Inspection of W 7-X plasma-facing components after the operation phase OP1.2b: observations and first assessments

C P Dhard[1,*], M Balden[2], J Baldzuhn[1], C Biedermann[1], T Bräuer[1], S Brezinsek[3], M Endler[1], Y Hayashi[4], D Hwangbo[5], S Kajita[6], M Krause[1], P Kornejew[1], S Masuzaki[4], M Mayer[2], G Motojima[4], D Naujoks[1], M Otte[1], V Rohde[2] and The W7-X Team[1]

[1]Max-Planck-Institut für Plasmaphysik, Wendelsteinstrasse 1, 17491 Greifswald, Germany
[2]Max-Plank-Institut für Plasmaphysik, Boltzmannstrasse 2, 85748 Garching, Germany
[3]Forschungszentrum Jülich GmbH, Institut für Energie- und Klimaforschung – Plasmaphysik, Partner of the Trilateral Euregio Cluster (TEC), 52425 Jülich, Germany
[4]National Institute for Fusion Science, 322-6 Oroshi, Toki 509-5292, Japan
[5]Department of Electrical Engineering, Graduate School of Engineering, Nagoya University, Furo-cho, Chikusa, Nagoya 464-8603, Japan
[6]Institute of Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa, Nagoya 464-8603, Japan

Email: dhard@ipp.mpg.de

Due to its twisted magnetic configuration, the plasma facing components of the Wendelstein 7-X stellarator are oriented in a 3D shape. The plasma facing components consist of graphite test divertor units, baffles, head shield tiles and toroidal divertor closures and stainless steel wall panels, pumping gap panels and poloidal closures. In order to document the status of these components as well as get the first foot-prints of the plasma wall interactions occurred during the plasma campaign, a detailed inspection of the whole plasma vessel after the plasma campaign is of vital importance. Such an inspection was carried out after the operation phase OP1.2b completed in October 2018. A number of observations were made, such as, molten stainless steel drops, melting of a long term probe, deposition on steel panels, arc traces, loosely bound particles and deposition stripes on the plasma vessel hidden behind the graphite tiles. In order to understand the possible cause, their implication and steps to avoid some of these problems for the next phase of machine operation, an assessment was made. The melting events should be avoided in the future, the others are due to usual plasma wall interaction mechanisms and will be monitored after every campaign.

Keywords: Wendelstein 7-X, Plasma facing components, Plasma wall interaction, Erosion and deposition, Arc traces

1. Introduction

Wendelstein 7-X (W7-X) is an optimized 3D helical shaped stellarator with 5 fold symmetry and designed for steady state plasma operation of up to 30 min. Over the consecutive operation phases the parameters are continuously being improved to achieve the designed values. As for Plasma Facing Components (PFCs), W7-X was equipped with inertially cooled 10 discrete island Test Divertor Units (TDUs) with baffles, toroidal divertor closures, wall protection heat shields made of fine grain graphite and Stainless Steel (SS) wall & divertor pumping gap panels and poloidal closures (see figure 1). In addition, graphite scraper elements were installed near two divertors in order to mitigate the convective plasma heat loads on the pumping gap panels in certain configurations with the evolution of bootstrap current [1-3]. During July-October 2018, the Operation Phase OP1.2b was completed successfully with an accumulated plasma duration of 9054 s with 1256 discharges distributed over four different plasma configurations. Prior to the first plasma operation, the plasma vessel was baked at 150°C for 162 h, the whole baking cycle lasted 265 h at elevated temperatures. In addition, hydrogen/helium glow discharge cleaning was performed for 11:25 h (H_2 9:35 h and He 1:50 h) before beginning the plasma operation and for 3:27 h (H_2 1:03 h and He 2:24 h) during the plasma campaign. Three boronizations (90% He + 10% B_2H_6) were performed within the plasma vessel, which helped in reducing the oxygen impurities substantially resulting in improved plasma parameters [3]. After completion of the plasma campaign, a close inspection of the plasma vessel is of vital importance in order to document unforeseen events as well as obtaining a qualitative picture of the erosion and deposition effects due to Plasma-Wall Interactions (PWI). Understanding these events and implementing steps to avoid these for the next operation phases is very much necessary for a safe device operation. Even though the plasma operations were not noticeably disturbed, a number of observations have been made during this inspection after OP1.2b. The details of these and their evaluations will be presented in the following sections.

