Comprehensive First Mirror Test for ITER at JET with Carbon Walls

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Abstract. Metallic mirrors will be essential components of all optical spectroscopy and imaging systems for plasma diagnosis that will be used on the next-step magnetic fusion experiment, ITER. Any change of the mirror performance, in particular reflectivity, will influence the quality and reliability of detected signals. On the request of the ITER Design Team, a First Mirror Test (FMT) has been carried out at JET during campaigns in 2005-2007 and 2008-2009. To date, it has been the most comprehensive test performed with a large number of test mirrors exposed in an environment containing both carbon and beryllium; the total plasma time (in 2005-2007 period) over 35 h including 27 h of X-point operation. 32 stainless steel and polycrystalline molybdenum flat-front and 45^{o} angled mirrors were installed in separate channels of cassettes on the outer wall and in the Mk-II HD divertor: inner leg, outer leg and base plate under the load bearing tile. Post exposure studies comprised reflectivity measurements and surface analyses with microscopy, secondary ion mass spectrometry, ion beam analysis and energy dispersive X-ray spectroscopy.. The essential results are: (i) on the outer wall high reflectivity (~90%) is maintained for mirrors close to the channel entrance but it is degraded by 30-40 % deeper in the channel (ii) reflectivity loss by 70-90% is measured for mirrors placed in the divertor: outer, inner and base; (iii) deuterium and carbon are the main elements detected on all mirror surfaces and the presence of beryllium is also found; (iv) thick deposits show rough columnar structure and thickness is 1-20 μm; (v) bubble-like structures are detected in deposits; (vi) the deposition in channels in the divertor cassettes is pronounced at the very entrance; (vii) photonic cleaning with laser removes deposits but the surface is damaged by laser pulses. In summary, reflectivity of all tested mirrors is degraded either by erosion with CX neutrals or by the formation of thick deposits. The implications of results obtained for first mirrors in next-step device are discussed and critical assessment of various methods for in-situ cleaning of mirrors is presented. The conclusion is that engineering solutions should be developed in order to install shutters or to implement a cassette with mirrors to replace periodically the degraded ones

1. Introduction

All optical spectroscopy and imaging systems for plasma diagnosis in ITER (International Thermonuclear Experimental Reactor) will rely on metallic mirrors; so-called first mirrors acting as essential plasma-facing components (PFC) for various diagnostics. It is planned to install in ITER over 80 first mirrors located at different distances from the plasma with some as close as 14 cm. It is reasonable to expect that erosion and deposition processes arising from plasma-wall interactions [1] might significantly change the performance of mirrors, i.e. reflectivity, thus having serious impact on the quality and reliability of detected signals which are vital for the plasma control and the safety of reactor operation. For this reason, on the request of the ITER Team, First Mirror Test (FMT) has been carried out at JET in order to

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* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

test the behaviour of mirrors under long-term exposure to fusion environment containing both carbon and beryllium [2,3]. Testing of mirror has been carried out in several tokamaks [4] but, to date, the test in JET has been the most comprehensive experiment performed with a large number of specimens located both in the divertor and on the main chamber wall.

The entire research program comprises: (a) the selection of material for test mirror, (b) manufacture of mirrors and their carriers for in-vessel installation, (c) optical pre-characterisation, (d) exposure in the plasma boundary of JET for a complete operational campaign, (e) a broad range of post exposure analyses by means of optical and surface analysis method, (f) correlation with erosion-deposition pattern measured by other wall diagnostics used in Tritium Retention Studies (TRS) [5] and (g) photonic cleaning of the exposed mirrors [6] followed by the analyses of cleaned surfaces. The intention of this paper is to provide an account of the characterization of the mirrors and their carriers: (i) the correlation between the surface state (composition and structure) and optical properties; (ii) the deposition inside channels; (iii) mirror properties after laser-assisted cleaning.

2. Experimental

Details of the entire technical the program (design of mirrors and their carriers and installation in the torus) have been presented earlier [2], hence, only a brief summary of essential elements is given below. 16 stainless steel (316L) and 16 polycrystalline molybdenum mirrors were tested. The material selection was based on the advice of the ITER Design Team. Flat-front and angled (45^o) mirrors were manufactured: blocks ($1x1x1\ cm^3$) with the plasma-facing surface of $1x1\ cm^2$ (flat-front) and $1x1.4\ cm^2$ (chamfered). Each mirror had a “leg” for unmistakable mounting in a “pan-pipe” shaped cassette with either three or five channels dependent on the availability of space in the place of installation. Cassettes were composed of two detachable plates in order to enable qualitative and quantitative studies of the composition of deposits along the channel. The mirrors were fixed in channels at different distance from the channel mouth: 0; 1.5; 3; 4.5 cm. Six units were installed in three locations in the divertor: inner leg, outer leg and under the load bearing tile on the base. Images in Fig. 1 (a) and (b) show respectively the virgin mirror samples (flat and angled) and cassettes installed on the outer divertor carrier. In all locations the cassettes were mounted in the vicinity of deposition-erosion monitors for TRS [5]. Two units with 5-channel cassettes, one with Mo and another with steel mirrors, were placed vertically (poloidal direction) on the outer wall in Octants 3 and 4, respectively. The unit installed in Octant 3 near the beryllium evaporator was equipped with a magnetic shutter protecting three mirrors placed near the channel mouth, as shown in Fig. 1 (c). Mirrors sitting deeper in the channel (3.0 and 4.5 cm) were not protected. This arrangement allowed for a check of possible impact of wall conditioning on reflectivity. The distance of mirrors in wall units to plasma was over 42 cm (mouth of the channel), whereas in the divertor it was 10 to 14.5 cm. The range of solid angles for particle bombardment (Ω_{PB}) was $6.3x10^{-3}$ - $5.5x10^{-2}$ sr. The solid angles and aspect ratio (depth in channel to aperture width: 1.5-4.5) simulated the experimental situation of many mirrors planned in ITER.

Total exposure time during 7048 pulses was 126 600 s (35 h) including 96900 s (27h) of X-point operation. This corresponds by divertor operation time to about 240 ITER pulses lasting 400 s. However, this would be only 7-8 pulses scaled with energy input or less than one ITER pulse when divertor fluxes are considered, as assessed by Pitts [7]. During the 2007 shut-down, 7 cassettes with 29 mirrors were removed for visual inspection and determination of total reflectivity and surface composition. Optical measurements were done in the range 400-1600 nm using equipment specially designed for handling materials contaminated by beryllium and tritium, for details see [2]. Surface composition was studied by means of several complementary methods: (a) scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX); (b) secondary ion mass spectrometry (SIMS); (c) ion beam analysis (IBA) using nuclear reaction analysis (NRA) with a 2.5 MeV $^3He^+$ beam and enhanced proton scattering (EPS) using a 2.5 MeV H^+ beam. IBA methods have also been applied to determine the distribution of deposition inside the channels of cassettes.

