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ScienceDirect

Journal of Nuclear Materials 363–365 (2007) 1395–1402

journal of nuclear materials

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Diagnostic mirrors for ITER: A material choice and the impact of erosion and deposition on their performance

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Abstract

Metal mirrors will be implemented in about half of the ITER diagnostics. Mirrors in ITER will have to withstand radiation loads, erosion by charge-exchange neutrals, deposition of impurities, particle implantation and neutron irradiation. It is believed that the optical properties of diagnostic mirrors will be primarily influenced by erosion and deposition. A solution is needed for optimal performance of mirrors in ITER throughout the entire lifetime of the machine. A multi-machine research on diagnostic mirrors is currently underway in fusion facilities at several institutions and laboratories worldwide. Among others, dedicated investigations of ITER-candidate mirror materials are ongoing in Tore-Supra, TEXTOR, DIII-D, TCV, T-10 and JET. Laboratory studies are underway at IPP Kharkov (Ukraine), Kurchatov Institute

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doi:10.1016/j.jnucmat.2007.01.281

(Russia) and the University of Basel (Switzerland). An overview of current research on diagnostic mirrors along with an outlook on future investigations is the subject of this paper.

PACS: 52.55.Fa; 52.40.Hf; 52.25.Vy; 52.70.Kz

Keywords: Materials properties; Reflectivity; Erosion and deposition; Diagnostic mirrors (suggestion); ITER

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1. Introduction

Diagnostic mirrors are foreseen as necessary optical components in ITER diagnostic systems. Mirrors will be used in approximately half of the ITER diagnostics. In the harsh environment, diagnostic mirrors will be exposed to intensive electromagnetic and gamma radiation, fluxes of neutrals and neutron radiation. Depending on their location, the mirrors will become eroded due to fast atoms or contaminated because of deposition of impurities originating from vessel wall and in-vessel components.

Investigations on first mirrors are recognized as high priority topic within the ITPA topical group on Diagnostics, with a dedicated Specialists Working Group working in this field. There is presently a vast research program on diagnostic mirrors ongoing at various institutions and laboratories worldwide, the experiments are underway on several tokamaks including Tore-Supra, TEXTOR, DIII-D, TCV, T-10 and JET [1–5].

The choice of proper material for the mirrors is of crucial importance. Among the main candidate mirror materials are molybdenum, tungsten, stainless steel, copper and rhodium. Erosion and deposition processes are believed to have the largest impact on the mirror reflectivity and polarization characteristics affecting the performance of the respective diagnostic systems.

Mirrors widely open to plasma are expected to suffer from net erosion in ITER [6]. Mirrors mounted deeply in the diagnostic ducts and divertor mirrors will most likely be subject to net deposition. The deposition can change drastically the optical characteristics. Results of recent investigations along with an outlook for the future studies are presented in this paper.

2. Diagnostic mirrors under erosion-dominated conditions

Erosion in ITER will be primarily caused by charge-exchange neutrals (CXN). The expected fluxes are in the range of 10^{17} atom/m^2 s in the main chamber and up to 10^{19} atom/m^2 s in the divertor region [7]. CXN energies are expected to be in the range of several tens of eV up to several keV, with an average value of 250–300 eV [8]. At these energies the physical sputtering of the metal candidate materials is significant [9]. Laboratory and tokamak experiments [1,2,10] have shown that the polycrystalline (PC) metallic mirrors cannot maintain their reflectivity under erosion-dominated conditions because of the increase of their roughness due to erosion. Therefore, the choice of mirror material, crystallographic structure and the development of techniques for prevention of erosion have gained large importance.

2.1. Performance of metal mirrors under net erosion conditions: laboratory research

Mirrors made from the single crystals (SC) are believed to be an attractive alternative to conventional polycrystalline mirrors in erosion-dominated conditions in ITER. In the experiment carried out at IPP Kharkov, Ukraine [10] the stainless steel, PC molybdenum and SC molybdenum mirrors were sputtered with D plasma ions. The single crystal Mo mirror was able to preserve its reflectivity after the sputtering of ∼5 μm of mirror surface, unlike all other mirror materials.