2. Impurity depositions

During the inspection depositions were observed at the following components:

2.1 Plasma vessel wall

On the whole inboard side plasma vessel wall behind the graphite tiles, sharp deposition stripes were observed, located at the gaps between the tiles as shown in figure 2. These depositions appeared also on a TAG number plate (see figure 2 inset (a)) incidentally fixed at the stripe location. This was removed and analyzed with Elastic Backscattering Spectrometry (EBS) with 2.5 MeV incident protons at the IPP tandem accelerator facility Bombardino using the BesTec manipulator [4]. The measured atomic concentrations are shown in table 1. The deposited material was found to be mainly consist of C with small amount of O and traces of B (H is not measured by the technique used). At the line crossing the deposition stripe (see figure 2 inset (a)), Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray spectroscopy (EDX) measurements were done (see figure 3) confirming the EBS results. With the values of stripe width and distance between the neighboring stripes, an array was generated for the whole inboard side of plasma vessel and the fraction of deposited area (3.23 m^2) compared to the total area (89.9 m^2) was estimated. Further, with the measured thickness, the total amount of deposited C (1.39x10^{22} atm.) was estimated to be 0.3 g. Deposition is also expected on the sides of the tiles forming the gap through which C travelled up to the vessel wall. These tile are presently being investigated.

Table 1. Atomic concentration of C, O and B atoms measured by EBS, here positions # 1 and # 2 are at the deposited stripe and # 3 at the base material, see figure 2a. Statistical uncertainties are + 5%.

Position	**C** (x10^{15}at./cm^2)	**O** (x10^{15}at./cm^2)	**B** (x10^{15}at./cm^2)
# 1	457.9 ± 52.2	98.1 ± 40.9	75.5 ± 25.2
# 2	406.5 ± 51.0	131.4 ± 41.1	76.4 ± 25.1
# 3	80.2 ± 47.1	61.0 ± 41.2	< 20

2.2 Inner divertor closures

The space behind the test divertor units were closed using 0.5 mm thin stainless steel plates named as inner divertor closures. When the TDUs were removed for installing the water cooled high heat flux divertors, depositions were seen on these closures. These depositions were analyzed using EBS as described above and Nuclear Reaction Analysis (NRA) with incident 2.5 MeV ^{3}He ions using the $^{12}C(^3He,p_0)^{14}N$ and $^{10}B(^3He,p_1)^{12}C$ reactions. A gradient of deposition was observed with the peak values of about 2x10^{18} atoms/cm^2 for C (see figure 4), the amounts of O and B were relatively small. These deposits were probably created during some of the plasma configurations during OP1.2a mimicking the scraper configurations, when the strike lines were moved close to the pumping gap panels and some of the convective loads could reach to the closures. For OP1.2b, however these were blocked by modified graphite baffle tiles (L-shaped tiles) in this region, further analysis would be carried out to find the deposition took place during OP1.2b. For the next phase of operations, together with the new divertor these closures will be also exchanged.

2.3 Wall & pumping gap panels and poloidal closures

During the inspection, deposits were observed on the stainless steel outer wall panels, pumping gap panels installed between the horizontal and vertical part of TDUs and the poloidal closures. An optical reflection measurement technique was employed for the in-situ measurements. In this technique the intensities of reflected Red, Green and Blue (RGB) lights from the measurement spot are measured and together with ellipsometric measurements, the deposited layer thickness is estimated [5]. All the panels around the torus were measured, the thickness profile on the wall panels shows a definitive pattern with the thickest deposition around the interface between the modules and the thinnest in the middle of a module [6]. Depositions were seen only on certain areas of pumping gap panels as well. Interesting deposition patterns were observed on the poloidal closures (see figure 5) with different depositions on upper and lower closures of one module indicating up-down asymmetry. Such asymmetry was observed in all the five modules.