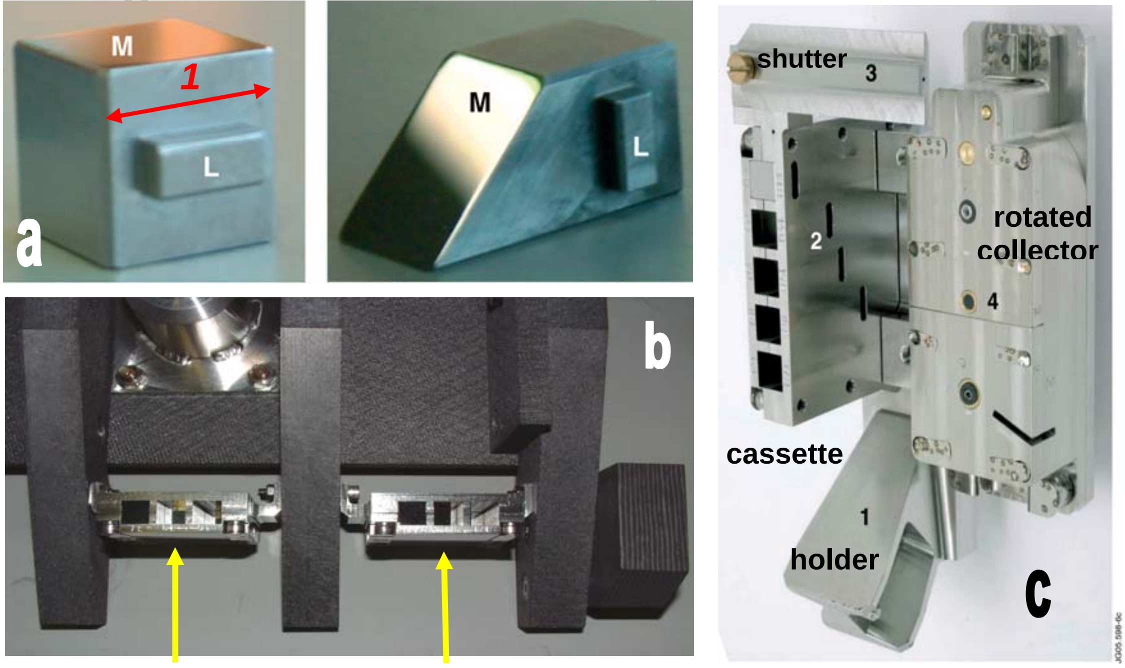

FIG. 1. (a) Flat-front and angled mirror samples: "L" denotes the leg for sample fixing and "M" stands for the mirror surface. (b)Cassettes with mirrors installed between the ribs on the outer divertor module; for clarity of view the Tile 7 blocks have been removed. (c) Bracket assembly for installation of mirrors and deposition monitors on the main chamber wall.

The surfaces of several exposed mirror were cleaned using a scanning YAG laser system. The "one pulse" damage threshold determined experimentally defined the maximum laser fluence to which the mirrors were exposed during the cleaning trials. The ranges of laser fluence used were 1.17-2.25 J/cm^2 and 2.80-6.34 J/cm^2 for steel and Mo mirrors, respectively. Following the irradiation surface properties were studied with optical and surface analysis methods.

3. Results

3.1 Surface Composition

Images in Fig. 2 (a) show the appearance of Mo mirrors retrieved from the divertor base, whereas steel samples (not protected by shutter) from the main chamber wall. The position of mirrors in cassettes is given, i.e. depth in channels. The quality of images is somewhat obscured by photographing through a window of the isolator. Visual inspection reveals distinct differences between mirrors from the two locations. Surfaces of all mirrors from the divertor are coated with deposits. In some cases, the layer had flaked and peeled-off. This process must occur *in-situ* during the exposure because discoloration is seen on the flake-free surface thus indicating the formation of a new co-deposit. It is impossible, however, to conclude whether the flaking happened only once or several times during the long-term exposure. For mirrors from the outer wall the picture is more complex. As shown in Fig. 2 (b), three Mo mirrors positioned near the mouth of the channel (0 and 1.5 cm protected by the shutter) are nearly free from a visible co-deposit, but some surface imperfections could be observed. Only a narrow deposition belt is noted on the chamfered surface. Mo samples from deeper locations (3 and 4.5 cm) are partly (not the whole surface) coated by thick films. Very similar deposition pattern also developed on steel samples located deep in the channel. These results suggest that deposition on all mirrors in wall units took place during tokamak discharges and it was not connected with wall conditioning. Some differences in deposition, like those observed on two adjacent steel samples at 1.5 cm, are probably related to some local geometrical effects that are difficult to identify having in mind the complexity of wall structures in JET.

Details of surface features are shown in Fig. 2 (c-e) for mirrors from three different locations: steel sample from the outer wall (1.5 cm in channel), Mo from the divertor base (channel mouth) and steel from the inner divertor (4.5 cm in channel), respectively. The formation of chains of bubble-like structures in Fig. 2 (c) may be considered as a precursor state for the layer detachment, disintegration and peeling-off. There are several factors that can contribute to this. There is a significant mismatch of thermo-mechanical properties between the metal surface polished to mirror quality and the carbon-based film. Possible temperature excursion during plasma operation or wall baking may introduce internal stress. Such stress in the film poorly adhered to the mirror surface causes detachment. It is difficult to conclude which factors prevail in the film disintegration. From the practical point of view the most important thing is that such processes occurring in the diagnostic channel would be a strong source of dust which can be charged and levitate thus obscuring the quality of spectroscopic measurements. Careful examination of the cracked deposit, Fig. 2 (d), reveals both granular and stratified structure of the film which has a thickness of about 3-5 μm. The deposit formed in the inner divertor Fig. 2 (e) shows a rough, dusty-like structure which is similar to that observed several times on PFC from other tokamaks [8-11].