2.2. Direct comparative test of SC and PC mirror materials under erosion conditions in the SOL of TEXTOR

To check the capability of SC materials to maintain their performance in a tokamak environment, a direct comparative test of SC and PC mirrors was made in TEXTOR using polycrystalline molybdenum mirror (PC Mo), a single crystal molybdenum mirror (110) (SC Mo) and a single crystal tungsten mirror (111) (SC W). Before exposure, the total and diffuse reflectivity, polarization characteristics and the surface elemental composition of mirrors were

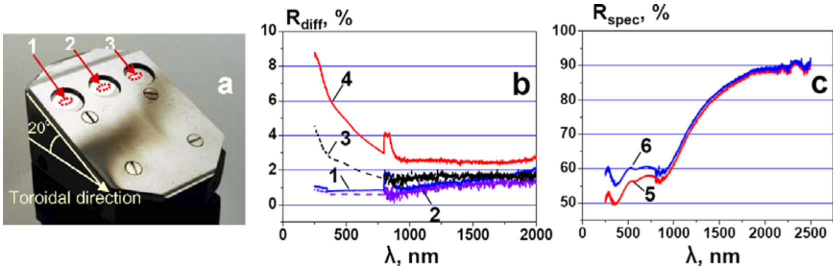

Fig. 1. Exposure of mirrors in the SOL of TEXTOR. (a) The view of a holder with mirrors: (1) PC Mo mirror; (2) SC Mo mirror; (3) SC W mirror. Dashed areas show the locations of optical measurements. (b) The evolution of diffuse reflectivity (R_{diff}) of SC Mo and PC Mo mirrors: (1) R_{diff} of a SC Mo mirror before exposure; (2) R_{diff} of a SC Mo mirror after exposure; (3) R_{diff} of a PC Mo mirror before exposure; (4) R_{diff} of a PC Mo mirror after exposure. (c) The specular reflectivity (R_{spec}) of SC Mo and PC Mo mirrors after exposure in TEXTOR: (5) R_{spec} of PC Mo mirror after exposure; (6) R_{spec} of a SC Mo mirror after exposure.

characterized. All mirrors have been exposed to the same plasma environment under erosion-dominated conditions in the SOL plasma of TEXTOR at an angle of 20° to the toroidal direction (Fig. 1(a)) for 36 identical NBI-heated plasma discharges with a total plasma duration of 210 s. The temperature of the holder was measured with thermocouples and was varying between 200 °C and 270 °C during the exposure. The energy of D^{+} ions impinging on the surface of mirrors was approximately 200–250 eV as inferred from the He-beam diagnostic measurements, taking into account $T_{\mathrm{e}}/T_{\mathrm{i}}$ ratio in TEXTOR [11] and sheath effects. Ion energy values are thus in a range as expected for CXN in ITER [8]. The ion flux density was $2.4 \times 10^{18}/(\mathrm{cm}^2 \times \mathrm{s})$ which is approximately 25000 times larger than the expected for flux of CXN on the first wall in ITER [7]. The averaged fluence on the mirror surface was 1.7×10^{20} ion/cm^2 which corresponds to more than 1000 ITER discharges. After exposure the optical reflectivity and polarization characteristics of the mirrors were measured on the same locations on the mirror as before (Fig. 1(a)). The total reflectivity for both SC and PC Mo mirrors was only slightly affected by the net erosion. The diffuse reflectivity of SC Mo mirror was below 1%, and this value was preserved after the exposure (see Fig. 1(b)). In contrast to the SC Mo mirror, the diffuse reflectivity of the PC Mo mirror did increase after the exposure reaching the value of 9% in the UV range. Significantly higher diffuse reflectivity of the PC mirror may be explained by a higher surface roughness which was supported by scanning electron microscope (SEM) observations.

