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ABSTRACT

First Mirror Test in JET with the ITER-Like Wall was performed with polycrystalline molybdenum mirrors. Two major types of experiments were done. Using a reciprocating probe system in the main chamber a short-term exposure was done during 0.3h of plasma operation in 71 discharges. The impact on reflectivity was negligible. In a long-term experiment, 19hs with 13h of X-point plasma during the entire campaign, twenty Mo mirrors were exposed, including four coated with a 1μm thick Rh layer. Optical performance of all mirrors exposed in the divertor has been degraded by up to 80% because of beryllium, carbon and tungsten co-deposits on surfaces. Total reflectivity of most Mo mirrors facing plasma in the main chamber was only slightly affected in the spectral range 400–1600nm, while the Rh-coated mirror lost its high original reflectivity by 30% thus decreasing to the level typical for molybdenum surfaces. Specular reflectivity was decreased most strongly in the UV range 250–400nm. Surface measurements with XPS and depth profiling with SIMS and Heavy Ion ERDA revealed that the very surface region on both types of mirrors had been modified by neutrals resulting eventually in the composition change: Be, C, D at the level below 1×10^{16} cm^{-2} mixed with traces of Ni, Fe in the layer 10–30nm thick. In several cases the original matrix material (Mo) has remained as the major constituent of the modified layer. The data obtained in two major phases of JET operation with carbon and full metal walls are compared. The implications of these results for first mirrors and their maintenance in a reactor-class device are discussed.

1. INTRODUCTION

Windows and so-called first mirrors are essential plasma-facing components (PFC) in all optical spectroscopy and imaging systems used for plasma diagnosis both in laboratory applications and in controlled fusion devices. The installation of more than eighty metallic first mirrors is planned in the International Thermonuclear Experimental Reactor (ITER). Detailed knowledge of their performance is crucial for reliable controlling of plasma operation thus having ultimate impact on the reactor safety and the quality of scientific work. Plasma-wall interaction (PWI) phenomena leading to material erosion and migration [1] may be decisive for the state of mirror surfaces and the degradation of their properties. To recognize the extent of changes a thorough First Mirror Test (FMT) has been carried out at the JET tokamak (Joint European Torus) on the request of the ITER Design Team [2–5]. The major goals of the test are to assess the optical performance, i.e. reflectivity, and – by detailed surface analyses – to determine the surface morphology in order to understand the causes of reflectivity changes.

Up to date, FMT has been the most comprehensive study program of mirror behaviour in fusion environments. JET is the most appropriate device for such activity because of the best possible today proximity to reactor conditions: divertor configuration, high power and long pulse operation in the presence of beryllium (Be) on the first wall. Both short- and long-term exposures can be performed during selected pulses or entire campaigns, respectively. The test has comprised a series of steps to ensure maximum outcome for ITER: (i) selection of materials for mirrors, (ii) selection of relevant

location on the main chamber wall and in the divertor of JET, (iii) design and manufacture of mirror carriers, (iv) pre-characterisation of reflectivity and surface properties of the tested mirrors, (v) installation of the optical system for studies of mirrors contaminated by beryllium and tritium during the exposure in JET, (vi) detailed reflectivity and surface studies of the exposed mirrors, (vii) the test of photonic and mechanical cleaning methods [6-8]. The test units with mirrors are installed in JET in the vicinity of other erosion-deposition probes in order to enhance the information on the effects of PWI processes [9,10].

The most important feature of FMT is that it has been carried out with a large number of test pieces under two distinct phases of the JET operation when plasma-facing components are considered: carbon walls coated regularly with evaporated beryllium [11] and ITER-Like Wall (ILW) with beryllium in the main chamber and tungsten (W) in the divertor [12-16]. The first phase, in JET with carbon walls, was completed. Mirrors exposed for up to 80h with 59.6h of X-point operation in 2005–2009 campaigns were examined and described in detail [3–5]. The morphology of all exposed specimens was modified by neutral species although their impact on reflectivity was dependent on the mirror location. The most important results can be summarized in brief by two points. Minimal reflectivity degradation due to co-implantation of neutrals in mirrors facing plasma at a big solid angle in the main chamber. Severe loss of reflectivity measured for all mirrors in the divertor was caused by the deposition of carbon, fuel species, beryllium containing layers, which thickness was exceeding even 20μm. Their removal by photonic means was unsuccessful during the earlier attempts [6,7] but the recent results are more promising [17].

The next phase of the test was continued in JET-ILW and the first step of the program was finished. The aim of this paper is to overview of results obtained following short- and long-term exposures and, to provide a brief comparison between the two phases of the JET operation.

2. EXPERIMENTAL

Two major types of experiments were done under ILW conditions with test mirrors: short- and long-term exposures. The short-term exposure was accomplished for three polycrystalline Mo (Mo–poly) mirrors inserted from top of the torus using the reciprocating probe as a carrier. The probe head was modified for that purpose: stainless steel with three channels for cylindrical mirrors. Images in Figure 1 (a–c) show details of the probe head assembly, the entire 505 mm long probe and its position in JET indicating the maximum radial position with respect to mushroom limiters. The specimens were placed 5–7cm in the shadow of mushroom limiters and exposed during 71 pulses for approximately 1200s (0.3h) [18].

Long-term exposure was performed during the entire experimental campaign with 20 mirrors Mo-poly mirrors of which four specimens were coated with a 1μm thick layer of rhodium (Rh). The coating was produced by magnetron sputtering, as described in [19,20]. Mirrors were installed in carriers: cassettes of pan-pipe shape with channels to cater for installation of specimens at different distance from the channel mouth, 0–4.5cm, thus giving different solid angle and aspect ratio resulting

from the mirror size (aperture) to channel length. The assembly on the main chamber wall and inner and outer divertor was the same as described in [2], while a new design was needed for placing mirrors in the divertor base under the load bearing tile made of pure tungsten [21], as shown in Figure 2. The exposure lasted in total 18.9 h with approximately 13.1h of X-point operation. For comparison, in the presence of the carbon wall some specimens in the inner divertor were exposed during two experimental campaigns, i.e. for totally 80 h.