3. Loosely bound particles

Loosely bound and free particles, flakes etc. provide useful information about the chemistry of PWI processes taking place during the plasma operations [7]. Keeping this in mind, once the vessel was accessible one of the first tasks was taken up to collect these particles avoiding the possibilities of external dust particles entering the vessel. Three different techniques, namely vacuum filters, sticky probes and brush-collection, were employed to collect the samples over whole vessel. Altogether 44 samples were collected. Only small amount of loosely bound particles were found pointing to the clean work during the assembly and the operation phases.

The samples were analyzed using SEM/EDX. Figure 6 shows the observed view of a C-flake. From the measurements, the observed particles could be classified in three categories: C-dominated flakes, Fe particles with Cr, Ni and Mn traces and Al-Cu particles. C originates mainly from the erosion of test divertor units and Fe, Cr, Ni and Mn from the stainless steel panels and structures. Cu is present in the Cu-Cr-Zr support structure of graphite tiles for the baffles, heat shields and toroidal closures. For Al the possible sources could be ceramic feedthroughs made from Al_2O_3 or glass windows. Since three boronizations were carried out for reducing the C and O impurities, it was explored if this was present in these samples, however these were found to be below the measurable levels.

In the future, after every plasma campaign, such particle samples will be collected and analyzed. Possibilities are being explored to install some of the particle collection boxes at fixed locations similar to the ones installed in ASDEX Upgrade [7].

4. Arcing

The whole plasma vessel including its components and the ports were checked for arc traces using a Dino-Lite digital microscope. Altogether only 212 arc traces have been found on the panels, ports, plasma vessel and the tile supports, out of these 158 were observed on the plasma facing side and the rest on the back side (see figure 7). The length of these traces varies from 1-2 cm up to about 0.5 m. Only a small fraction i.e. <10% of these have been found to follow $-JxB$ direction due the magnetic field generated by the main superconducting coils. The majority of the tracks are oriented in random directions. Besides, about 25% of these arcs even occurred on non-plasma facing sides, indicating the origin of the arcs to be due to the glow discharge cleaning. The depth of these traces appears to be very small and no observable material erosion was seen.

5. Molten SS probes

Melting events were observed on the following SS probes:

5.1 Magnetic flux surface mapping probe

One of the probes installed in the plasma vessel in module 1 for the 3D magnetic flux surface mapping [1] was retracted into the port during the whole OP1.2b. Despite of this port remaining closed with a shutter, part of a 3.0 × 0.5 mm SS probe tube was molten and flowing out of the sealed flange and drops were falling down as well as spread on the neighboring tiles (see figure 8). The problems probably have occurred due to an inappropriate setting of polarization for the Electron Cyclotron Resonance Heating (ECRH) remote launcher that makes use of the shutter as a reflector. For the future operations this will be corrected by introducing an interlock in the ECRH control software. Furthermore, the shutter and frontend will be water-cooled in the future.

5.2 Si-wafer probe

44 pieces of long term deposition probes of three different types, i.e. Si-wafer, directional material and cavity probes [8, 9] were installed at the outboard wall as well as at the pumping gap panels in module 4 (see figure 1) for monitoring depositions on these low loaded components. One of the edges of a SS probe holding the Si-wafer installed around the mid-plane was found to be molten. All the other probes were intact, despite some of these located on the pumping gap panels, being closer to the plasma. According to the mass of the molten SS, about 100 J for a second could melt the edge. Resulting from simulations with the ASCOT code [10], the melt event had occurred due to neutral beam injected fast ion orbit losses (see figure 9). The estimated fast ion heat load at this probe location is about 180 W which is sufficient for the observed melting. For future operations, no probe will be installed at this location, besides, in order to account for the plasma operations with reversed magnetic field, another probe at the mirror opposite location will be removed as well.