Specular reflectivity $R_{\mathrm{spec}} = R_{\mathrm{tot}} - R_{\mathrm{diff}}$ is one of the most important characteristics of a diagnostic mirrors for ITER, since it sets the amplitude of signal transmitted from plasma towards the detecting hardware. The specular reflectivity in the erosion zones on the exposed molybdenum mirrors is shown in Fig. 1(c). R_{spec} of the PC Mo mirror is much lower after exposure in the visible (VIS) and ultraviolet (UV) wavelength ranges (250–1000 nm) than that of SC Mo mirror, whereas little changes were detected in the range of 1000–2500 nm. Similar dependences were also obtained for the SC W mirror. Erosion did not affect the polarization characteristics significantly [12]. The polarization characteristics correlated well with the theory curve [13].

During elemental analyses, the material sputtered from the mirror holder was found locally deposited on the mirror surfaces, which implies the necessity to optimize geometry in future diagnostic systems.

Taking into account the evolution of the optical properties after exposure, it can be concluded that single crystal materials can best withstand the erosion conditions and preserve their optical properties. This also implies that the SC mirrors should be treated as leading candidates to be used in ITER in the net erosion environment.

2.3. Erosion of SC and PC mirrors during long-term exposure in Tore-Supra

Mirror samples made from single crystal (110) molybdenum (SC Mo), polycrystalline stainless steel (SS, an analogue of the ANSI 316 steel, containing 0.04% of C, 16% of Cr, 16% of Ni, 11% of Mo and 3% of Ti) and polycrystalline oxygen-free copper (Cu) mirror were installed in Tore-Supra (TS) for long-term exposure during the 2003–2004 experimental campaign [14]. All mirrors including

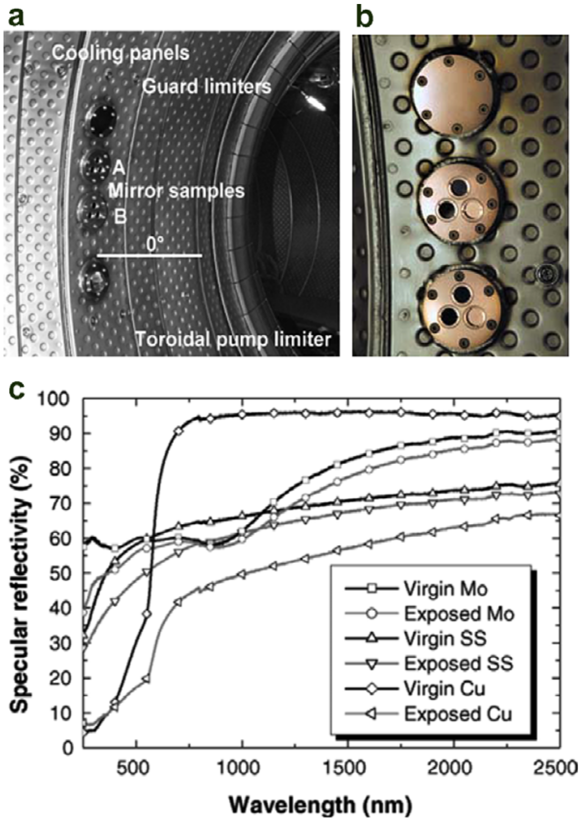

Fig. 2. Exposure of mirrors in Tore-Supra: (a) Mirror locations; (b) view of holder with mirrors; (c) dependence of specular reflectivity on a wavelength for exposed and reference non-exposed mirrors.

non-exposed samples for reference measurements were supplied by IPP Kharkov, Ukraine.

Two mirrors of each material have been installed on the high field side of the TS plasma vessel at a poloidal angle of $\Theta = 15.4°$ (set A) and 7.6° (set B) above the equatorial plane ($R = 2421$ mm, $r \sim 880$ mm) and positioned approximately 140 mm behind the LCFS as shown in Fig. 2(a) and (b). The reflecting surfaces of all mirrors were oriented along the toroidal direction, recessed 5 mm behind the holder edge. Mirrors did not have shutter protection and were cooled by a contact with the wall panels.

During the exposure, about 1400 plasma pulses (mainly D_2) with plasma current Ip $\geqslant$ 200 kA ($n_{e0} \sim 2\text{–}4 \times 10^{19}$ m^{-3}) were performed with a cumulative pulse length of ~26 000 s (7 h 10 min). The integrated injected energy in TS was roughly 37 Gigajoules (GJ) composed of ~13 GJ Ohmic, ~22 GJ lower hybrid and ~2 GJ ICRH. In addition, wall conditioning glow discharges in He ($t = 362$ h), in D_2 ($t = 606$ h) and 13 h of boronization were performed during the exposure.

Baking cycles of the vacuum vessel were made at temperatures around 200 °C. The mirror temperature did not exceed ~150 °C for a typical 'Gigajoule' scenario as was shown by 2D-thermohydraulic finite element modeling.

After exposure, the optical characteristics and elemental surface composition of mirrors were compared with those of non-exposed reference samples. The SC Mo mirror was found to suffer from net erosion depth of ~0.12 μm as measured with confocal microscopy. During Secondary Ion Mass-Spectrometry (SIMS) surface investigations thin (<12 nm) carbon deposits enriched with hydrogen, deuterium, boron and oxygen [1] were detected.

The specular reflectivity of a SC Mo mirror showed a slight decrease compared to the virgin sample due to light absorption in the thin deposit. This decrease is more pronounced in the UV region. The respective dependences are presented in Fig. 2(c). The exposed SS mirror had an eroded depth of roughly 0.22 μm. A decrease of specular reflectivity is observed after exposure, which may be attributed to the increase of surface roughness due to net erosion.

The most dramatic surface change was observed on copper mirrors. The specular reflectivity dropped to extreme values of about ~40% at 800 nm, mainly due to erosion processes.

In order to assess the contribution of conditioning glow discharges into erosion of TS mirrors, reference mirror samples from the same fabrication set were exposed ex-vessel (EV) to He and D_2 ions in a laboratory chamber using the same glow electrode/mirror assembly configuration and similar discharge parameters as in TS. From these comparative experiments and erosion calculations, it was concluded that mirror erosion in TS was dominated by glow discharges. The numerical simulations made with the EIRENE code lead to the same conclusion [9,15].

3. Diagnostic mirrors subject to net deposition

Diagnostic mirrors located deep in diagnostic ducts are expected to receive the negligible fluxes of eroding charge-exchange particles. However, the material eroded from the wall and in-vessel components can be transported through the ducts towards the mirrors. These mirrors will operate under net deposition conditions.

Similarly, the mirrors are expected to suffer from net deposition in the ITER divertor. The first mirror tests in tokamaks under deposition-dominated conditions were made [2] and the dedicated studies in a divertor are just started. Below is an overview of last investigations.

3.1. Exposures of molybdenum diagnostic mirrors in DIII-D divertor

The first dedicated exposures of diagnostic mirrors in tokamak divertor were made in DIII-D as a joint effort of IPP Forschungszentrum Jülich (FZJ, Germany), DIII-D Team and the University of Basel (Switzerland). The optical and elemental characteristics of SC Mo mirrors were pre-characterized at FZJ and in the University of Basel. The molybdenum mirrors were supplied by FZJ, were mounted onto the DiMES transport system [16], installed into the DIII-D divertor and exposed for series of identical ELMy H-mode discharges. The divertor plasma was partially detached. This regime is presently treated as the main working scenario for ITER divertor [17]. The mirrors were exposed in the private flux region (PFR), similarly to ITER where the dome mirrors will be in PFR [18]. Uppermost edges of the mirrors were recessed by 1 cm below the divertor floor (Fig. 3). Mirrors were oriented along the major radius of a machine. The mirror facing the toroidal field direction was called an 'upstream' mirror, while the mirror turned back from toroidal direction is referred as 'downstream' mirror.

