Erosion and deposition investigations on Wendelstein 7-X first wall components for the first operation phase in divertor configuration

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In the stellarator Wendelstein 7-X with its twisted 3D magnetic field geometry, studies of material migration with respect to first wall components become very important in view of the envisioned long-pulse operation. A variety of erosion/deposition samples were installed on the plasma-facing components exposed at three different nominal heat load levels between 0.1 and 10 MW/m^2. After the first successful operation phase in divertor configuration, all the probes at higher and lower load levels were removed, whereas at the intermediate load levels, 352 out of 30 000 screws have been exchanged at selected locations along the toroidal and poloidal directions. The exchanged probes have been analyzed by various measurement techniques. At the higher load levels where the probes were installed within the divertor, heavy erosion has been observed presumably at the strike line positions. Both, erosion and deposition phenomena have been found on the screw heads. The optical reflection measurement profile of the whole plasma vessel show the deposition patterns at similar locations in all the five modules. At the low load level, the Si-wafer probes are under investigation.

Keywords: Nuclear fusion device, Stellarator, Wendelstein 7-X, Plasma wall interaction, erosion/deposition.

1. Introduction

The Wendelstein 7-X (W7-X) stellarator is in operation since 2015. After the first Operational Phase (OP1.1) with graphite limiters as main Plasma Facing Components (PFC), for the second phase i.e. OP1.2a, several PFCs in the form of Test Divertor Units (TDU), baffles, heat shield and toroidal/poloidal closures were installed [1, 2]. Except the poloidal closure, all others are made of fine grain graphite.

For the future stellarator fusion power plant, due to the 3D twisted plasma and the surrounding PFC geometry and use of various plasma configurations, the understanding of Plasma Wall Interaction (PWI) processes and the resulting material migration becomes quite important. Various probes have been installed at different heat load levels (0.1-10 MW/m^2) to study this behavior [3]. At the location of the highest heat loads, 18 exchangeable divertor target elements were coated with C/Mo marker layers on graphite and for the lower loads, 44 Si-wafer probes were installed. An extensive array of >30 000 probes in form of amorphous carbon (a-C) coated Ti-Zr-Mo (TZM) screw heads was installed around the torus capable to withstand ≤ 0.5 MW/m^2. After the successful plasma campaign distributed over 16 weeks resulting in about 1 hour of accumulated plasma exposure in hydrogen and helium, all the probes, as well as 352 TZM screws out of 30 000, were exchanged. The details of measurements and analysis are presented in the following sections.

2. Experimental results and analysis

2.1 Exchangeable target elements on TDU

C/Mo marker layers were used for determining erosion of carbon and deposition of potential materials i.e. C, O, Ni, Fe etc. on TDU tiles. The marker layers were deposited as an about 2 cm wide stripe in the middle of the tiles using the magnetron sputtering [4]. The markers consist of an about 200 nm thick Mo layer and a 5-10 µm thick C layer on top. The Mo serves as marker for distinguishing the C layer from the bulk C of the tile.

The marker layers were analyzed before and after exposure in W7-X during OP1.2a using Rutherford Back

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scattering Spectroscopy (RBS) at the IPP tandem accelerator facility's Bombardino device using the BesTec manipulator. 2.5 MeV incident protons at normal incidence and a scattering angle of 165° were used. A passivated implanted planar silicon detector with a thickness of 300 µm and nominal energy resolution of about 12 keV was used. The pre-exposure measurements were performed with a step width of 20 mm in order to determine variations of the initial layer thicknesses. The post-exposure measurements were made with a step width of 5 mm resulting in more than 2000 recorded spectra.

A typical RBS spectrum before exposure in W7-X is shown in Fig. 1. The signal in channels 500 – 600 is due to the carbon marker layer, the dip around channel 500 and the large peak around channel 700 are due to the Mo interlayer. The signal in channels below 400 is due to bulk C. A small peak of O is visible in channels around 650, and Ar together with W (both originating from the coating procedure) are responsible for the small signal in channels above 750. The C layers initially contained less than 2-3 at.% O, 0.5-1 at.% Ar and <0.05 at.% W.

