of nitrogen deposited on PCF. The exact balance could not determined, but the result shows effective co-deposition of toroidally puffed nitrogen. Experiments in TEXTOR [3] and in ASDEX [4] indicate the retention of about 30% of the injected gas. Also helium co-deposition and retention has been confirmed [3]. It is associated with He glow discharge. The level is quite significant (1×10^{17} cm^{-2}). Therefore, it can be recommended to study helium trapping following He-based ion cyclotron wall conditioning [9], i.e. a method considered for a reactor-class machine.

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