Before and after exposure mirrors underwent detailed surface analysis using optical techniques to determine total and specular reflectivity, microscopy for surface topography, sputter-assisted X-ray photoelectron spectroscopy (XPS) and a number of ion beam analysis (IBA) including accelerator-based methods and secondary ion mass spectrometry (SIMS).

Before and after exposure mirrors underwent detailed surface analysis using optical methods, ion beam and microscopy techniques. Total reflectivity was measured in the in the range 350 – 1700 nm using a photo-spectrometer (GetSpec) system complying with work procedures on materials retrieved from JET [2], i.e. contaminated with beryllium and tritium [22–24]. The integrating sphere was placed in the glove-box and connected by fibre optics with externally located photo-spectrometers. The second, not-contaminated sphere, was used for pre-characterisation of the mirrors. Full optical characteristic of some specimens from the main chamber wall was performed using a Varian Cary 5 apparatus working in the range 250–2500nm.

Rutherford backscattering spectroscopy (RBS) for heavy metals (e.g. W), and nuclear reaction analysis (NRA) for light nuclei were carried out with a 2.3–2.8MeV $^{3}He^{+}$ beam. NRA was used to quantify deuterium, carbon (^{12}C) and beryllium by detecting protons emerging from the following reactions: $^{3}He(d,p)^{4}He$, $^{3}He(^{12}C,p)^{14}N$, $^{3}He(^{9}Be,p)^{11}B$. Carbon and beryllium were also determined by enhanced proton scattering (EPS) with a 2.3MeV H^{+} beam which allowed simultaneous studies of heavier elements using proton-induced X-ray emission (PIXE). Time-of-flight heavy ion elastic recoil detection (ToF-HIERDA) [25] with 36MeV $^{127}I8^{+}$ ions was used for the quantification and depth profiling of light and heavy nuclei in the very surface region of the mirrors. This is done with a beam impinging on the sample at the angle of 22.5°, whereas the recoils are detected at 135° with respect to the incoming beam. The time-of-flight tube consists of two very thin carbon foils and an implanted silicon solid-state energy detector. When the recoiled species passes through the foils a signal is triggered and the flight time can be measured. To reduce the noise, the signal from the second foil is used as the start signal for the timing and, the signal from the first detector is delayed and then used as the stop signal [25]. Finally the total remaining energy of the recoil is collected by the solid-state detector. The reversed flight time and the energy gives banana-shaped traces for each recoiled mass from which the depth distribution can be calculated for smooth surfaces [26]. Secondary ion mass spectrometry (SIMS) with a VG IX70S double focusing magnetic sector equipment allowed depth profiling of deuterium, beryllium (^{9}Be), carbon (^{12}C), nickel (^{58}Ni), molybdenum (^{98}Mo) and rhodium (^{103}Rh). The analyses were performed using primary oxygen beam (O_2^{+}, 5keV, ion current 250 nA). The sputtering at the rate of 0.35 nm/s was done on areas

$300\times220\mu m^2$. Topography was determined using scanning electron microscopy (SEM) with a field emission gun (Zeiss Gemini), whereas composition was studied with energy dispersive X-ray spectroscopy using an Oxford Instruments detector. X-ray photoelectron spectroscopy (XPS) was used to study the material mixing on some mirrors from the main chamber wall. Chemical shift of the core levels: Rh3d, Mo3d, O1s, C1s was determined. Surface and sub-surface composition was studied using ion and electron beam methods. The application of XPS, HIERDA and SIMS has ensured a complementary set of data: information from only the very surface layer (up to 3nm) by XPS and high sensitivity depth profiling by HIERDA (up to 200nm) and SIMS (over 1μm).

3. RESULTS AND DISCUSSION

3.1. VISUAL INSPECTION

In total 20 test mirrors were retrieved from the JET vessel during the first shutdown since the start of the ILW operation. During this campaign ten mirrors we exposed in the mid-plane on the outer wall of JET while other ten mirrors were located in various areas in the divertor: three in the outer and inner, and four under the load bearing plate.

Already during the first visual inspection all divertor mirrors appeared to be covered by smooth colourful layers shown in Figure 3(a–c). Only in one location (mirror at the channel mouth from the inner divertor) deposit on the mirror surface was delaminating as can be seen in Figure 3(a). No flaking or detachment of the deposited layers was observed on all other mirrors.

All specimens exposed in the main chamber, both the long-term samples from the midplane holders on the outer wall and the short-term probes exposed from the top of the machine, look clean and shiny after exposure. This observation is notably different from the results after JET operation with the carbon wall where small deposition was seen only on the mirrors located near the channel mouth (0cm and 1.5cm), while significant amount of deposition was observed on the wall mirrors placed deeper (3cm and 4.5cm) in the cassette channels [3–5].

3.2 REFLECTIVITY MEASUREMENTS

Total reflectivity of all exposed mirrors was measured and compared to the reflectivity values recorded prior to exposure in 2009. Plots in Figure 4 show the initial and post-exposure reflectivity of mirrors exposed in the inner divertor (a), outer divertor (b) and under the divertor base (c). Reflectivity of all Mo-poly and rhodium-coated mirrors degraded in all locations in the divertor. There are two major features: (i) the greatest loss of total reflectivity is measured for the mirrors located at the channel mouth, i.e. at 0cm; (ii) the most significant loss, by 50–85%, is in the visible range, although there are cases when the poor total reflectivity is measured over the entire spectrum, e.g. inner divertor, 0cm.

During the previous exposures of mirrors in JET with carbon wall a clear dependence between the reflectivity and the depth in the cassette channel was observed. The reflectivity loss for mirrors close to plasma was larger than deep in the channel [3–5]. The recent results after exposure in JET-

ILW do not fully follow this pattern. The only location where a clear dependence on the channel depth exists is the inner divertor, see Figure 4 (a). This difference can be related to the morphology of the deposits, as discussed in Paragraph 3.3.

Total reflectivity of two sets of mirrors (five mirrors each) from the main chamber wall is shown in Fig.5 (a,b). There are several important features. First of all, total reflectivity of most Mo-poly mirrors has not been degraded. On the contrary, even a small improvement by a few per cent can be perceived in the spectral range 500–800nm. Secondly, only one front (0cm) mirror shown in Fig.5 (b) suffered big reflectivity loss. This difference between front mirrors from the two cassettes is most probably associated with the wall geometry in the positions where the mirror carries were installed. The mirror showing poor optical performance was located only 24cm from the outer poloidal limiter (OPL). On its side facing the cassette there are molted areas as found by detailed inspection of high-resolution photographic documentation. The other cassette was 33cm from the nearest OPL and 67cm from the Faraday screen of the lower hybrid antenna, but no proof of the Be melting was observed on those wall components. The third point is concerned with the Rh-coated mirror. The surface having originally very high reflectivity has significantly lost the performance which decreased to the level typical for Mo-poly mirrors in most of the spectral range under examination. There are some differences between the total reflectivity of respective mirrors and there are no two mirrors whose performance changed in the identical way. In general mirrors from the wall belong to three categories when the total reflectivity is considered: (i) not affected or even slightly improved; (ii) small reflectivity loss; (iii) significant reflectivity loss as observed in single case, as mentioned above. The reasons for such behaviour are discussed in Section 3.3.2. For the mirrors of the second category (partial reflectivity loss) there has also been measured a loss of specular reflectivity. It is shown in Figure 6. The degraded performance is observed in the entire spectral range (250–2500nm) but the most significant decrease is in the UV range (250 – 400nm). It is caused by the presence of impurities including oxygen.

The issue of oxygen impurity is of particular importance. Oxygen and water vapour adsorption or even the formation of a thin surface oxide layer (MoO_3, MoO_2) is unavoidable. Mirrors prior to the JET operation are exposed to air and during the pump-down phase they are subject to adsorption of residual gases such as carbon monoxide. In the case described in the paper, the time interval between the mirror production and installation on the holders and, eventually, the pump-down of the torus was over 3.5 years. Two pre-characterisations were performed with the interval of two years: after the production (using Varian Carry 5) and then before the installation (using GetSpet equipment at JET). The results for two mirrors are shown in Fig.7. There is a difference (decrease) which rather cannot be simply attributed to possible inaccuracy in measurements by both types of photo-spectrometers. The data from the later measurements are taken as a reference level for discussion of reflectivity. The reflectivity decrease over two years is most probably associated with the growth of the Mo oxide in air. In this sense, the optical properties of Mo surfaces exposed in JET are lower than could be expected from calculations based on data given by Palik [27]. Also

the retrieval from the torus and storage before the analyses is not done in vacuum. All handling is done remotely [11-13]. A vacuum-tight transfer system would have impractical complexity and it would be prohibitively expensive. Therefore, the operation with test mirrors at JET reflects a realistic situation expected also in ITER when ample time will pass between the mirror installation and pump-down of the torus. One may assume that operation under the surface bombardment with energetic particles, i.e. fluxes of neutral hydrogen isotopes, will at least partly remove oxygen species from the mirror surface.

In summary, for most wall mirrors a small improvement of the total reflectivity in the visible range was observed. A similar result was reported for the mirrors exposed during the JET operation with carbon wall where an improvement of reflectivity was recorded for wall mirrors installed close to the channel mouth [5]. The nature of this effect is most probably related to the modification of mirror surfaces due to erosion-deposition processes in the ILW environment with a decreased amount of carbon impurities [16] in comparison to JET with C walls [28]. Therefore, very thorough surface studies have been initiated, as detailed in the next section.

3.3 SURFACE MORPHOLOGY

3.3.1 Mirrors from the divertor

The surface layer composition was determined by several complementary IBA techniques for mirrors retrieved from JET. Figure 8 shows a HI-ERDA spectrum for a Rh-coated mirror from the outer divertor, 1.5cm deep in the cassette. Features of hydrogen isotopes, beryllium-9, carbon-12, nitrogen-14, oxygen-16 and inconel components are clearly identified. There are also traces of tungsten. The shape of all those lines clearly indicates the presence of a deposited surface layer (250 – 300 nm) on rhodium. Plots in Figure 9 are detailed depth profiles determined from the HI-ERDA for a Rh-coated mirror from the inner divertor, 1.5cm from the channel mouth. Atomic density (10^{15} atoms/cm^2/nm) of eight species is given. From these data one infers the absolute content of elements (isotopes for light nuclei) and the structure of the layer, and – from this – a history of deposition which reflects the history of plasma operation.

The co-deposit thickness is around 100nm (where only Rh is detected), but the interface is fairly broad, approximately 50nm where features of Rh and other species are mixed. This width can be associated with two reasons: the beam spot area and material mixing. The beam impinges at a grazing angle thus resulting in a relatively large and elongated beam spot area of 1.2×4mm. Some non-uniformity in the layer thickness, surface imperfections in the mirror surface and small variations in the concentration may have an impact on the pattern in the deposit-surface interface. The second point is inter-diffusion of components when the mirrors were for one year and a half at elevated temperature of approximately 250^{o}C. The major components are beryllium, carbon, nitrogen, oxygen and deuterium, but their profiles are different. The Be content is high and fairly uniform. The oxygen feature has two maxima: at the surface and at the interface what is most probably associated with its adsorption on the exposed surface and on the original mirror when it was installed in JET. The

region from 25nm to 75nm informs about the oxygen impurity deposition during plasma operation. This resulted in the oxygen content 5-7 lower than at maxima. Carbon is found predominantly at the depth of 60–100nm, thus corresponding to the initial period of the JET-ILW operation. At the smaller depth the content decreased by a factor of about seven what agrees with spectroscopy measurements of C impurity species [15,16,29]. The concentration of nitrogen increases towards the deposit surface thus reflecting the history of the H-mode operation associated with N2 impurity seeding predominantly done during the second half of the operational campaign. The profile of deuterium shows some variations, but its concentration is in general fairly low. However, the most striking feature is the presence of tungsten in the deposit and a "wavy" structure of the W feature. Its content is low but rising with a sharp increase at the surface of the deposit corresponding to the increase of heating power in JET operation. The increase of the W signal is also accompanied by the appearance of the nickel what may indicate its erosion from the antennae grills or even damage to the beryllium coating on Inconel cladding tiles. Both metals have also been recorded with SIMS. In Figure 10 depths profiles of several elements are collected for the front mirror from the outer divertor. SIMS is very sensitive hence traces of W and Ni are identified. Although no quantitative conclusions can be drawn [30], the profiles clearly display the "wavy" structure of deposition of those heavy species. This confirms qualitatively HI-ERDA results thus indicating that metals could appear in off-normal leading to high heat deposition and, eventually to enhanced sputtering or even evaporation followed by the deposition of neutrals in the shadowed regions.

Figure 11 gives an overview of the quantitative deposition of different species on all three mirrors in the inner divertor, as measured with NRA, RBS and HI-ERDA. Integrated amounts in the entire co-deposited layers are given. The concentration of all species decreases with the depth in the channel. The main element is beryllium (up to $5x10^{18}$ at cm^{-2} in the thickest layer) accompanied by smaller amounts of carbon and deuterium. Oxygen, as discussed earlier, comes partly from air during the storage of mirrors in atmosphere following their retrieval from the torus. Data for all divertor mirrors are summarized in Table 1. The greatest numbers in each column are for the front mirrors in a given cassette. Besides C, Be and D tungsten is found in all deposits. Although the quantities are small ($< 7.0 \cdot 10^{16}$ at/cm^2) the presence of tungsten in co-deposits must be taken into account when cleaning techniques of mirrors are considered. Another remarkable feature is a high level of nitrogen retained in the layers. This result is in line with earlier works showing the retention of nitrogen following edge cooling with by impurity seeding in operation with tungsten PFC [31-33].

In the inner and outer divertor the thickness of deposits on mirrors is varying from 40–100nm for mirrors located in the deepest cassette channels (4.5cm) to over 600nm for the closest to plasma mirrors (0.0cm). Smaller level of deposition is observed on the mirrors located in the divertor base (see images in Fig.2) and the thickest deposited layer was not exceeding 160nm. This significant difference between the deposition in the base and other parts of the divertor points to impact of operation scenario on the material transport. Operation in ELMy H-mode carried out predominantly

on Tiles 3 and 5 [15] could enhance metal sputtering and, consequently, the material transport to the inner and outer divertor. Transport in a form of volatile BeD_2, as considered in [32], cannot be fully excluded.

In summary, the layer thickness on neither specimen from the inner divertor exceeds 600−700nm, i.e. it s much smaller than in JET with carbon wall when layers thicker than 20μm were found [5]. Taking into account that the operation time in JET with the carbon and metal walls the deposition of C atoms per hour in JET-ILW is at least 10 times lower than in the presence of carbon. This number is in full agreement with the decrease of carbon fluxes determined in the divertor with spectroscopy [15,16].

3.3.2 Mirrors from the main chamber wall

Figure 12 (a, b) shows the surface composition the mirrors facing plasma in the main chamber. In the HI-ERDA spectrum, Fig.12 (b), one identifies deuterium, beryllium, carbon and oxygen with some admixture of Inconel components. All features indicate very low concentrations of these elements being present only in a very surface layer. This is confirmed by depth profiles, Fig.12(b), which show that Mo is the main element and, that the modified layer does not exceed 20−30nm. Small amount of residual carbon is identified as a main impurity. It should be stressed that the above described data are for the mirror located 3cm deep in the channel. The surface appears to be fairly clean, while during the JET operation with C walls mirrors placed at that depth were fully coated by carbon deposits [3-5]. In JET-ILW seven of ten mirrors exposed in the main chamber have revealed high total reflectivity. see Paragraph 3.2 and Fig.5. In general, concentrations of impurity species on those seven mirrors are very low, as shown in Table 2, and the thickness of the modified layer is in the range 10–30nm. The quantities of impurity species are very small and for most mirrors they do not exceed the level of $2 \cdot 10^{16}$ at/cm^2. In the second column there are results for two mirrors (Mo-poly and Rh-coated, both at 1.5cm deep in the channel) which partly lost total reflectivity in the UV range, as it was proven by measurements with Varian Carry 5 equipment. The data in Table 3 show the very surface composition, first 3 nm, determined with XPS for both categories of mirrors: two specimens which retained reflectivity and two which partly lost the performance. In all cases the thin surface region contains light impurities mentioned above (especially large oxygen content) and small quantities of metals such as Ni, Fe, W and Cu. Elements are in the form of compounds, mainly oxides and, in the case of carbon, carbide or a-C:H. The most important issue is the presence of the substrate material: Mo or Rh. There is a direct correlation between the presence of those metals and reflectivity: surfaces where the original substrate material is identified retained reflectivity, whereas lack of Mo or Rh has lead to the degradation of performance. It should be stressed that all mirrors were placed 1.5cm deep in the channel. The set of good performance was in the cassette not affected by Be release from the outer poloidal limiter, while the other two mirrors were close to the molten side of the limiter. The data for the front mirror located near OPL are in the last column of Table 2. Only on that single mirror (of the set of ten) a greater amount of

beryllium, but not carbon, was found. The thickness of that Be-rich layer is about 60−70nm. It is important to state that only traces of tungsten and no nitrogen have been detected on any specimen thus indicating that these impurities are confined in the divertor; for comparison see Fig. 8 and Table 1. In summary, the results obtained in JET-ILW confirm prediction from the studies of mirrors exposed on the main wall in the presence of carbon walls [5].

CONCLUDING REMARKS

The study carried out with twenty test mirrors in JET-ILW prove that the morphology of all exposed surfaces have been modified, but the impact of the PWI processes on the divertor and main chamber mirrors is significantly different. All mirrors from the divertor lost reflectivity by 50%−85% because of Be, C, N, O and W deposition. The amount of deposition and the corresponding layer thickness are smaller than those formed in JET with carbon walls, but the extent of optical degradation is quite similar. Tungsten deposition on the divertor mirrors is probably the most important fact because that element, especially in the case of a thick layer, would to very hard to remove by cleaning techniques. It points to the need of looking for alternative solutions for optical components in ITER divertor diagnostics. With massive deposition even a periodic exchange of mirrors would be of limited use or even fully impractical.

Reflectivity of mirrors on the main chamber wall has changed minimally although a presence of a modified surface has been clearly detected by sensitive quantitative measurements of high depth resolution. The modified layer in most cases is thin and it contains small amount of mainly low-Z impurities in the surface/sub-surface region of a metal mirror (Mo or Rh). Although the layer does not resemble co-deposits, such as found in the divertor, its morphology is a net result of erosion and deposition processes, where deposited light species were efficiently removed by the incoming flux of neutral particles. The presence of impurities is related to several processes including shallow co-implantation. With particles of 200−300eV this would result in the implantation of less than only 3nm. A greater extent of the layer indicates that the layer 10−30nm thick can be a result of impurity diffusion when mirrors are at the wall temperature of 250^{o}C. The other probable factor is a deposition in small imperfections on mirror surfaces. Equilibrium between the incoming and eroded particle fluxes might even prevent the mirror surface from sputter erosion. The bombardment by energetic hydrogen neutrals occurring under hydrogen-rich atmosphere on materials maintained at 250^{o}C could clean the mirror by removing a thin oxide layer and other species adsorbed (e.g. O_2, N_2,) on surfaces when they were exposed to air prior to the mirror installation in JET and during the pump down phase of the vacuum vessel, when CO is one of the main residual impurities.

In summary, there is no simple explanation how the formation of modified surface layers influenced the preservation of reflectivity. It is a consequence of several processes occurring simultaneously under dynamic conditions. The quantities of elements and the extent of the modified layer are small thus making it difficult to assess which process is decisive. As the end effect, the material mix formed on the surface shows reflectivity at the level typical for molybdenum. This

could partly explain why the reflectivity of Mo-poly and Rh-coated mirrors is nearly the same. In the visual range the total reflectivity is similar to the one shown by beryllium surfaces [35]. One may expect that a similar set of phenomena will occur in ITER. The data indicate that the reflectivity of diagnostic mirrors in systems installed in the main chamber might not be degraded by thick deposits unless large amounts of Be are locally released from the wall by off-normal events. There is no doubt that maintenance of the mirror performance will be needed. A practical solution for mirrors in the main chamber diagnostics can be based on a periodic evaporation of a fresh molybdenum layer on the mirror surface. This approach, limited to mirror surfaces without flaking layers, can be applied in-situ and its implementation and application is more realistic than photonic cleaning, application of protective filters, local plasma or gas puff or and other methods critically assessed in earlier works [3,6,8]. To implement an evaporation is challenging but it is less complex that the installation of a mirror exchanger, as discussed in [3].

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Species	**Divertor (10^{15} at/cm^2)**		
	Inner	**Base**	**Outer**
Be	170 – 4500	185 – 850	1350 – 4960
C	20 – 930	27 – 330	88 – 685
W	2 – 68	18 – 70	2 – 63
D	120 – 1600	105 – 229	287 – 1000
N	61 – 387	17 – 57	38 – (> 137)
O	100 – 1391	310 – 457	291 – (> 650)

Table 1: Composition of co-deposits on the test mirrors exposed in the divertor.

Species	Improved reflectivity	Small reflectivity loss	Big reflectivity loss (1 mirror)
Be	1.0 – 15	53 – 76	486
C	24 – 44	not determined	47
D	5 – 11	7 – 18	26
O	14 – 90	not determined	115
Ni	not detected	not determined	5

Table 2: Composition of the modified layers on the test mirrors exposed on the main chamber wall. Data, 10^{15} at/cm^2, are for three categories of mirrors with the changed total reflectivity.

Mirror	Mirror material	% Mo	% Rh	% Be	% C	% W	% O	% Fe	% Ni	% Cu
1.5 cm (97)	**Mo**	11.3		27.1	26.3	1	30.9	2.3	0.7	0.4
1.5 cm (98)	**Mo**	5		36	19.6	0.4	34.9	3.7	0.3	
1.5 cm (93)	**Mo**	0.8		33	27		36.3	2.6	0.4	
1.5 cm (61)	**Rh**		0.4	24.3	41.3	Trace	31	2.5	0.3	

Table 3: Composition of the surface layer (3nm) on mirrors exposed to plasma on the main chamber wall