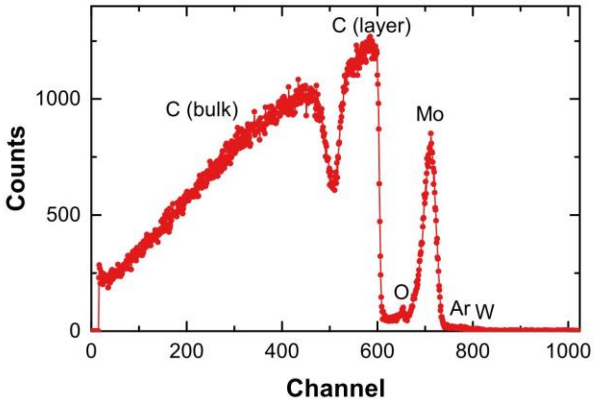

Fig. 1: Typical RBS spectrum using 2.5 MeV protons from a C/Mo marker layer before exposure in W7-X.

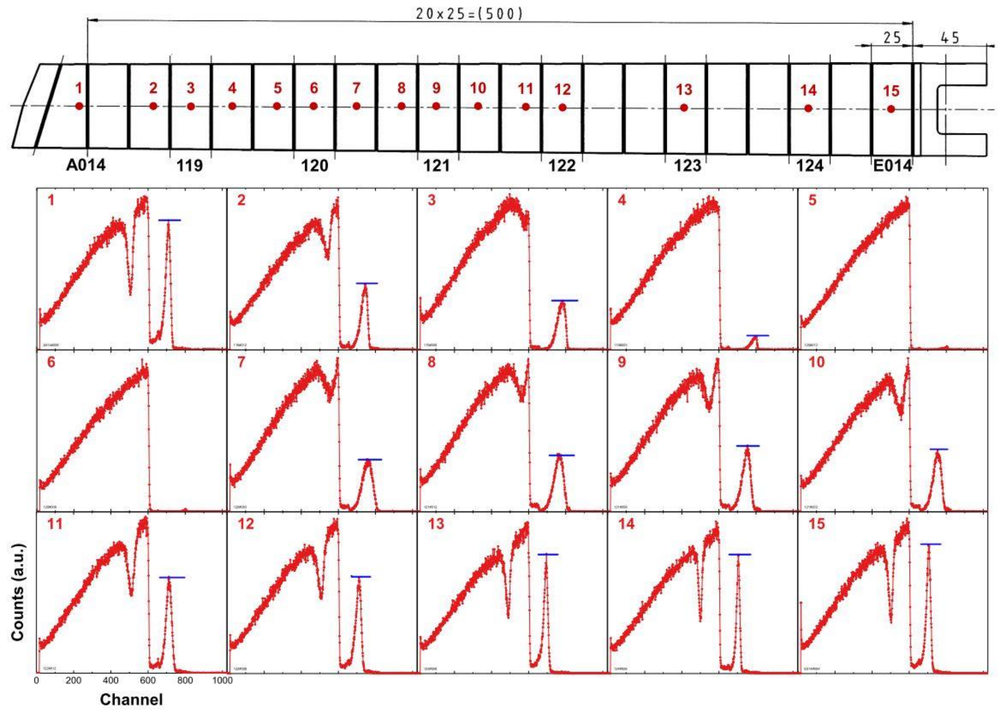

Fig. 2: RBS spectra using 2.5 MeV protons from position 1 – 15 on target TE-TM2h6 from half module 21. The TE consists of tiles A014, 119 – 124 and E014. The horizontal blue line shows the maximum height of the Mo spectra. The axes are same for all images.

Typical RBS spectra after exposure in W7-X are shown in Fig. 2 for Target Element (TE) TM2h6 from half module 21. The TE consists of the tiles A014, 119 – 124 and E014, the total length of the TE is more than 580 mm, the maximum width is about 56 mm. Only small changes are observed on tile A014 (located at in-board side), a typical spectrum is shown from about the middle of the tile (position 1). On tile 119 erosion of the C marker layer is observed (position 2 and 3) until finally the whole C layer is eroded and the underlying Mo layer gets partly eroded (position 4). On positions 5 and 6 both the C and Mo layers are fully eroded. On positions 7–10 partial erosion of the C layer is observed. On position 11 only a very small erosion of the C layer is visible, while on the rest of the TE (positions 12 – 15) only very small changes are detected. Some oxygen on the surface (peaking in channel 655) is visible on all tiles. Thicker deposits of C are not observed on the whole TE, and deposition of elements from the stainless-steel wall (Fe, Cr, Ni) is not detected within the detection limit, showing this as a net erosion zone in TDU.

The observed high erosion of C and Mo within the strike line region could be due to the sputtering from high-energetic particles (H, He and impurities). In addition, chemical erosion by H or O could play a significant role in case of C. This is not fully conclusive from the present data on TE because O at the surface was already visible before exposure in W7-X, see Fig. 1. However, Scanning Electron Microscope (SEM) views on Focused Ion Beam (FIB) prepared cross-sections together with Energy Dispersion X-ray spectroscopy (EDX) analysis on the heat shield tiles recovered after OP1.2a (fig. 3) show O in deposition zones indicating the source of O present during the plasma operation.

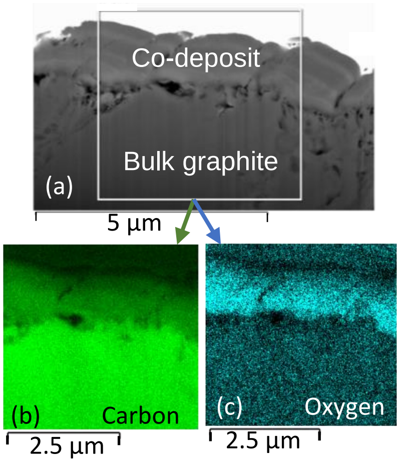

Fig. 3. SEM-FIB image of a co-deposited layer (a) together with EDX analysis of C (b) and O (c) concentrations

2.2 TZM screw heads

The screw heads were few millimeter deeper than the tile surfaces on which these were installed. The thickness of a-C marker layer on the 352 screws heads, recovered after the operational campaign OP1.2a, were measured using betascope (Helmut Fischer GmbH) [3] in order to map the erosion/deposition pattern over the first wall components (see fig. 4). An erosion of thickness ≤ 0.5 µm was observed for about 1/3 of the screws, however the deposition of the similar thickness was found for about 1/7 of these, on the other hand for about ½ of the screws no thickness change was seen within the detection limits of ~250 nm. Only 2.8% and 0.6% of the screws showed erosion within 0.5-1.0 µm and 1.0-1.5 µm range respectively. No erosion / deposition was observed beyond this range. Among the individual components (see table 1), the upper and lower baffles (Baffle-U and Baffle-L) in module 1 and the heat shield in module 3, the maximum number of screws i.e. 17-18 were found with erosion. On the other hand, maximum deposition had occurred on the heat shields of modules 1, 4 and 5. The lower and upper Toroidal Divertor Closures (TDC-L and TDC-U) of module 4 showed preferred erosion and depositions respectively. The above variation in the deposition/erosion patterns are the accumulated effects over the whole campaign with the total plasma duration of about 1 hour. There were several plasma configurations used, moreover, the asymmetric heat load over the ten island divertors during the initial phases of operations also contributed to these variations. In order to characterize the deposited material as well as the H/He plasma gas retention, few of these screws have been also analyzed with laser-induced breakdown spectroscopy [5].

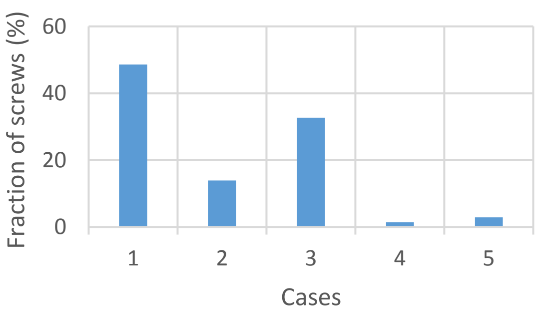

Fig. 4. Fraction (% of total 352) of screws with erosion/ deposition patterns after plasma exposure. Case 1: no thickness change, cases 2: deposition 0 ≤ t ≤ 0.5 µm, cases 3: erosion 0 ≤ t ≤ 0.5 µm, cases 4: deposition 0.5 µm ≤ t ≤ 1 µm and cases 5: erosion 0.5 µm ≤ t ≤ 1 µm.

Table 1. Distribution of number of screws with deposited/ eroded thickness over different components and W7-X modules. Here, H-Shield → Heat shield, L→ Lower and U→ Upper.