A first exposure was made to obtain the reference deposition patterns on the mirrors at room temperature of a holder. Six discharges were made with total plasma duration of 25 plasma seconds. Exposure parameters were monitored with several diagnostics [3]. After the exposure, deposits were found on both mirrors. The inhomogeneous deposition pattern was observed on the downstream mirror (Fig. 4(a)) with the thickness of up to 90–110 nm on the plasma-closest edge of a mirror, as measured with ellipsometry and calibrated SIMS techniques. Contrary, the deposition pattern on the upstream mirror was homogeneous, with an estimated deposit thickness of 50 nm. Such a difference may be due to the different processes contributing to the deposition (e.g. the local sputtering of a divertor floor near DiMES leading to predominant deposition onto the downstream mirror, see Fig. 3).

The aim of the second exposure was to mitigate the carbon deposition on the mirror surfaces by heating the mirrors and thus intensifying the

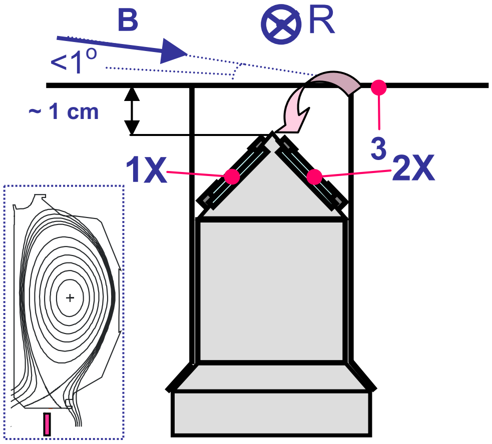

Fig. 3. Scheme of mirror exposure in DIII-D divertor: (1X) Upstream mirror; (2X) downstream mirror; (3) divertor floor.

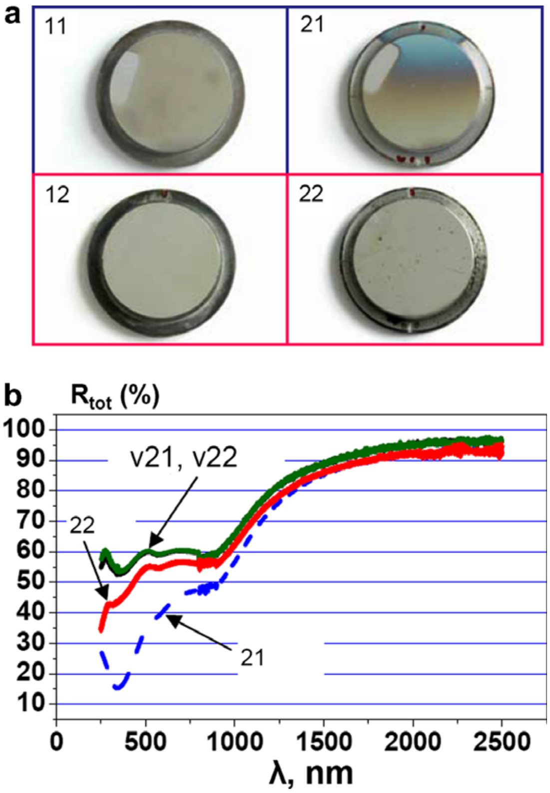

Fig. 4. Mirrors after exposure in DIII-D divertor. (a) View of mirrors after exposure: (11) Non-heated upstream mirror; (21) Non-heated downstream mirror; (12) Heated upstream mirror; (22) Heated downstream mirror. (b) Evolution of total reflectivity (R_{tot}) of downstream mirrors: v21, v22 R_{tot} of heated and non-heated mirrors before exposure; (21) R_{tot} of non-heated mirror after exposure; (22) R_{tot} of heated mirror after exposure.