6. Summary

Detailed inspection of the PFCs, plasma vessel wall, ports etc. after the completion of W7-X operation phase OP1.2b yields only a minor damages. Deposits of a:CH, typical for all devices using C PFCs were found at remote areas. Only small amount of loosely bound particles and some arc traces were found. Even after 9054 s with plasma energy up to 200 MJ, no serious erosion is found. Appropriate steps have been taken to ensure the events relevant for device safety are strictly avoided for the next W7-X operational phases. Deposition due to the usual plasma wall interactions cannot be avoided and will occur also in the future. However, these will be monitored and analyzed every time the plasma vessel is accessible. For the next operation phase, the inertially cooled test divertor units will be replaced with the water cooled carbon fiber composite high heat flux divertor, cryo-vacuum pumps will be installed behind the divertors and the water cooling for all the PFCs is foreseen. This will have an impact on PFCs operating temperatures and neutral pressures in the divertor region leading to some change in the erosion/deposition patterns. Si-wafer probes will be removed at two locations where higher power loads due to fast ion losses are expected. The deposition stripes on the plasma vessel contains mainly C with a total amount of ca. 0.3 g. This doesn't pose any problems for the operation (for example due to flaking), however the mechanism resulting in these depositions will be explored further. Deposition on the wall panels and the poloidal gaps and arc traces will be monitored regularly. Collection of loosely bound particles and their analysis for identifying their source and the chemical processes will continue after every operation.

Acknowledgments

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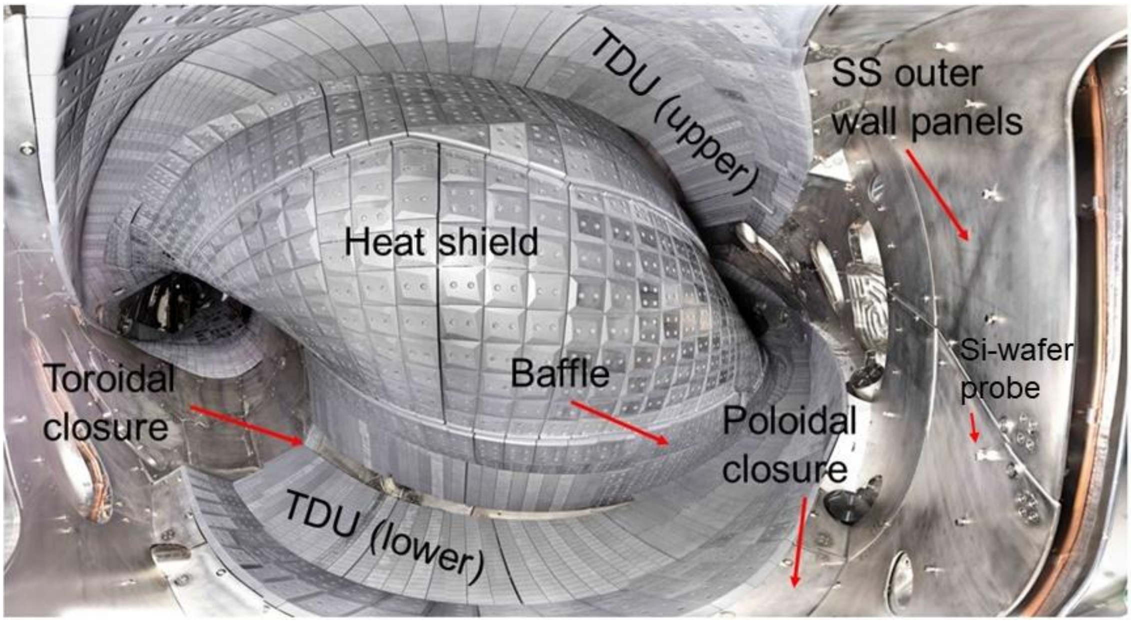

Figure 1. Panorama view into the W7-X plasma vessel from W7-X module 4, showing the installed plasma facing components.

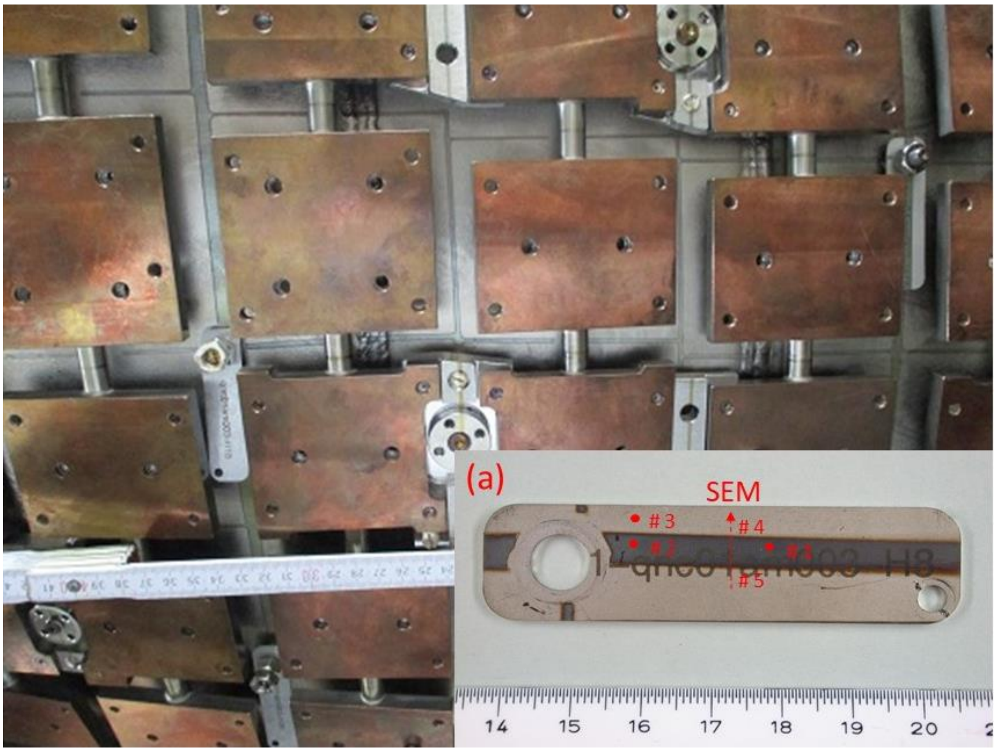

Figure 2. View of the inboard side plasma vessel showing the Cu-Cr-Zr support plates after removing the graphite tiles installed on these plates. The deposition stripes on the vessel wall are visible behind the support plates, inset (a) shows a TAG number plate installed on the vessel on which the stripes were also deposited.

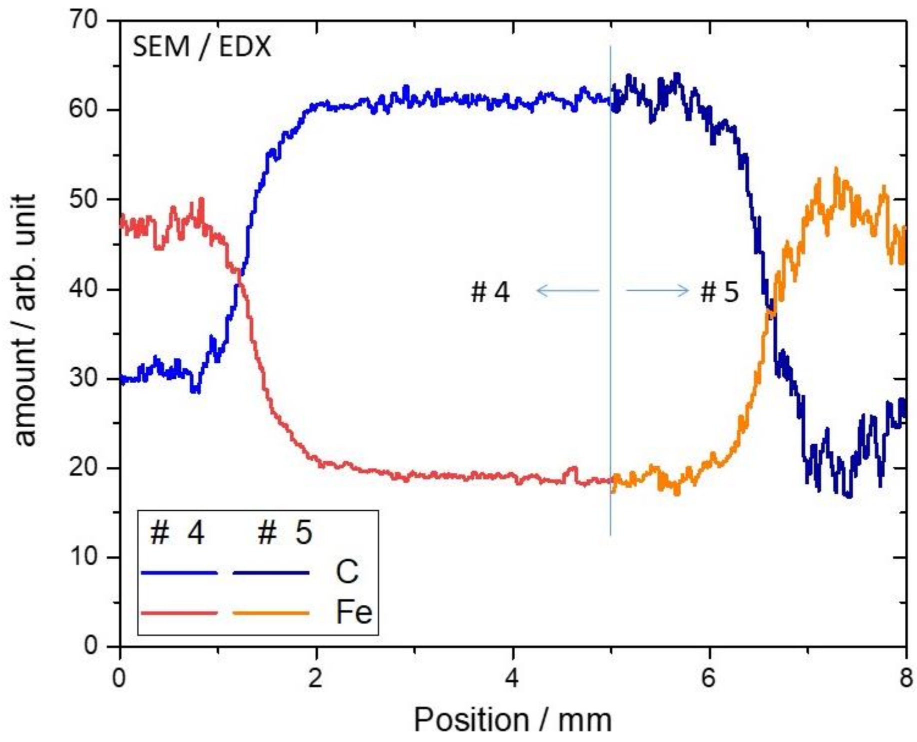

Figure 3. SEM/EDX measurements on the TAG number plate at the line crossing the deposition stripe at the locations # 4 and # 5 shown in figure 2.

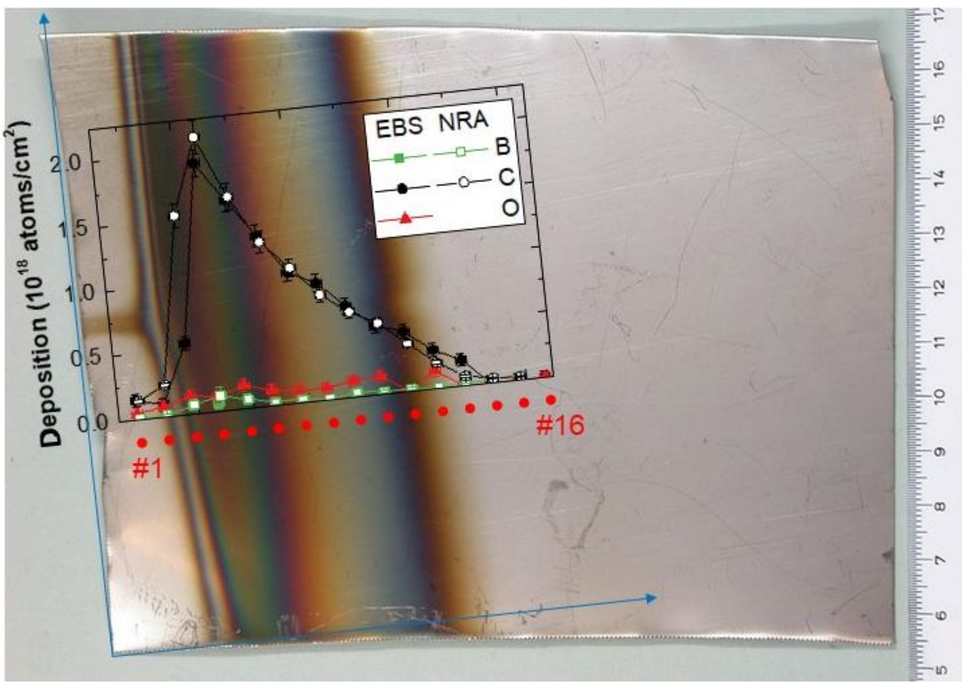

Figure 4. Inner divertor closure plate removed after OP1.2b from the lower TDU in module-2. Deposition layers are visible on the left side of the plate. The plot of EBS/NRA measurements

superimposed at the 16 measuring positions on the plate, shows variation of deposited layer thicknesses.