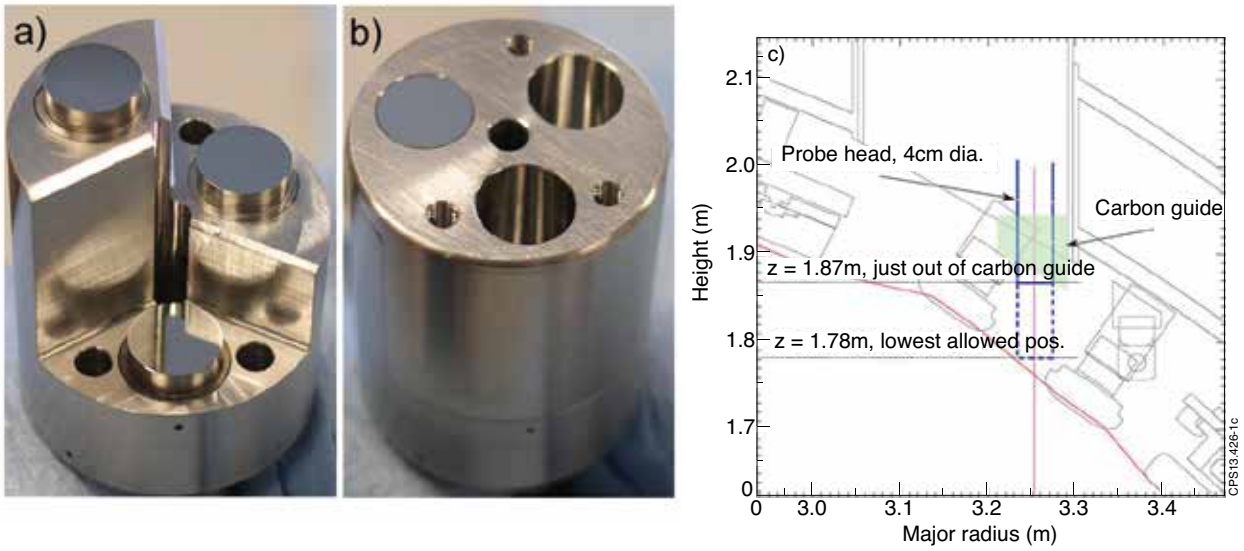

Figure 1: The assembly of mirrors on the reciprocating probe head: (a) holder with three installed mirrors; (b) the stainless steel probe head with installed mirrors; (c) position in JET.

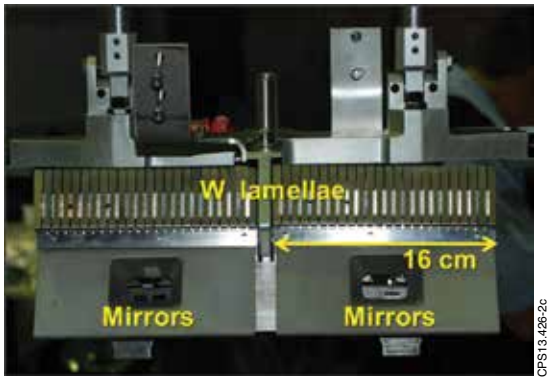

Figure 2: Cassettes with mirrors under the tungsten load bearing tile in the divertor base.

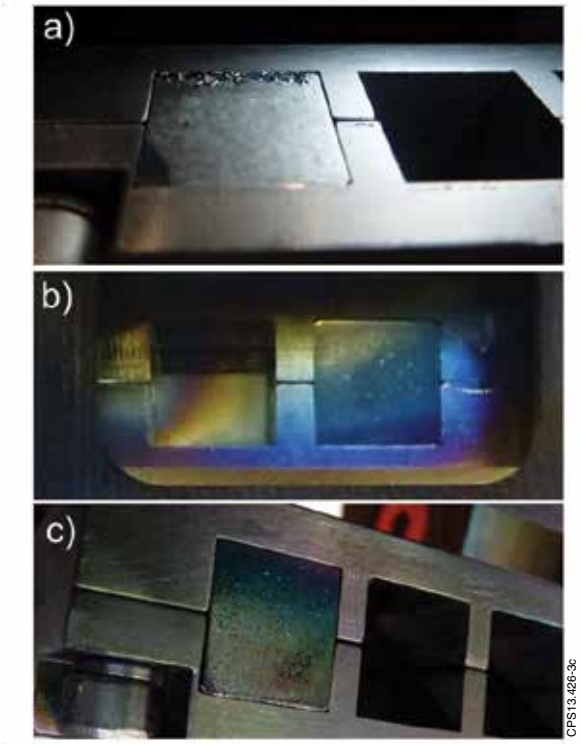

Figure 3: Surface of the test mirrors exposed in the JET divertor: (a) outer divertor; (b) divertor base; (c) inner divertor.

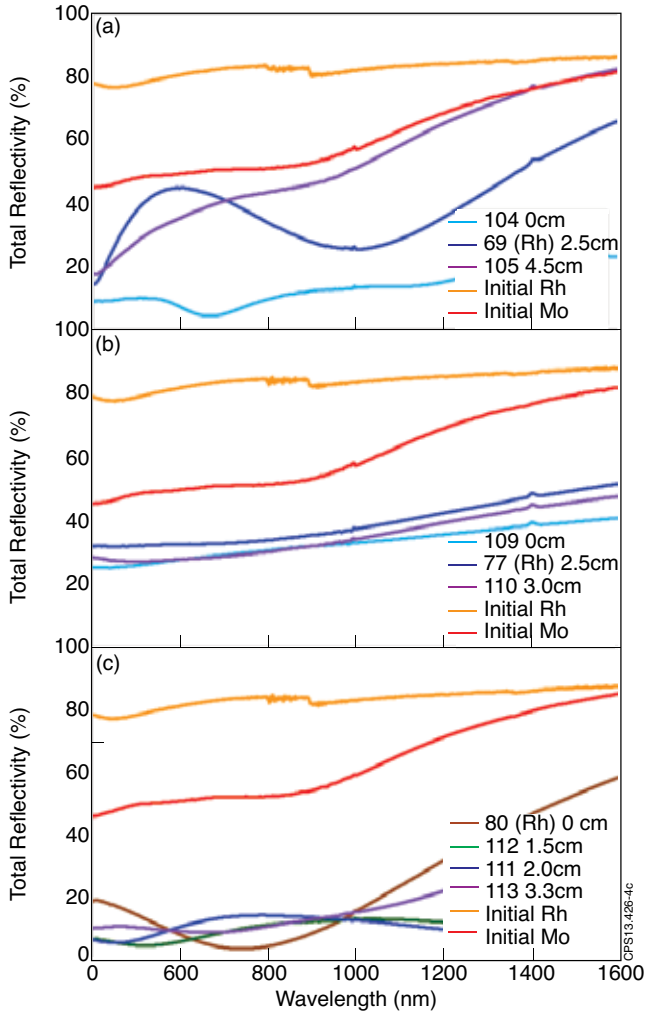

Figure 4: Total reflectivity of test mirrors exposed in JET with ITER-Like Wall. Reflectivity is shown for mirrors exposed: (a) in the inner divertor; (b) in the outer divertor; (c) under the divertor base.