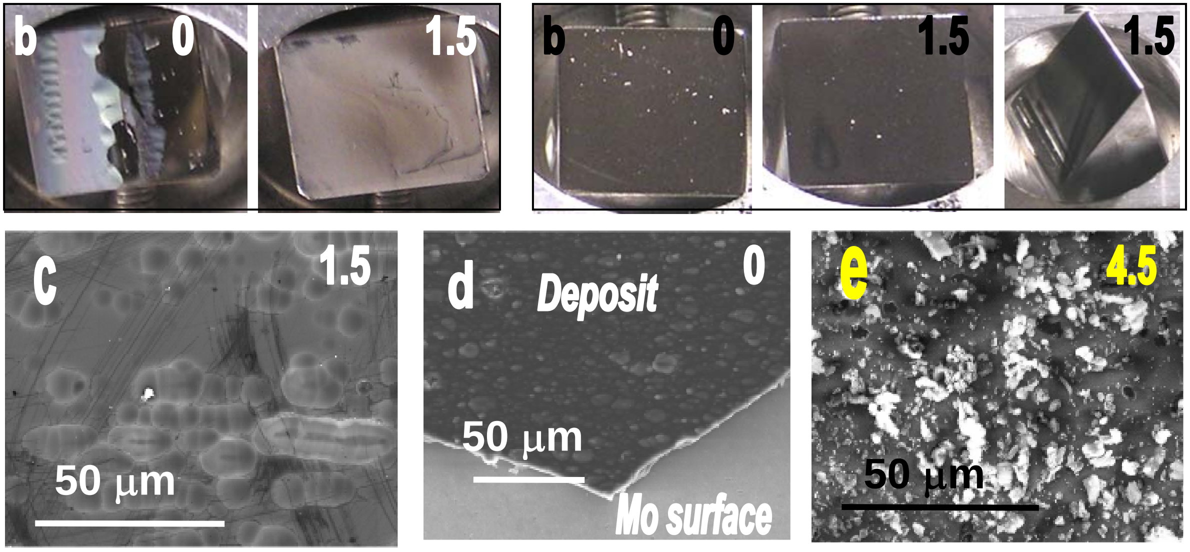

FIG. 2. Appearance of mirrors after exposure in JET, position of mirrors in cassettes is marked: (a) divertor base, steel; (b) outer wall, molybdenum, shutter-protected. Surface topography of mirrors after exposure: (c) bubble-like structure of the peeling-off deposit on steel mirror from the outer wall; (d) flake on Mo mirror from the divertor base; (e) dusty deposit on steel mirror from the inner divertor.

SIMS and IBA results are shown in graphs on Fig. 3 (a-c) and (d), respectively for Mo mirrors from the outer divertor leg. From the SIMS plots one infers the qualitative composition of the films (carbon, deuterium and beryllium) and the layer thickness of approximately 6.5, 4 and 0.85 μm on mirrors located 0; 1.5 and 3 cm from the front of the channel, respectively. The interface between the Mo substrate and the layer is not perfectly sharp especially in the case of thinner films, i.e. on the mirrors located at 1.5 and 3 cm in the channels. It is an indicator of material mixing during the layer formation. One may assume that the arriving flux of neutral carbon and small quantities of beryllium atoms caused sputter erosion of the Mo surface. As a result, these erosion products and the arriving species were deposited together on the mirror surface. The formation of carbides on the interface cannot also be excluded but SIMS and IBA do not permit conclusive statements on that matter. Quantitative EPS measurements plotted in Fig. 3 (d) show that the carbon films contain 4.3×10^{19}, 1.8×10^{19} and 0.6×10^{19} C at cm^{-2}, thus corresponding to 6.6, 3.0 and 1.0 μm, respectively. Assuming the deposit density of about 1.3 g cm^{-3} equal to 6.5×10^{22} C at cm^{-3} [12] the agreement between SIMS and IBA results is nearly perfect; some discrepancies may be attributed to the non-uniformity of the layer thickness especially due to flaking of the deposits, as can be seen in the image inserted in Fig. 3 (c). The beryllium content in these films is in the level from 5×10^{17} to 1×10^{18} cm^{-2}, i.e. a few atomic per cent.

