



An overview of a comprehensive First Mirror Test for ITER at JET

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ABSTRACT

The test was performed with 32 stainless steel and molybdenum mirrors placed in pan-pipe shaped cassettes and exposed in JET in the divertor and on the main chamber wall for 127 000 s including 97 000 s of X-point operation. Surface composition and total reflectivity were determined afterwards. All mirrors from the divertor were coated with deuterated carbon deposits causing the reflectivity loss by a factor of 6–10 in the visible range. Flaking and exfoliation of deposits were observed in some cases. On the main chamber wall the deposition occurred mainly on mirrors located deep in cassette channels, whereas mirrors close to the channels entrances were free from deposits and retained fair reflectivity (~90% of initial value) especially in the infra-red range. No significant differences in behaviour of steel and molybdenum were noted. The need for development of methods for mirror cleaning and/or protection in a reactor-class device is addressed.

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1. Introduction

Metallic mirrors will be essential plasma-facing components (so-called first mirrors) of all optical spectroscopy and imaging systems used for plasma diagnosis on the next-step magnetic fusion experiment [1]. Over 80 first mirrors are planned in ITER to enable detailed characterization of the main chamber and divertor plasma. They will be of different size (up to 350 mm in diameter or 440 mm high) and will be placed at different distance from plasma, starting even from 140 mm. When assessing the plasma impact on mirrors, three parameters are important: (i) the distance to plasma; (ii) solid angle resulting from the mirror-to-aperture distance and (iii) aspect ratio the aperture–mirror distance to aperture diameter or width. Any change of the mirror performance, in particular reflectivity, will influence and degrade the quality and reliability of detected signals. Mirror behaviour under fusion environment has been tested in several tokamaks [2–5]. On the request of the ITER Design Team, a First Mirror Test (FMT) was initiated at JET [6]. Recently completed experiment has been the most comprehensive test performed with a large number of metallic mirrors exposed in an environment containing both carbon and

beryllium. This paper provides an overview of results obtained for mirrors retrieved from the torus after campaigns covering the period 2005–2007.

2. Experimental

Details of the entire technical the program (design of mirrors and their carriers and installation in the torus) have been presented earlier [6], 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°) mirrors were manufactured: blocks (1 × 1 × 1 cm³) with the plasma-facing surface of 1 × 1 cm² (flat-front) and 1 × 1.4 cm² (chamfered). Each mirror had a ‘feet’ 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 distances (0, 1.5, 3 and 4.5 cm). This paper is focused only on the analyses of mirrors.

Six units were installed in three locations in the divertor: inner leg, outer leg and under the load bearing tile on the base. Fig. 1 shows cassettes installed on the outer divertor carrier; for clarity of view the Tile 4 blocks have been removed. In all locations the

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¹ See Appendix to paper: M.L. Watkins et al., Fusion Energy 2006, in: Proceedings of 21st International Conference on Chengdu, China, 2006.

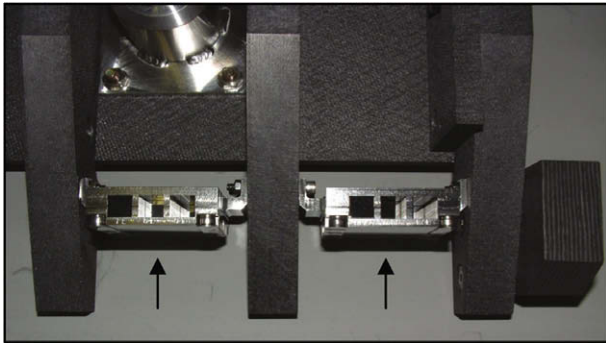


Fig. 1. Cassettes with mirrors installed between the ribs on the outer divertor module.

cassettes were mounted in the vicinity of deposition–erosion monitors [7]. 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. 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 from 42 cm (mouth of the channel) to 46.5 cm, whereas in the divertor it was 10 to 14.5 cm. The range of solid angles for particle bombardment (Ω_{PB}) was 6.3×10^{-3} – 5.5×10^{-2} sr. These solid angles and aspect ratio for mirrors in cassettes (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 126600 s (35 h) including 96900 s (27 h) 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 [8]. 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 [6]. Surface composition was studied by means of nuclear reaction analysis (NRA) with a 2.5 MeV $^3\text{He}^+$ beam and enhanced proton scattering (EPS) using a 2.5 MeV H^+ beam.

3. Results and discussion

3.1. Surface morphology

Images in Fig. 2 show the appearance of mirrors retrieved from the inner divertor leg (steel, Fig. 2(a)) and base (Mo, Fig. 2(b)), whereas samples from the main chamber wall are in Fig. 2(c) (Mo, shutter-protected) and 2d (steel, not protected). 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(c), 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. In addition, a flat-front mirror at 1.5 cm was coated, whereas on the adjacent chamfered sample (1.5 cm at the center) the deposit covered only a small area, as inferred from Fig. 2(d). 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. Microscopy studies have not been accomplished yet for technical reason (Be and T contamination of mirrors), but one may suggest that lack of visible deposits on mirrors placed at the channel mouth in main chamber units is related to removal of deposited species by charge exchange neutrals reaching these surfaces.

IBA results are shown in graphs on Fig. 3(a) and (b) for Mo mirrors from the outer divertor leg and the main chamber wall, respectively. The most distinct difference is that the deposition on samples from the divertor decreases with the depth in channel for all studied samples, whereas the opposite trend is characteristic for wall samples: only 1.3 – 1.5×10^{17} C at cm^{-2} have been detected

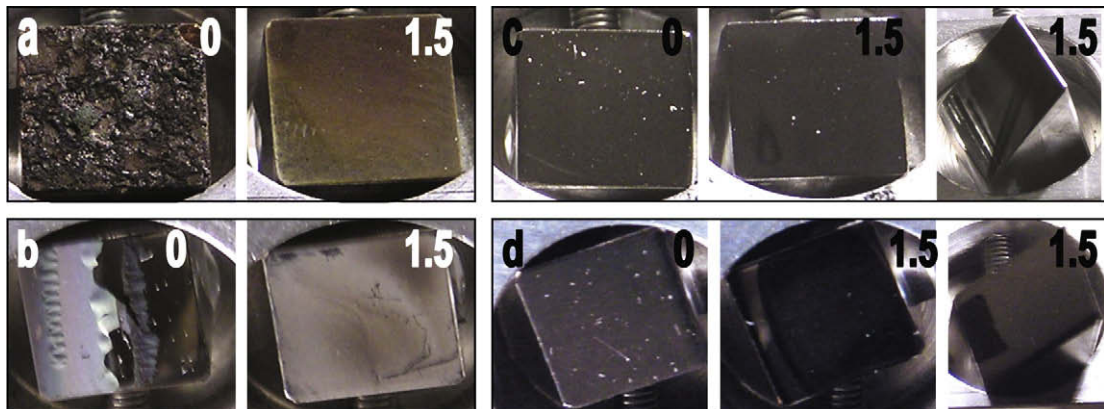


Fig. 2. Appearance of mirrors after exposure in JET, position of mirrors in cassettes is marked: (a) inner divertor, steel; (b) divertor base, steel; (c) main chamber wall, molybdenum, shutter-protected; (d) main chamber wall, steel, not protected by shutter.

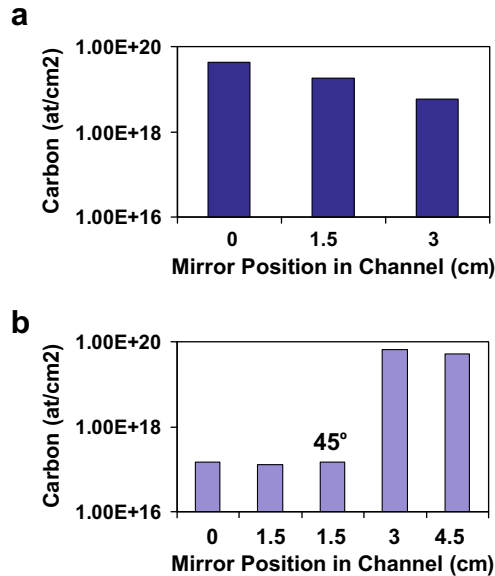


Fig. 3. Carbon deposition on Mo mirrors in: (a) outer divertor; (b) main chamber wall.

on the three front samples from the main chamber. Thus, IBA data confirm the general observation from the visual inspection. The quantitative results for carbon deposition on steel mirrors from the outer divertor were nearly identical, within $\pm 5\%$, to those shown for Mo in Fig. 3(a). The recorded EPS spectra for thick carbon layers were modeled with SIMNRA [9] to obtain the concentrations and layer thickness, e.g. 10 μm and 7 μm for the thickest deposits on the samples from the main chamber and outer divertor, respectively. However, proper assessment has not been possible for very thick layers formed on the inner divertor sample located at the channel mouth, see Fig. 2(a).

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 [10,11]. 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.

All deposits, whether thin or thick, contain carbon-12 and deuterium as the main components (D/C concentration ratio ~ 0.65 for the outer and inner divertor samples) and small quantities of beryllium and carbon-13. The concentration of these minority species was in the range $5 \times 10^{16} - 1 \times 10^{18} \text{ cm}^{-2}$, but no systematic tendency regarding their deposition could be traced. The presence

of C-13 in measurable quantity derives from three experiments using $^{13}\text{CH}_4$ tracer in material migration studies [8,12,13]. The last experiment of this kind was performed just on the last operation day before the shut-down. The high D/C ratio indicates that mirror surfaces were not overheated during the exposure. The temperature of units in the main chamber (45–50 cm from the plasma) corresponded to the wall temperature (around 200 °C), whereas in the divertor it can be assessed in the range 150–200 °C as determined by thermocouples installed in the vicinity of the mirror carriers.

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% [6]. 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.

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 $\sim 30\%$ 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 ($\sim 90\%$) is maintained at infra-red 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.

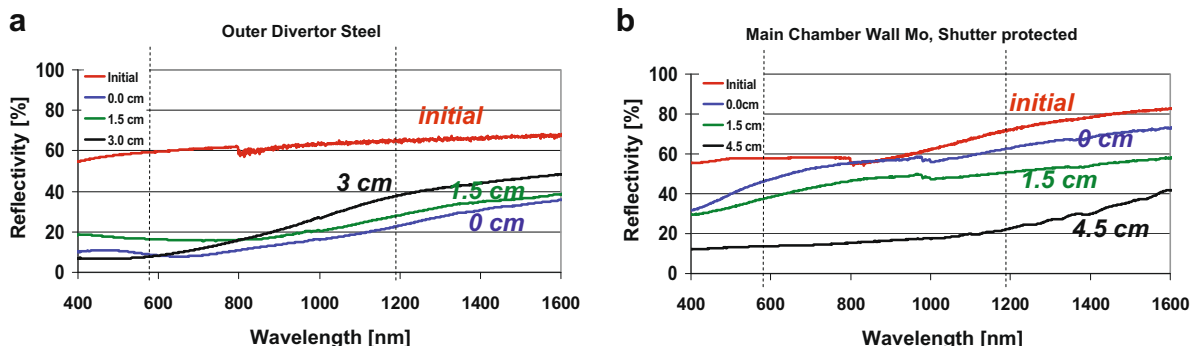


Fig. 4. Total reflectivity of mirrors from: (a) outer divertor, steel and (b) main chamber wall, Mo.

- (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.

4. Concluding remarks

Examination of surface morphology and reflectivity of the tested mirrors create a coherent picture showing major differences for samples from the two main locations. However, 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 [13–15]. 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.

Taking into account that the entire test at JET has corresponded at the best to less than 10 ITER shots one may expect similar problems with at least some mirrors in vital diagnostic systems, especially if the option with a carbon divertor is pursued. Even mirrors accessed by CX fluxes will be damaged by erosion (increased surface roughness) or material mixing by implantation of incoming flux. 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. Protection by using replaceable transparent glass/ceramic filters in front of mirrors is difficult to conceive because filters would also quickly lose performance under gamma and neutron irradiation. A controlled gas puff in the vicinity of mirrors would change the erosion–deposition balance by decreasing the mean free path of species in the diagnostic channel, but such a puff may result in mobilization of dust or flakes of co-deposits present in that region, thus disturbing spectroscopy measurements. Cleaning of mirrors by laser-light [16] would require knowledge on the deposit composition and thickness to set up proper irradiation conditions to avoid damage of the cleaned surface. Similar requirements apply to a local plasma glow in the diagnostic channel and the technique would be limited only to

the periods when the magnetic field is turned-off. Heating of mirrors to remove carbon deposit may result either in the formation of dust from the peeled-off deposit or/and carbide formation on the mirror surface which would destroy optical properties. All these ideas have been discussed for some time, but no in-vessel experiments have been performed to prove the concept as a working solution. Another option is to implement a cassette with mirrors to replace periodically the degraded ones. This is difficult from the engineering point of view but feasibility studies should probably be performed in case no other viable solution to protect or clean mirrors is found.

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