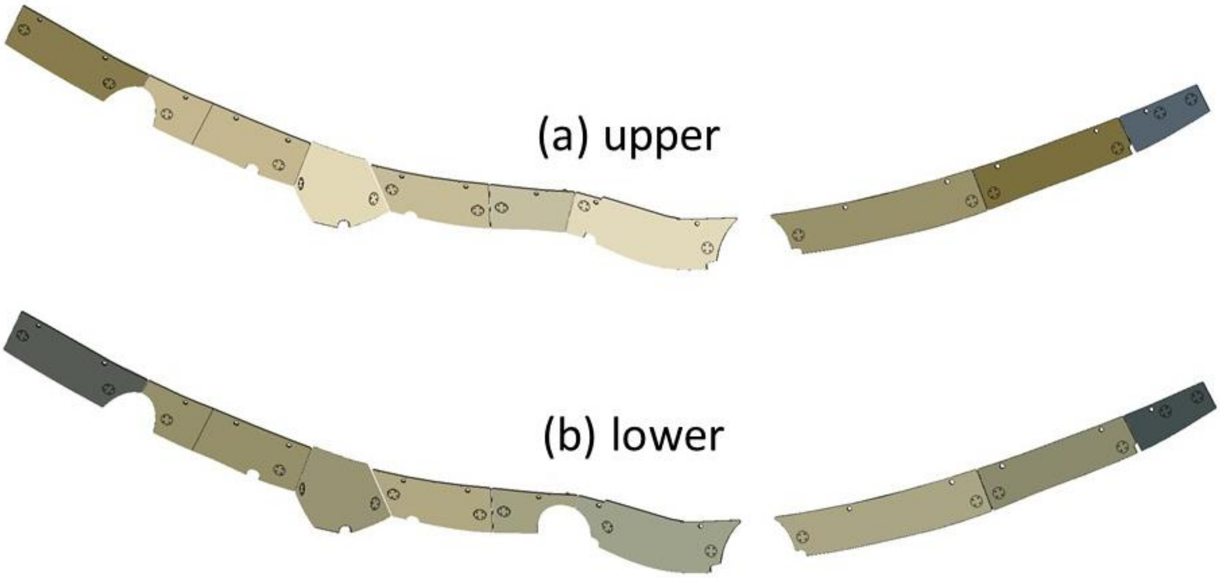

Figure 5. Views of the upper (a) and lower (b) poloidal closures from module-4, the difference in colors of both these indicate the up down asymmetry of the depositions.

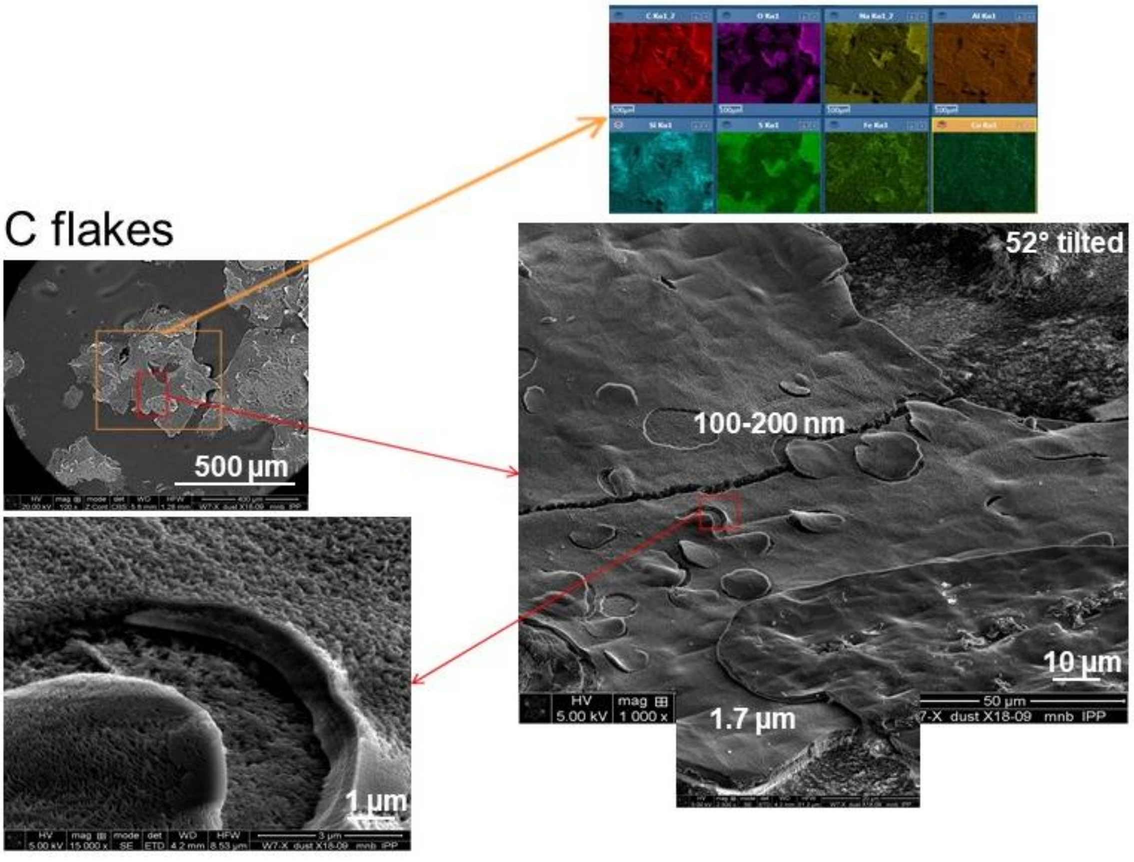

Figure 6. SEM/EDX image of a C flake sample collected from a tile.