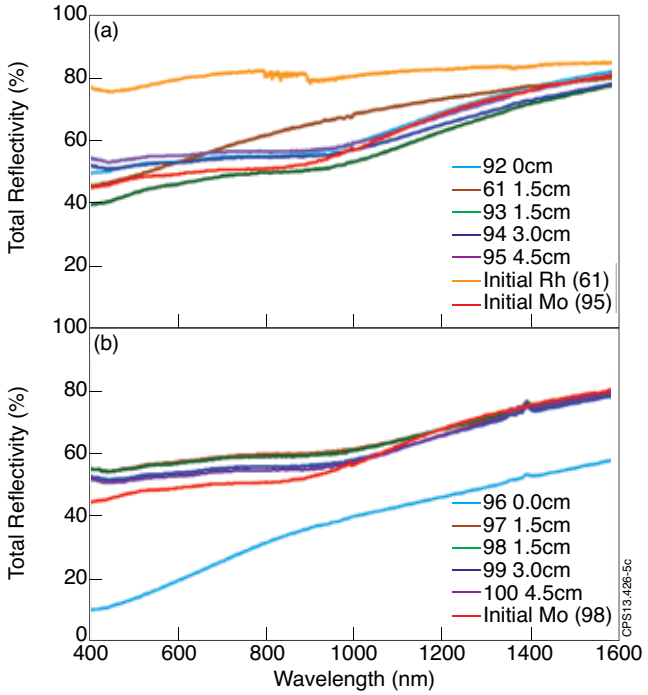

Figure 5: Total reflectivity of test mirrors from two cassettes located on the main chamber wall of JET-ILW.

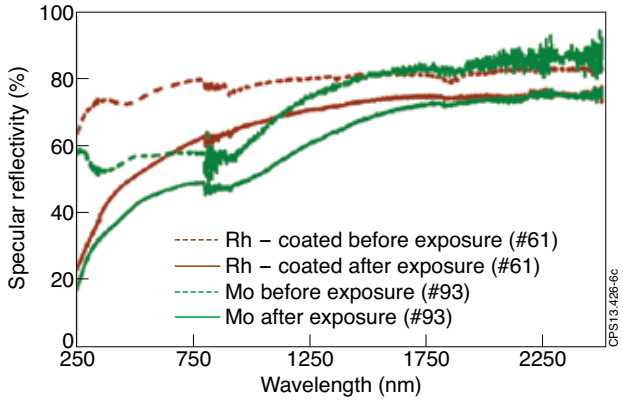

Figure 6: Specular reflectivity of molybdenum and Rh-coated mirrors which partly lost performance after exposure on the main chamber wall of JET-ILW.

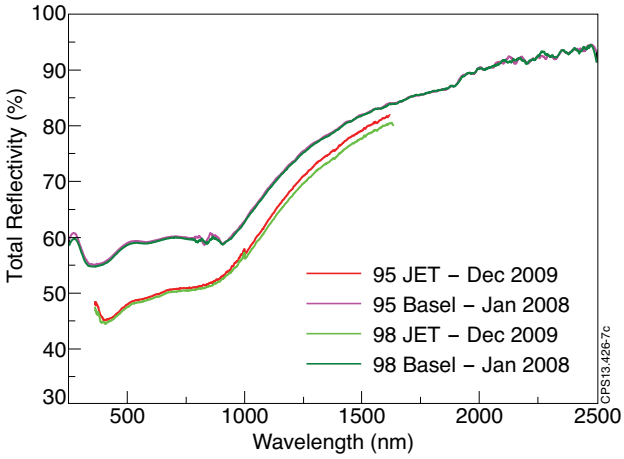

Figure 7: Total reflectivity of Mo-poly mirrors measured twice at time interval of two years storage before exposure to plasma.

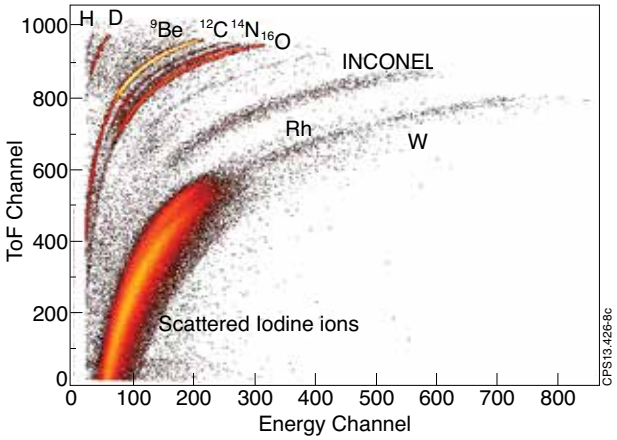

Figure 8: HI-ERDA spectrum for the Rh-coated mirror from the outer divertor located in the cassette 1.5cm from the channel mouth.

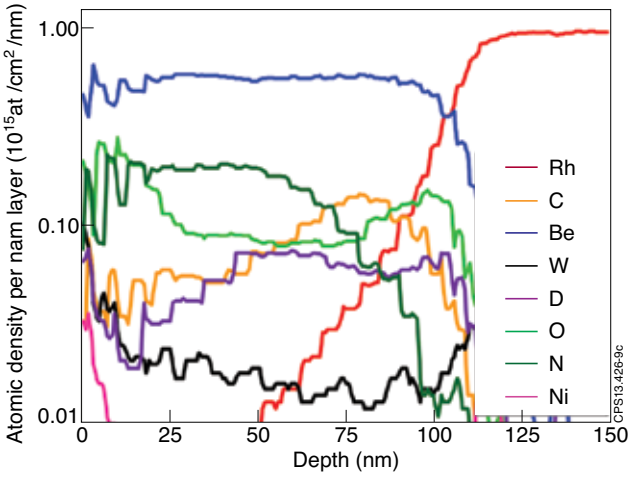

Figure 9: HI-ERDA depth profiles of co-deposited elements on the Rh-coated mirror from the inner divertor located in the cassette 1.5cm from the channel mouth.