Component	W7-X module	Unchanged	Deposition ≤ 0.5µm	Erosion ≤0.5µm
Baffle-L	1	14	1	17
Baffle-U	1	12	4	18
Baffle-L	4	25	3	7
Baffle-U	4	21	2	11
H-shield	1	14	8	12
H-shield	2	21	3	12
H-shield	3	14	4	18
H-shield	4	18	9	10
H-shield	5	16	8	5
TDC-L	4	8	1	5
TDC-U	4	8	6	0

2.3 Optical reflection measurements

The graphite tiles, mounted within the TDU, baffles, heat shields and toroidal divertor closures cover a significant part of PFC. Nevertheless a big area, ca. 75m^2 (ca. 40% area of all PFC) of stainless steel panels from the wall, TDU pumping gap and the poloidal closures remain exposed to the plasma. Depositions on these panels also provide useful informations about the material migrations over the first wall components interacting with the plasma. Measurements of the optical reflection of the Red, Green and Blue (RGB) colors have provided such informations in Large Helical Device [6]. Using this compact color analyzer, whole W7-X plasma vessel metal surfaces along the torus were mapped by taking ca. 5300 measurements. For the stainless steel wall panels, the measured RGB values are presented in fig. 5 where the dark color represent the areas with the depositions. A clear change in the values is seen, the deposition pattern appears to be similar in all the five modules. The deposition pattern on these panels mounted on the outboard side differs from the erosion / deposition pattern observed on the graphite tiles from the inboard side. Heavy depositions were observed on the TDU pumping gap panels due to the impurities generated in the nearby divertor strike line region.

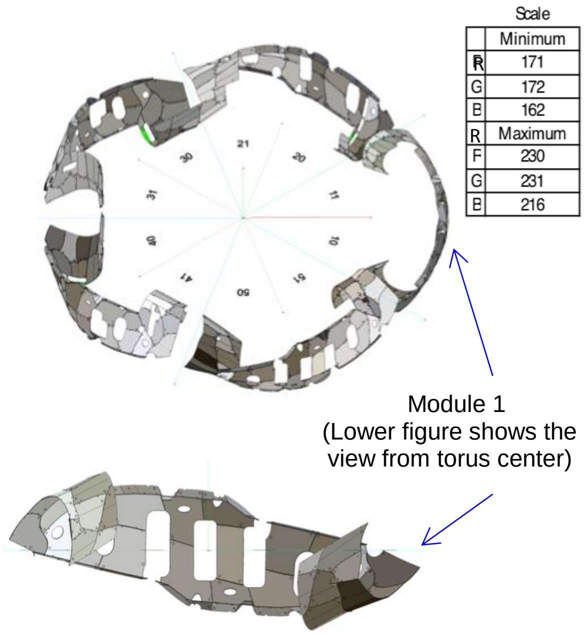

Fig. 5. Scaled RGB values represented in terms of changed in darkness. Increase in darkness corresponds to the increase in deposition.

3. Further studies

After completion of OP1.2a, all the PWI probes have been exchanged for the next operation campaign 1.2b which is ongoing. For the first time tungsten coated graphite tiles as PWI probes have been introduced in W7-X. At the higher load levels, three such tiles in one of the TE within TDU and one complete TE in two scraper elements [7] have been installed. At the lower load levels, 21 W coated tiles distributed over all the modules have been installed, the actual locations are presented in table 2. It has been estimated that erosion by charge exchange hydrogen can be neglected as well as the erosion by hydrogen plasma ions. The resulting central concentration of tungsten and the corresponding radiation losses are expected to be marginal. Considerable erosion of the tungsten tiles has to be expected only when sputtering by impurity ions such as carbon or oxygen ions will contribute, however after the boronisation substantial reduction of oxygen impurity is observed.

Table 2. Details of the W coated graphite tiles installed in W7-X. TS represents the Triangular Shape.

Locations	No. of tiles	Distance from separatrix	W coating thickness
Bean shape	10	≈ 80 mm	≈ 50 nm
TS protection house	6	> 200 mm	≈ 150 nm
TS outboard side	5	> 200 mm	≈ 50 nm

352 TZM screws distributed over a toroidal ring and ten poloidal lines in the heat shield tiles as well as the along the complete length of baffles, have been exchanged. At the wall panels, 28 new long-term Si-wafer probes, 12 directional material probes and 4 cavity probes have been installed for the OP1.2b campaign.

4. Conclusions

The TEs in TDU, show severe erosion at few locations along the length, lying within the strike line areas, however since the strike line pattern varied depending upon the plasma configuration, the detailed analysis would show the actual correlation. The TZM screw heads show as well the erosion/depositions patterns over the heat shield, baffle and toroidal closure areas distributed over all the modules. The RGB color analyzer showed the similar deposition pattern in all the five modules. All the exchanged probes will be removed once the OP1.2b campaign will be concluded in mid-October 2018 and analyzed, the results will be compared with the previous campaign.

Acknowledgments

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