Figure 7. Arc traces observed on the front side (a) and backside (b) of a panel, ports (c) & (d) and an enlarged view of a random arc trace with microscope (e).

Figure 8. View of the magnetic flux surface measurement probe installed on the upper side in module-1, (a) shows the probe with shutter opened, the melted steel drops are on the panel below (b) and neighboring graphite tile (c).

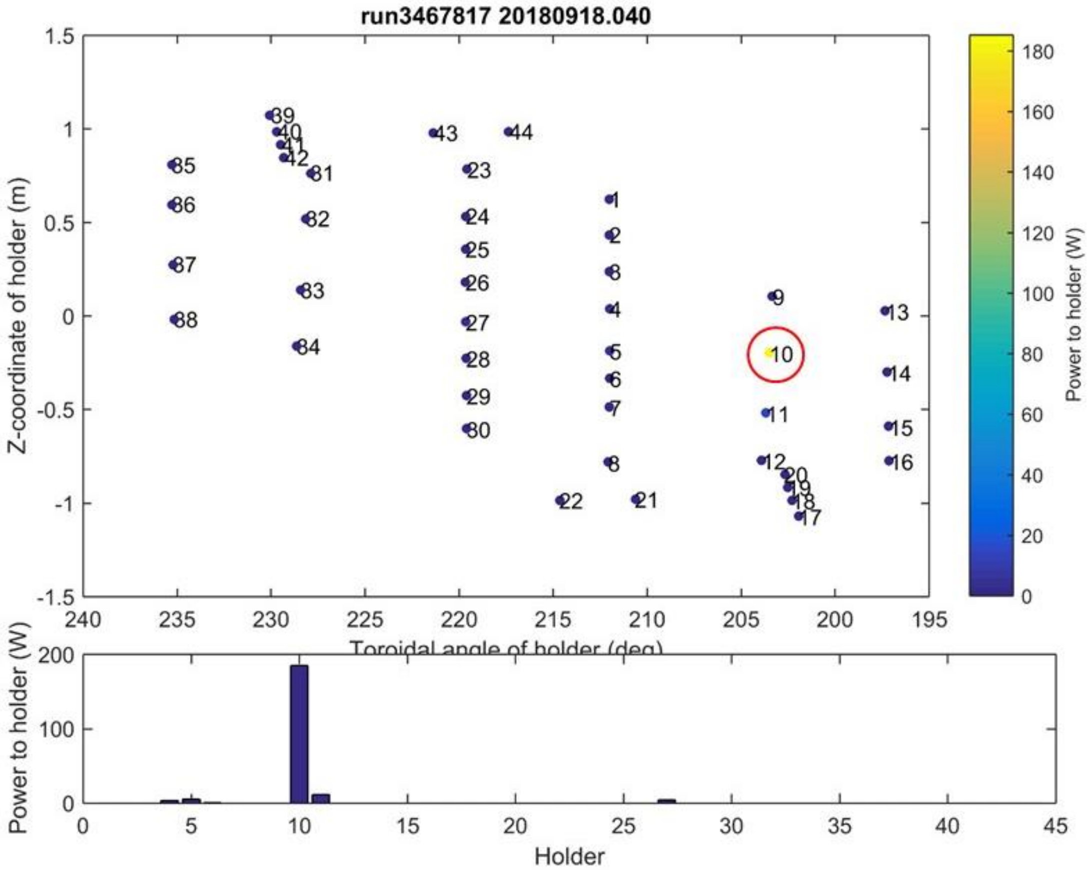

Figure 9. Estimations from the ASCOT code showing the heat loads due to the fast ions around the locations in module-4 where the Si-wafer was installed. The molten Si-wafer probe at location 10 (marked with a circle) received maximum loads above 180 W.