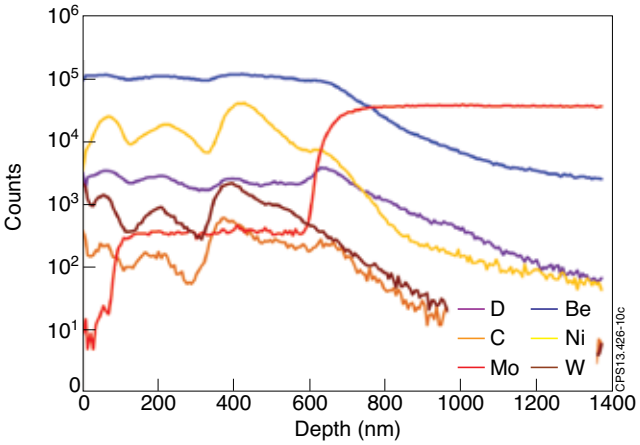

Figure 10: SIMS depth profiles of co-deposited elements on the front mirror from the outer divertor.

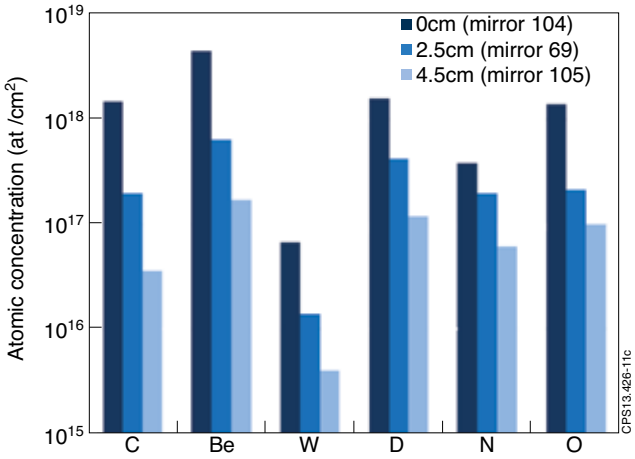

Figure 11: Quantitative elemental composition of co-deposits on all three mirrors from the inner divertor.

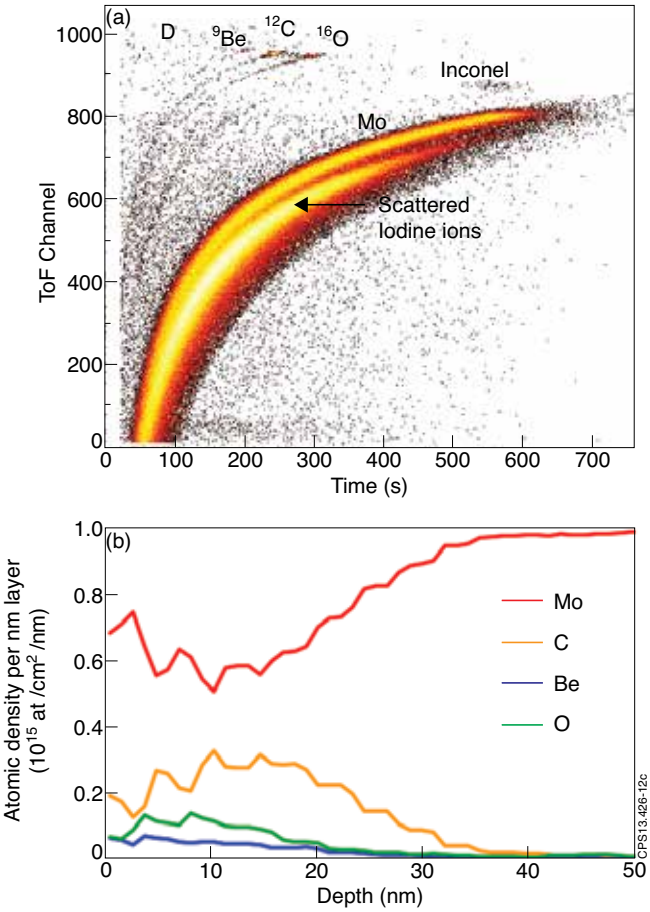

Figure 12: HI-ERDA spectrum (a) and depth profiles (b) for a Mo-poly mirror from the outer wall located 3 cm deep in the channel (#99).

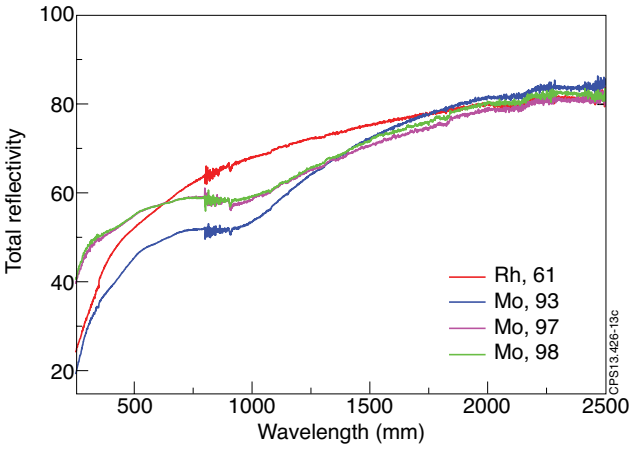

Figure 13: Total reflectivity of Mo-poly and Rh-coated mirrors after the exposure on the main chamber wall,1.5 cm deep in the cassette channel in all cases. The data are for two categories of specimens detailed in Table 2: with maintained high reflectivity and partly lost performance.