processes of chemical re-erosion [19,20]. Seventeen discharges were made, identical to the exposure of non-heated mirrors with a total plasma duration of 75 s. Unfortunately, the heater has failed and the temperature of the mirror holder was dropping from 140 °C to 80 °C during the exposure. However, actual temperature of mirrors may be higher than that of holder. The dedicated finite element modeling (ANSYS) is underway to estimate the temperature of mirrors. The appearance of the mirrors after exposure is presented in Fig. 4(a) (mirrors 12 and 22). No carbon deposits were found neither on upstream nor downstream heated mirrors as confirmed by SIMS and Nuclear Reaction Analysis (NRA) investigations.

The total reflectivity of non-heated mirrors was degraded after the exposure. The most affected wavelength region 250–1500 nm, negligible deviations from initial reflectivity were observed in the range of 1500–2500 nm (Fig. 4(b)). A decrease of total reflectivity was detected either on both heated mirrors. This decrease occurred due to surface oxidation as measured with X-ray photoelectron spectroscopy (XPS) and SIMS techniques. It is yet to be determined if an exposure in plasma with residual oxygen impurities or the storage of mirrors in atmosphere may have caused this oxidation.

It should be noted however, that the decrease in reflectivity on the heated mirrors was less than on non-heated ones, despite for three times longer heated exposure. This indicates the significant reduction of degradation rates of heated mirrors in comparison with non-heated ones. Polarization measurements made on all exposed mirrors [3] showed the degradation of polarization characteristics, similarly to observations in TEXTOR [2]. Again, the degradation of polarization characteristics was essentially minimized on heated mirrors.

3.2. An effect of mirror temperature on the net deposition efficiency: laboratory investigations

The effect of mirror temperature on the deposition efficiency and reflectivity is being studied in Kurchatov Institute, Russia. Several identical stainless steel mirrors were exposed for 2 h to a DC magnetron discharge in 43% Ar, 35% CH_2D_2 and 22% D_2 mixture at several temperatures in the range of 150–400 °C. Mirror reflectivity was studied with a spectrophotometer and the surface elemental composition was monitored with SIMS, Rutherford Backscattering Spectroscopy (RBS) and elastic-recoil detection analysis (ERDA). A continuous growth of a-C:H films with $H/C \sim 1$ at the temperatures 150–300 °C was observed which resulted in a degradation of the reflectivity. The film growth was mitigated at higher temperature. However, deposits were still detected on the surfaces of the heated mirrors causing 10–20% reflectivity decrease in the UV range. The reflectivity of the heated mirrors has dropped similarly to the observations made after the experiments in DIII-D divertor. One of the hypotheses is that the chemical processes, like carbide and oxide formation became intensified at elevated temperatures thus changing the deposited film and decreasing the efficiency of deposit removal by thermally activated chemical re-erosion processes.

3.3. Influence of the mirror substrate material on the deposition efficiency: exposures of diagnostic mirrors in the TCV divertor

The deposition efficiency of carbon may be influenced by the substrate material as it was shown in the dedicated experiments and modeling performed on TEXTOR [21]. Investigations were made in the divertor of the TCV tokamak to address this issue specifically for diagnostic mirrors.

Series of Si, Mo and W mirrors were mounted in pairs on the holder and exposed for a number of diverted plasma configurations. The mirrors were recessed down to 5 cm below the surface of the divertor tiles, without direct contact to plasma. Sets of mirrors were exposed for several weeks of tokamak operation lasting for hundreds of discharges combined with He glow conditioning with up to several hours of total duration. During glow conditioning, the mirrors were floating to minimize the sputtering effect of glow discharge cleaning.

After exposures, the mirrors were analyzed using SIMS, XPS, ellipsometry and stylus profiling techniques. Some results are shown in the Table 1.

Table 1
Results of exposures of molybdenum and silicon mirrors in the TCV divertor

Experiment	Mirror material	Number of exposure discharges	Glow discharge duration (h)	Deposit thickness (nm)
4	Mo	223	24.5	1.3
	Si			15.9
5	Mo	820	90.5	4.0
	Si			24.0

A drastic difference in carbon deposition efficiency on Si and Mo substrates was detected. These results were qualitatively reproduced with Monte-Carlo SDTrimSP (TRIDYN) code modeling [22]. Further details are provided in [23].

4. Summary and conclusions

Laboratory research and dedicated tests in TEXTOR and Tore-Supra have demonstrated that SC mirror materials are promising candidates for use in ITER diagnostic systems under erosion-dominated conditions. However, the technological capability to manufacture single-crystal mirrors of ITER-relevant size is yet to be demonstrated. Cost-effective alternative solutions, such as coating of polycrystalline substrates with sputter-resistant reflective films and the use of amorphous metal mirrors need to be explored. Additionally, other highly reflective materials, such as rhodium may become an attractive alternative. Experiments in Tore-Supra have revealed the importance of mirror protection during conditioning discharges.

Suppression of carbon deposition at elevated temperature of exposed mirrors was observed in an experiment made in the DIII-D divertor. This is potentially good news for ITER diagnostics. However, the temperature dependence of the deposition efficiency turns out to be a complicated process, depending not only on temperature but on several parameters as it was demonstrated during the laboratory experiments.

The strong asymmetry of deposition observed during experiments on DIII-D and the local sputtering of mirror holders during experiments in TEXTOR imply the necessity to optimize the geometry of diagnostic ducts in ITER to avoid the transport of sputtered duct materials towards the mirrors. The oxidation of DIII-D mirrors would mean the need to implement in situ cleaning systems in ITER diagnostics even if the deposition mitigation techniques are applied.

The effect of substrate material on the deposition efficiency is being investigated in TEXTOR and in TCV tokamaks and detected lower deposition rates on high-Z mirror materials demonstrate their advantages under deposition-dominated conditions.

5. Outlook

Significant progress has been achieved in the understanding of the performance of metal mirrors foreseen for ITER diagnostics. Additionally, important results should be delivered from the ongoing mirror experiment at JET, where sets of mirrors are installed both in the main chamber and in the divertor.

However, there are still a number of open issues which need to be addressed in the nearest future. Among these issues are:

- Modeling of mirror performance in ITER, including impurity transport towards the mirrors.
- Development and tests of techniques for deposition mitigation and in situ cleaning of mirrors, including mirror tests in beryllium environment and development of reliable shutters.
- Estimation of the impact caused by off-normal events (such as ELMs) on mirror characteristics.
- Further detailed assessment of radiation- and neutron-induced damages possibly affecting the performance of mirrors.

Addressing these issues requires concentrated effort in the direction of ITER-specific diagnostics. For experimental investigations this implies that the high priority should be given to experiments with prototypes or mockups of ITER diagnostic systems.

In ITER diagnostics a combination of several actions is foreseen for an active prevention/mitigation of deposition including: the use of shutters, heating procedures, in situ cleaning and the possibility of mirror exchange. This combination of actions is still to be developed and its effectiveness to be critically assessed.

Acknowledgements

The investigations were supported by the European Fusion Development Agreement contracts: TW2-TPDS-DIADEV, TW4-TPDS-DIADEV, US Department of Energy contracts: DE-FG02-04ER54758, W-7405-ENG-48 and DE-FC02-04ER54698, and contracts 1.23.19.19.05.512 and 6.23.19.19.06.846 of the Russian Federal Agency on Atomic Energy. Experiments in DIII-D were performed in the frame of the US-EURATOM Exchange Programme.

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