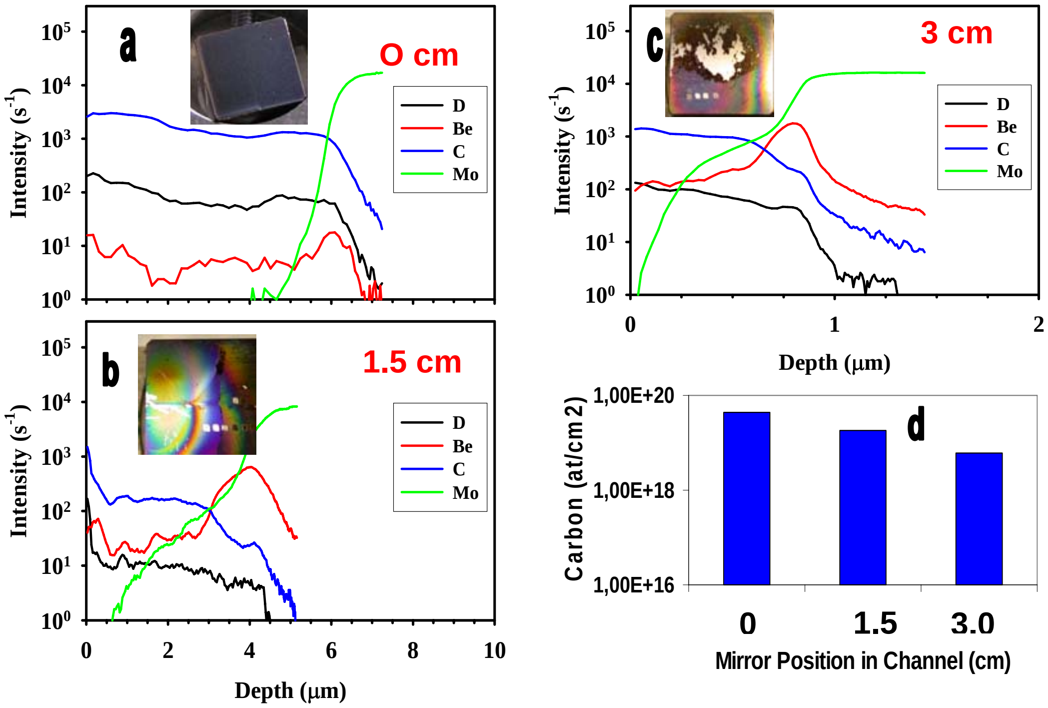

FIG. 3. Surface composition and thickness of deposits on Mo mirrors from the outer divertor: SIMS depth profiles and total carbon content in films measured with EPS.

The results in Fig. 3 are representative for all divertor samples: deposition decreases with the depth in the channel. An opposite trend is characteristic for mirrors from the main chamber wall, where very small amount of deposited species is detected on the mirrors located near the channel mouth (e.g. only $1.3\text{-}1.5 \times 10^{17}$ C at cm^{-2} on the three front sample at 0 and 1.5 cm), but thicker deposits are found deeper in the channel at 3 and 4.5 mm. Thus, IBA and SIMS data confirm the general observation from the visual inspection. Moreover, the data obtained for the front mirrors (i.e. located at 0 cm) in the divertor agree qualitatively with the deposition pattern observed on the sensors of quartz microbalance (QMB) devices installed in the vicinity of the mirrors: most significant deposition in the inner divertor, less deposition in the outer leg [13]. Only limited comparison can be made because the QMB crystals were exposed to selected discharges, whereas the mirrors were facing plasma continuously during all operation scenarios.

3.2. Reflectivity

Total reflectivity was measured for all 29 mirrors retrieved from the torus and it was compared with the initial reflectivity which was determined for all the mirrors before their installation; the scatter was well below 5% [2]. Therefore, for the clarity of presentation, the initial reflectivity is represented by single plots in Fig. 4 (a) and (b) which show results for mirrors located at different distances from the channel mouth in cassettes from the outer divertor and main chamber wall, respectively. These results are representative for all mirrors from the two major locations, i.e. the divertor and main wall. Though some differences within each category have been noted, the general tendency is well reflected in Fig. 4: the increase of reflectivity with the depth in channel for mirrors in the divertor and the decrease of reflectivity with the depth for mirrors on the wall.

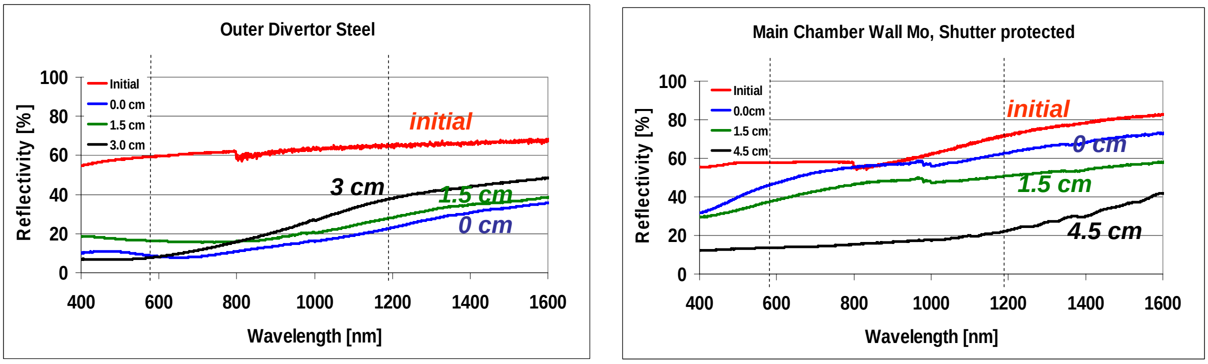

FIG. 4. Reflectivity of mirrors from: (a) outer divertor, steel and (b) main chamber wall, Mo.

The results regarding optical properties of all tested mirrors may be summarized as follows.

(i) In the divertor base very significant loss of reflectivity is measured close to the channel mouth: in the visible range by a factor of 6-10 at 0 and 1.5 cm.

(ii) In the outer and inner divertor reflectivity drop by a factor of 10 in visible range (400-800 nm) is recorded at all locations. At 1400 nm it reaches eventually 50% of the original value for mirrors deep in the channel (3 cm) and ~30% for mirrors located close to the channel entrance (0 and 1.5 cm).

(iii) On the main chamber wall, close to the channels entrances high reflectivity (~90%) is maintained at infrared range by both steel and Mo surfaces. However, in the range 400-600 nm the drop by 15% (steel) and 30% (Mo) is measured. 1.5 cm from the channel entrance the reflectivity drops by 35-50% and at deeper locations (3, 4.5 cm) it is only 20-25% of the original value due to deposits. These results suggest that fair reflectivity of mirrors near the channel mouth is due to the instant removal of deposits by the flux of charge exchange (CX) neutrals. However, the deposition prevailed over erosion deeper in the channel because of the decreased CX flux to that location.

(iv) No significant differences have been noted between Mo and steel mirrors, because their optical properties have been eventually governed by carbon deposition which occurs at the same pace on both polished substrates.

3.3. Deposition in channels

Fig. 5 shows the deposition profiles of C, Be and D in a channel of a cassette housing mirrors on the outer wall. The cassette was located in the midplane of Octant 4, toroidally about 40^{o} from the beryllium evaporator; the channels of this cassette were not protected during the evaporations by the magnetic shutter. Two regions of the deposition can be distinguished in the profiles. There is a greater content of all species up to 10 mm deep into the channel. The profile in that region is not decreasing exponentially but has a peak at about 2-4 mm. It can be attributed to the erosion of species deposited near the channel mouth. In the deeper part of the channel (15 - 45 mm) the co-deposit is fairly thin containing 0.8-2 $\times10^{17}$ cm^{-2} of C and Be atoms. Qualitatively similar in shape deposition profiles have been recorded for other cassettes housing mirrors in other locations. The major difference between the cassettes from the outer wall and the divertor was that in the latter case only very small quantities or no beryllium (especially inner divertor) have been detected. The result is in full agreement with measurements of deposition in previous campaigns in JET with a series of divertors: Mk-IIA [14,15] Mk-IIGB (Gas Box) [16] and Mk-IISRP (Septum Replacement Plate) [17]. It also agrees with the analysis of other erosion-deposition diagnostic tools used in TRS and exposed along with the mirrors in the presence of the Mk-IIHD (High Delta) divertor [18] and with general results of material migration studies in JET [19].

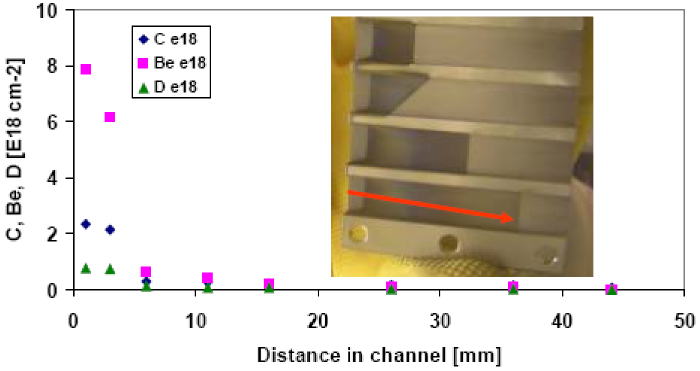

FIG. 5. Deposition profiles and contents of beryllium, carbon and deuterium along the channel in the cassette located on the outer wall.

3.4. Mirrors after cleaning with laser pulses

Plots in Fig. 6 (a) show the changes of reflectivity (mirror after the exposure and then after cleaning in comparison to the original values. One may infer that the regain of reflectivity after claening was 50% in the visible range and over 85% in infra-red. Despite pre-calibration of the laser power density the surface was damaged as seen on the migrograph in Fig. 6 (b). Similar type of damage was observed on all laser irradiated mirrors; details are in [6].

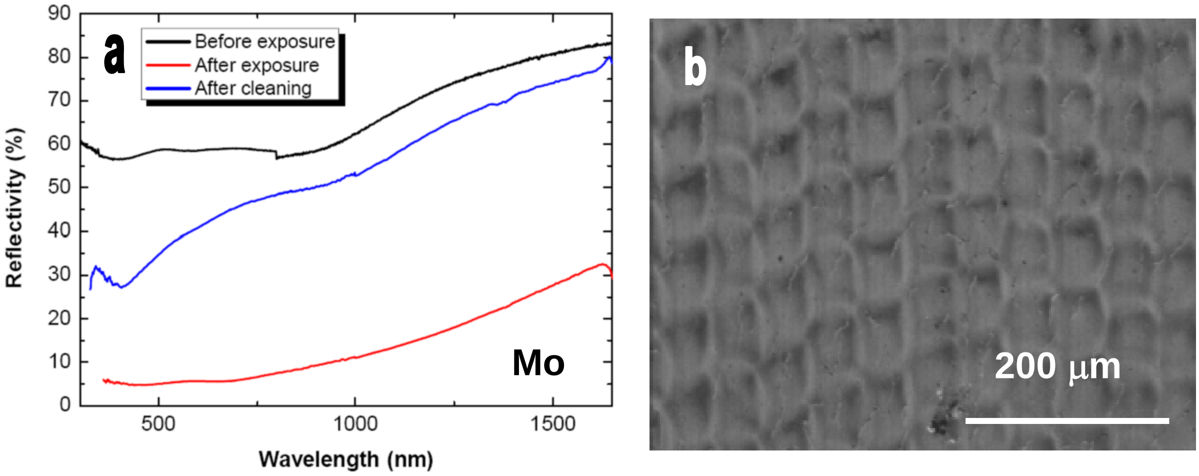

FIG. 6. (a) Reflectivity of a Mo mirror before and after exposure in JET and after laser-assisted cleaning. (b) Damage on the Mo surface cleaned by laser pulses.

4. Concluding remarks

The reported mirror test at JET was performed with a large number of samples located in positions (divertor and main chamber wall) important from the point of view of ITER diagnostics. The essential result is that the optical properties of all mirrors have been significantly degraded mainly by carbon deposition due to the long-range transport of hydrocarbons. In some locations the layer growth rate is inhibited by CX-induced removal of deposits, but this process would finally also lead to degradation of performance because of erosion and possible material mixing on the surface. It is not straightforward, and it is not intended here, to translate immediately these results to the ITER operation because of different densities and another wall composition. However, the results indicate that in the case of carbon PFC in ITER the diagnostic mirrors, especially in the divertor region, may be coated with deposits in less than some tens of shots, especially if the option with a carbon divertor is pursued. Therefore, the main effort should be concentrated on the development of methods for in-situ cleaning and/or protection of mirrors in a reactor-class device. Initial photonic cleaning has not given satisfactory results [6] showing that such methods inside the diagnostic channels may be ineffective or even damage the mirrors. Several other options for deposit removal have been critically assessed earlier [3]. Protection by using replaceable transparent glass/ceramic filters in front of mirrors is not an option because filters would also quickly lose performance under gamma and neutron irradiation. It all points to the need for development of engineering solutions: implementation of shutters limiting the exposure time as now considered at ITER [23] or a cassette with spare mirrors to replace periodically the degraded ones. This is a very difficult engineering task but feasibility studies should probably be performed if the use of solid-state mirrors is considered in ITER and, if no other viable solution to protect or clean mirrors is found. Another important point is to test the mirror performance in operation with a full metal wall. Such a test will be soon performed during the JET operation with ITER-Like Wall [20,21].

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