First Mirrors for Diagnostic Systems of ITER

A. Litnovsky[a] , V. S. Voitsenya[b] for the SWG on First Mirrors of the ITPA Topical Group on Diagnostics

[a]Institut für Plasmaphysik, Forschungszentrum Jülich, Partner in the Trilateral Euregio Cluster, Ass. EURATOM- FZ Jülich, D-52425 Jülich, Germany, a.litnovsky@fz-juelich.de;

[b]IPP, NSC Kharkov Institute of Physics and Technology, Kharkov 310108, Ukraine, voitseny@ipp.kharkov.ua.

Abstract

About half of all diagnostics presently foreseen for ITER will implement in-vessel metallic mirrors as plasma-viewing components. Mirrors are used for the observation of the plasma radiation in a very wide wavelength range: from about 1 nm up to a few mm. In the hostile ITER environment, mirrors will be subject to erosion, deposition, particle implantation and other adverse effects which will change their optical properties affecting the entire performance of the respective diagnostic systems. The Specialists Working Group (SWG) on first mirrors was established under the wings of the International Tokamak Physics Activity (ITPA) Topical Group (TG) on Diagnostics to coordinate and guide the investigations on diagnostic mirrors towards the development of optimal, robust and durable solutions for ITER diagnostic systems. The results of tests of various ITER-candidate mirror materials, performed in Tore-Supra, TEXTOR, DIII-D, TCV, T-10 and LHD under various plasma conditions, as well as an overview of laboratory investigations of mirror performance and mirror cleaning techniques are presented in the paper. The current tasks in the R&D of diagnostic mirrors will be addressed.

1. Introduction

Mirrors will be used in about 50% of ITER diagnostics viewing the plasma radiation in a wide wavelength range. Diagnostic mirrors have to operate in a harsh environment with an intense electromagnetic radiation, high fluxes of energetic particles and neutron irradiation. The performance of the respective diagnostic systems will directly depend on mirror characteristics. Therefore, the mirrors are being treated as critical components of diagnostic systems. Molybdenum, tungsten, copper and stainless steel are among the main candidate mirror materials. The solutions must be found to maintain the best possible performance of diagnostic mirrors in ITER throughout the entire lifetime of a machine. These solutions are being pursued in a frame of the multi-machine ITPA-IEA Joint Experiments (task DIAG-2) and recognized as a High Priority Topic of the ITPA TG on diagnostics [1].

2. First mirrors: main issues in the research and development program

2.1. Impact of erosion and deposition on the optical characteristics of mirrors and the material choice

It is believed that the main impact on the optical and polarization characteristics will be caused by the erosion processes caused by the fast charge-exchange neutrals (CXN) and by deposition of impurities eroded from in-vessel components of ITER. An extended overview of these issues is provided in [2]. Generally, these two processes are accompanying each other, therefore conditions where the erosion prevails over deposition is often referred as erosion-dominated conditions or conditions of net erosion. Contrary, if deposition processes are more efficient, such conditions are called as the deposition-dominated ones or conditions of net deposition. The mirrors located in the main chamber and having an open geometry towards the plasma will likely be subject to net erosion, whereas the mirrors located in ITER divertor will likely suffer from the deposition. Similar patterns were observed in LHD, where stainless steel mirrors in the divertor region and in the diagnostic port became heavily coated with carbon-based films in contrast to a mirror that was widely open to the plasma, which maintained its optical properties [3].

Single-crystal (SC) materials have demonstrated the best performance under net erosion conditions in the laboratory experiments [4] and during a recent exposure in Tore-Supra [5]. Finally, the direct comparative test of single-crystal and polycrystalline (PC) molybdenum mirrors was performed in the scrape-off layer (SOL) plasma of TEXTOR. After exposure to a ion fluence corresponding to CXN fluence accumulated during several hundreds of ITER discharges, the single crystal mirrors have preserved their optical properties, including the reflectivity of polarized light, unlike the polycrystalline ones. The specular reflectivity of SC and PC mirrors as a function of a wavelength after exposure is shown in figure 1. The respective investigations are described in [6].

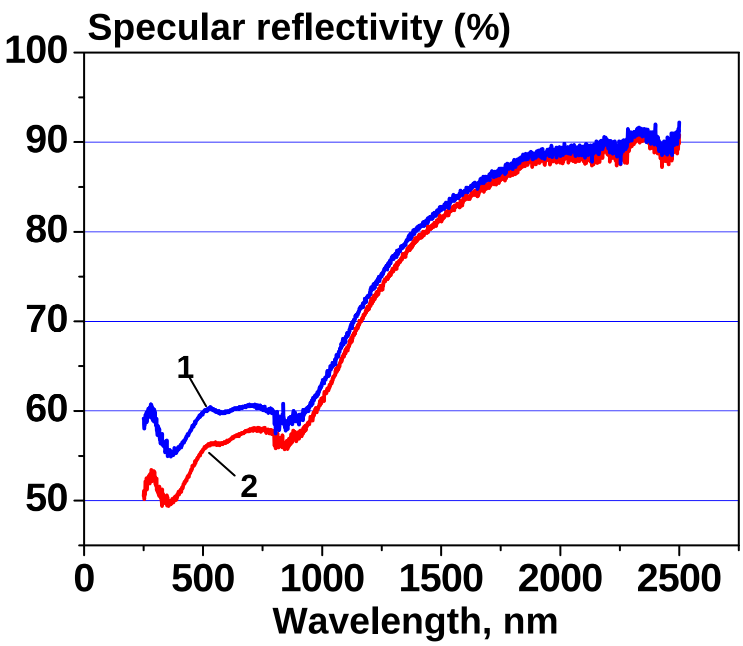

Figure 1: The specular reflectivity of molybdenum mirror after exposure in TEXTOR: 1) for SC Mo mirror 2) for PC Mo mirror;

The deposition expected in the ITER divertor may drastically change the reflectivity of mirrors for both polarized and non-polarized light as it was observed already elsewhere (see e.g.[7]). Therefore, the techniques for prevention from deposition have gained large importance. One of such techniques is the heating of the mirror samples. Dedicated experiments in the divertor of a tokamak were needed addressing specifically the issue of impurity deposition and its mitigation. Such investigations were started with the first exposures of molybdenum mirrors in the DIII-D divertor [8].

Two exposures were made in the divertor: one with mirrors kept at room temperature of a holder and another with a set of mirror samples kept at moderately elevated temperature of 90^oC to 175^oC. The mirrors were exposed under identical plasma conditions. After exposures, on the cold mirrors a deposition of carbon at a rate of ~2-3 nm/sec was observed, whereas on the heated mirror samples the deposition was suppressed: at elevated temperature carbon content was reduced down by a factor of 100 compared to that at room temperature as measured with Nuclear Reaction Analysis (NRA). The decrease of reflectivity of the heated mirrors was largely minimized albeit the complete maintaince of optical characteristics was not achieved as presented in figure 2. Surface analyses have revealed the presence of a thin (<15 nm in thickness) oxide film which has caused a significant degradation of the total reflectivity R_{tot} in the ultraviolet (UV) and visible (VIS) range.

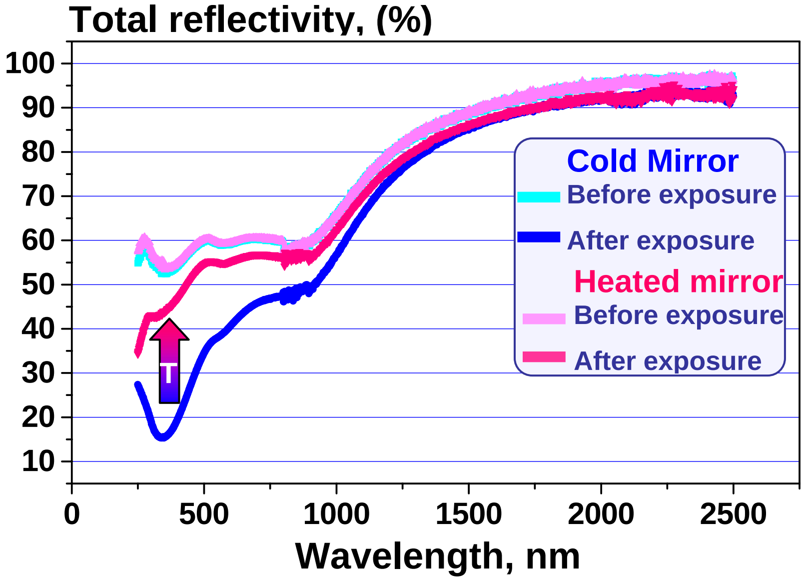

Figure 2: The evolution of the total reflectivity of molybdenum mirrors before and after exposures in DIII-D divertor. The data from [8] is used.

Studies of the temperature effect on the deposition efficiency are also being carried out in Kurchatov institute [9]. It appeared, that the increase of the temperature may not only inhibit the a:C-H layer formation, but it simultaneously leads to the intensified and undesirable surface chemistry processes. The new contaminants formed under these conditions significantly change the reflectivity of mirrors for both polarized and non-polarized light despite the suppression of deposition. Hence, the temperature effect needs to be investigated in more detail to allow the reliable conclusions. At the same time, it became clear that in ITER the *in-situ* cleaning techniques have to be applied along with the deposition mitigation and prevention methods.

Another potentially important technique to mitigate deposition is the proper choice of mirror materials. Recent experiments made with various substrate materials exposed in the same conditions in the SOL of TEXTOR [10], have demonstrated a lower deposition efficiency of carbon on high-Z substrate materials. The direct test addressing the choice of substrate material for diagnostic mirrors was made in TCV. Several mirror samples were installed by pairs on a specially instrumented holder in the lower divertor and exposed for a number of diverted discharges in the same plasma environment. As it was detected after exposure, the high-Z (Mo) samples have showed a deposition efficiency of at least a factor of 4-10 lower than that of low-Z (Si) samples. The dynamic surface Monte-Carlo code TRIDYN [11] has qualitatively reconstructed the differences in the deposition efficiency. Further details are provided in [12]. These findings basically outline the advantages of using diagnostic mirrors made from hard-to-sputter, high-Z materials both under net erosion and net deposition conditions.

2.2. Engineering and technical issues

The material choice for the mirrors in ITER will depend partly on the technology issues. An important aspect is the technological capability to manufacture the mirrors of the desired size and quality. For instance, the capability to produce the large-size (tens of cm) single-crystal molybdenum mirrors is yet to be demonstrated. Alternative techniques need to be pursued. A promising technique is to cover the polycrystalline large size substrate with a molybdenum film having a characteristic columnar structure with a column cross-section of 30-50 nm (figure 3).

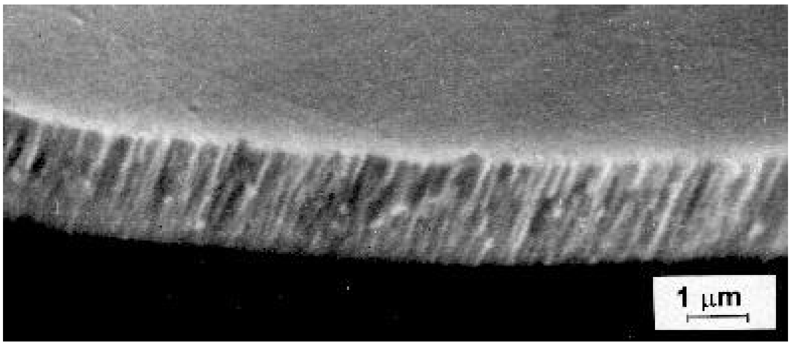

Figure3. Scanning Electron Microscope (SEM) image of a molybdenum film with a columnar structure [12].

The idea behind this technology is that the size of nanostructure, typical for metallic films, will limit the surface roughness during exposure under erosion-dominated conditions. This, in turn will limit the undesirable rise of the diffuse reflectivity, which depends on surface roughness, for a lifetime of such a mirror.
Another promising concept is to use the coating of polycrystalline substrate with a highly reflective material. The characteristic reflectivity values for tungsten, molybdenum and rhodium (Rh) are shown in Figure 4. As one can see, coating the mirrors with rhodium may increase the total reflectivity in the UV and VIS range of up to 75 percent, gaining ~ 10-25% more than from pure molybdenum. The technology of producing the Rh-coated mirrors is presently being developed in several laboratories: ISSP “Chernogolovka”, Kurchatov Institute, University of Basel and ENEA Frascatti. The respective values of the reflectivity of Rh-coated mirrors from several producers are shown in figure 5.

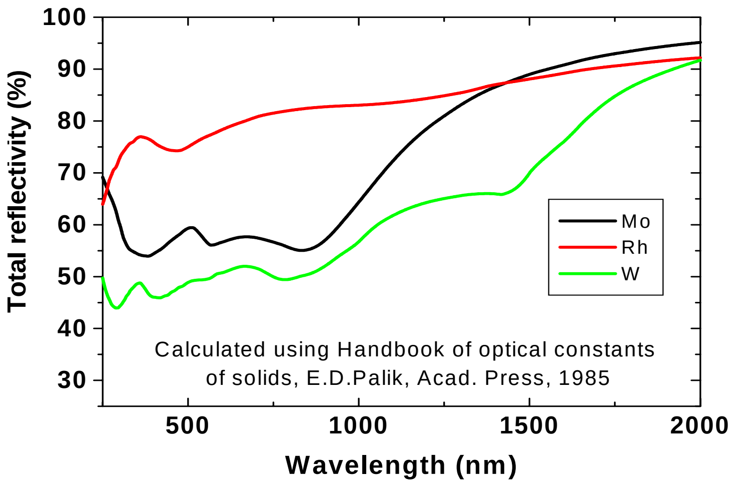

Figure 4 . The reflectivity as a function of a wavelength for molybdenum, tungsten and rhodium mirror materials.

On the other hand, polishing and surface finishing techniques cause a strong effect on the optical properties of mirrors. It was shown [6] that the conventional polishing techniques introduce the defects into mirrors' surfaces, thus destroying the initially perfect crystal structure. Annealing treatments and/or pre-sputtering of the defect layer from the mirror surface are shown to minimize the negative effect of polishing techniques but more efforts are needed in this direction. Additionally, annealing of polycrystalline mirrors or mirror substrates prior to installation into ITER may reduce their thermal shrinking/expansion under the thermal excursions during their operation.

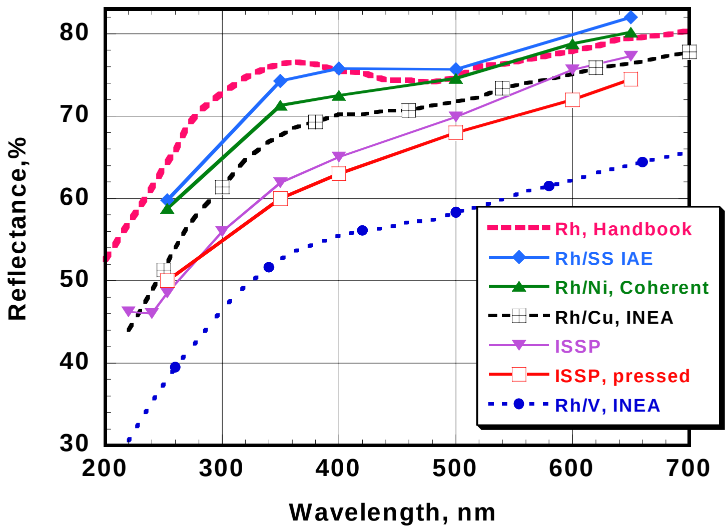

Figure 5 .The dependence of a total reflectivity on a wavelength for Rh-coated mirrors from various producers [14].

2.3. Mirror protection and cleaning

Recent experiments in Tore-Supra [5], where the major part of erosion was due to conditioning discharges, clearly demonstrated the necessity of mirror protection against the wall conditioning. In the present dedicated mirror experiments the protection measures are taken: the retraction of the Limiter Lock [15] systems with mirrors in TEXTOR and the DiMES [16] transport system in DIII-D during glow discharge cleaning and boronizations, floating of the mirror holder in TCV to minimize the effect of wall conditioning. The respective studies are in progress in HL-2A [17] where several protection geometries are being investigated. For the future ITER diagnostic systems the complex of protection measures is needed, similarly like it presently proposed for the upper port CXRS system [18] where the optical components will be placed in the diagnostic tubes (figure 6) and protected with the shutters during all the wall conditioning procedures and partly during the working discharges. The diagnostic tube that is proposed is a separate unit which can be retracted as whole from the diagnostics and repaired or replaced.
Recent experiments in DIII-D have emphasized an urgent need for *in-situ* cleaning of mirrors in ITER diagnostics. For the initial cleaning prior to mirror installation into the diagnostic system, a hydrogen glow discharge treatment represents the good opportunity. Oxidized mirrors were successfully cleaned prior to exposure in TEXTOR at the University of Basel using the H-glow discharge with energy of ions being below the threshold for physical sputtering [6]. At the same time, more ITER-relevant techniques, compatible with constant

magnetic field are being explored and promising results are obtained at Kurchatov Institute [19] and at the Ioffe Institute of Physics and Technology [20].

2.4. Other effects affecting the optical performance of diagnostic mirrors

In ITER the diagnostic mirrors will be exposed in conditions which are quite different from those in any existing fusion device. In particular, the neutron dose levels in ITER will be an order of magnitude higher [21]. Neutron irradiation tests of candidate mirror materials were made, and the results were rather promising for metal mirrors [22]. At the same time, new mirror materials and technologies are presently under consideration, like Mo-film coated and Rh-coated mirrors, multi-layer dielectric mirrors etc. The stability of these new candidate mirror materials under neutron impact is yet to be critically assessed.
Another potentially dangerous effect can cause the operation under intensive gamma environment, which may significantly increase the chemical reactivity of the mirror towards impurities. The respective studies of stainless steel and molybdenum mirrors are planned to be performed at Kurchatov Institute.
As soon as the coated mirrors are concerned, an adhesion and the thermo-mechanical stability of coating layer represent the critical issue [23]. The respective tests are ongoing.

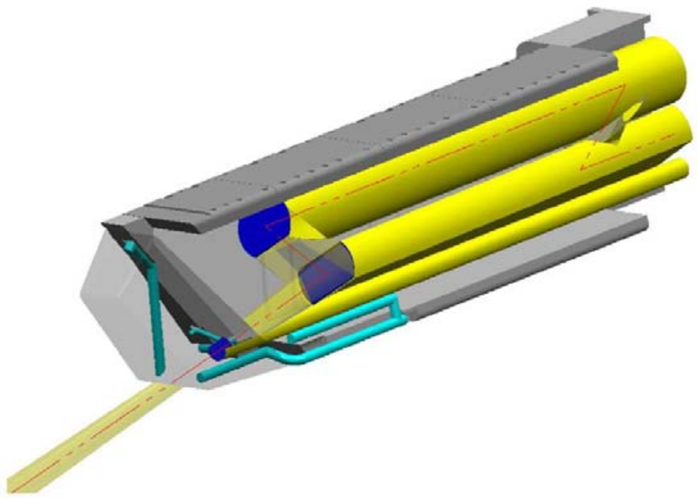

Figure 6. Scheme of core CXRS system for ITER with exchangeable diagnostic tubes

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2.5. Modeling of mirror performance

Since ITER will have a unique set of basic engineering and plasma parameters which cannot be met in any of existing fusion devices, the predictive modeling of mirror performance in ITER is crucially important for the successful R&D on the first mirrors. Presently the modeling is focused on a) estimation of the plasma in the edge plasma of ITER near the wall in the vicinity of diagnostic ducts and neutral fluxes to the mirrors; and b) the subsequent impurity transport modeling inside the selected diagnostic ducts. The main modeling activity is now being concentrated in Argonne National Laboratory (USA) where the impurity transport MC Mirror code is being developed in order to address primarily the US-credited Motional Stark Effect (MSE) diagnostic system. Modeling is also started at the Forschungszentrum Jülich, where the B2-Eirene [24, 25] Monte-Carlo plasma-neutral code is being applied to reconstruct the edge parameters of ITER. Subsequently, the ERO Monte-Carlo impurity transport code [26] will be applied to evaluate the erosion and deposition patterns for the two EU-credited diagnostics: core Charge eXchange Recombination Spectroscopy (CXRS) and LIght Detection And Ranging (LIDAR) system. The modeling is underway.

3. Summary

In the recent years the research and development program on first mirrors was essentially intensified and the significant progress was achieved pursuing the first mirror issue for ITER. Better understanding of the mirror performance under erosion-dominated conditions was attained, the materials capable to withstand the erosion without significant losses of optical properties were found. New techniques for the deposition mitigation have demonstrated the promising results. Methods for the *in-situ* mirror cleaning in ITER are under development. The first attempts to model the mirror performance in ITER are being made. All these directions have to be further developed in future. At the same time there are many outstanding issues which need to be addressed in the nearest future.
Among these issues are: extensive tests of new mirror materials, reflecting coatings as an alternative to the existing mirror candidate solutions, including tests in the neutron and gamma environment and performance tests in the beryllium environment.

4. Prospects for future

The future research on first mirrors will be characterized by the three main features.

- A new structure of investigations will be applied. A review of all diagnostic systems of ITER using mirrors is presently under progress and based on this review the groups of diagnostics in which the mirrors will be exposed under same/similar conditions will be selected. This will allow the selection of the critical, dominant processes influencing the mirror performance for the particular groups of diagnostics.
- Diagnostic-specific programs will be launched, in which the investigations will be focused on the diagnostic-specific issues and demands, taking into account the main processes influencing the mirror performance for the selected diagnostics as defined above.
- The research will be accompanied by the dedicated predictive modeling addressing the expected performance of the respective diagnostic systems in ITER.

References

* Members of the Specialists Working Group on the first mirrors of the ITPA Topical Group on Diagnostics are: A. Costley (ITER IT), Y. Hirooka (Japan), H. Zushi (Japan), N.Klassen (Russia), D. Orlinski (Russia), V. Voitsenya (Ukraine, Chair), K. Vukolov (Russia), G. De Temmerman (EU), E. Hogdson (EU), M.Lipa (EU), A. Litnovsky (EU, Co-Chair), R. Koenig (EU), J. Brooks (USA), J. Hogan (USA), D. Rudakov (USA), Ch. Skinner (USA), J. Chen (China), Y.Zhou (China), S.J. Yoo (South Korea), V. Kumar (India) and S. Pandya (India).
Additional contributing authors: A. J. H. Donné, M. von Hellermann, A. Rogov and L. Marot

[1] A. J. H. Donné et al., IT/P1-24, these proceedings.
[2] A. