First Mirrors Test in JET for ITER: An overview of optical performance and surface morphology

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ABSTRACT

Metallic mirrors will be essential components of all optical systems for plasma diagnosis in ITER. A comprehensive First Mirror Test (FMT) has been carried out in the JET tokamak. The exposure was followed by a characterisation of mirrors and their carriers. The main results obtained by optical and surface analysis methods are: (i) reflectivity of all tested mirrors is degraded either by erosion with charge exchange neutrals or by the formation of thick deposits; (ii) deuterium and carbon are the main elements detected on all mirror surfaces and the presence of beryllium is also found in several cases; (iii) thick deposits show columnar structure; (iv) bubble-like structures are detected in deposits; their formation is a probable reason for deposits' disintegration and peeling-off; (v) the deposition in channels in the divertor cassettes is pronounced at the very entrance and then it sharply decreases with the distance from the plasma, $\lambda \sim 5\text{--}7\text{ mm}$.

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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 mirror performance, 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 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. Mirrors samples ($1 \times 1 \times 1\text{ cm}^3$) were held in carriers of pan-pipe shape, i.e. comprising channels of different length with mirror surface being from 0 to 4.5 cm deep into the channel. The distance of mirrors at the channel mouth in the divertor was at least 12 cm and on the main chamber wall around 50 cm; see [2] for the overview of technical details.

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 and examination of products generated by the laser light impact. The change of optical properties of mirrors retrieved from the vessel after the experimental campaigns in 2005–2007 has been discussed earlier [3]. The essential result is that the reflectivity of all tested mirrors was significantly degraded either by erosion with charge exchange

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¹ See Appendix to: F. Romanelli et al., Fusion Energy 2008 (Proceedings of the 22nd International Conference, Geneva, Switzerland, 2008).

neutrals or by the formation of thick deposits. The intention of this paper is to provide a broad account of the characterisation of the mirrors and their carriers: (a) the correlation between the surface state (composition and structure) and optical properties; and (b) the deposition inside the channels.

2. Experimental

The test was carried out for 32 stainless steel and polycrystalline molybdenum flat-front and angled mirrors (45°) with pre-characterised optical properties. The decision on testing two materials was taken in 2002 and the motivation regarding the material choice can be found in [2]: (a) both materials were on the list of candidates for first mirrors in ITER; (b) Mo is hard, easy-to-polish metal of high thermal conductivity and low sputter erosion; (c) steel, foreseen for actively cooled mirrors, is the same material as the support structure thus the mirror distortion would be minimized. In addition, relatively low price of both materials and easy machining were important because, based on very broad erosion–deposition studies in JET [7,8] it could be expected that the reflectivity degradation would be caused mainly by co-deposition. Once carbon film starts to grow, the underlying substrate plays secondary role, as it was proven by earlier studies of co-deposition on different metallic surfaces [9]. The samples installed in separate channels of 8 pan-pipe shaped cassettes placed on the outer wall and in the Mk-II HD divertor: inner leg, outer leg and base plate under the load bearing tile; for details see [2]. They were exposed during experimental campaigns covering the period 2005–2007 and then retrieved during the major shut-down of JET in 2007. The total plasma time was over 35 h including 27 h of X-point operation. This exposure time would correspond to only small number of full power ITER pulses when scaled with divertor fluxes [10].

The mirrors were placed in channels in cassettes of a pan-pipe shape in order: (a) to expose mirrors at different distances to plasma, (b) to ensure a range of solid angles for particle bombardment (Ω_{PB} in range from 1.3×10^{-3} to 6×10^{-2} sr) and corresponding different aspect ratios (up to 4.5) of the mirror size-to-depth in channel, (c) to obtain deposition profiles along channels in diagnostic ports. Reflectivity of the exposed mirrors was determined in the range 400–1400 nm using equipment specially designed for handling materials contaminated by beryllium and tritium [2]. Comprehensive analyses of the surface state of mirrors and their carriers were performed by means of microscopy, energy dispersive X-ray spectroscopy (EDX) with 15 keV electron beam, secondary ion mass spectrometry (SIMS) and accelerator-based ion beam analysis (IBA) to measure deuterium (D), carbon (C) and beryllium (Be) with nuclear reaction analysis (NRA) and enhanced proton scattering (EPS) techniques.

3. Results and discussion

Images in Fig. 1(a) show the appearance of three steel mirrors from the divertor base. The distance to the plasma was about 12, 13.5 and 15 cm for the mirrors located at 0 cm (channel mouth), 1.5 and 3.0 cm, respectively. The deposit on the mirror located at the entrance of the channel has disintegrated and it peeled-off forming dust. Another layer of deposit is seen to be growing on the surface free from the flaking film. This clearly indicates that the film disintegration on the mirror took place in the torus. It cannot be fully excluded that the formation of some flakes also occurred when the deposit was exposed to ambient air after

Fig. 1. Mirrors from the divertor base: (a) surface features and (b) reflectivity of mirrors located at the increasing distance in channels.

retrieval from the torus. Such process has been observed on PFC (limiter and divertor plates) exposed to air atmosphere which also contains some water vapour; the reasons have been discussed in [11]. The other mirrors located in the channels 1.5 and 3 cm from the entrance are all over coated with deposits. It is not possible, however, to conclude whether the observed films are the first and only layers formed on those mirrors. It may be noted that the deposit formed on the surface 3 cm deep in the channel is highly non-uniform. Moreover, peeling-off films were found also on mirrors located deep in the channels, as will be shown later in Fig. 4(c). Results of reflectivity measurements, shown in Fig. 1(b), prove a significant loss of optical performance for all mirrors. The most pronounced loss in the whole spectral range is measured for the mirror at the channel mouth (0 cm). Optical properties of other surfaces are also strongly degraded especially in the visible range. This tendency has been found on all other mirrors from the divertor.

Details of surface features are shown in Fig. 2(a–c) for mirrors from three different locations: steel sample from the outer wall (1.5 cm in channel and 53.5 cm from plasma), Mo from the divertor base (channel mouth and 12 cm from plasma) and steel from the inner divertor (4.5 cm in channel and 16.5 cm from plasma), respectively. The formation of chains of bubble-like structures in Fig. 2(a) 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(b)) 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(c)) shows a rough, dust-like structure which is similar to that observed several times on PFC from other tokamaks [12–15].

Fig. 2. Surface topography of mirrors after exposure: (a) bubble-like structure of the peeling-off deposit on steel mirror from the outer wall; (b) flake on Mo mirror from the divertor base and (c) dusty carbon deposit on steel mirror from the inner divertor.

X-ray spectra in Fig. 3 show results of EDX analysis performed at several points on the steel mirror that is located at the channel mouth of the unit from the divertor base; general appearance is shown in Fig. 1(a). One may distinguish three regions marked as 1–3. Only steel components (Fe, Ni, Cr) are recorded in the

Fig. 3. Surface composition in different regions of a steel mirror from the divertor base; peeling of deposit is visible.

deposit-free area (1). In addition to these elements, in the region covered with a thin deposit (2), a strong carbon signal is recorded whereas in area (3) only carbon and small quantities of oxygen are detected. This indicates that the film thickness exceeds $4.0\text{ }\mu\text{m}$ as no X-ray signal is emitted from the underlying steel substrate (penetration depth of 15 keV electrons used in EDX is carbon films of around $3.8\text{ }\mu\text{m}$). A series of SIMS depth profiles on Mo mirrors from the outer divertor is presented in Fig. 4(a–c). From the plots one infers the qualitative composition of the films (carbon, deuterium and beryllium) and the layer thickness of approximately 6.5 , 4 and $0.85\text{ }\mu\text{m}$ 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 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. Quantitative information on neutral fluxes cannot be provided because such time-integrated validated data are not available for the campaign-long experiment: 35 h of plasma operation. Approximate data would be too speculative and even misleading if used for modeling, which is usually done with some additional assumptions. The formation of carbides also on the interface cannot be excluded but SIMS and IBA do not permit conclusive statements on that matter. To quantify the deposition, EPS measurements were performed using a 2.5 MeV H^+ beam. The carbon films, as shown in Fig. 4(d), contain 4.3×10^{19} , 1.8×10^{19} and $0.6 \times 10^{19}\text{ Cat cm}^{-2}$, thus corresponding to 6.6 , 3.0 and $1.0\text{ }\mu\text{m}$, respectively. Assuming the deposit density of about 1.3 g cm^{-3} equal to $6.5 \times 10^{22}\text{ Cat cm}^{-3}$ [16] 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. 4(c). The beryllium content in these films is in the level from 5×10^{17} to $1 \times 10^{18}\text{ cm}^{-2}$, i.e. a few atomic percent.

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° from the beryllium evaporator; the channels of this cassette were not protected during the evaporations by the magnetic shutter.

Fig. 4. 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.

Beryllium evaporation, performed usually once a week, is a method for conditioning of the main chamber wall of JET by depositing a thin Be coating (some tens of nm) which has

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

beneficial effect on the operation especially in the start-up phase of a discharge; details can be found in [17,18]. Two distinct regions of the deposition can be distinguished in the profiles in Fig. 5. There is a significant 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 3–4 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 $0.8\text{--}2 \times 10^{17} \text{ cm}^{-2}$ 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 [7,8] Mk-IIGB (Gas Box) [19] and Mk-IISRP (Septum Replacement Plate) [20]. 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 [21] and with general results of material migration studies in JET [22].

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 finally this process would 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 these results immediately 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. Several options for deposit removal have been critically assessed earlier [3] and photonic cleaning has been recently tested on the JET mirrors [6]. It has shown that photonic methods inside the diagnostic channels may be ineffective or even damage the mirrors. 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 points to the need to develop engineering solutions: implementation of shutters limiting the exposure time as now considered at ITER [23] or a cassette with spare mirrors to periodically replace 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 [24,25].

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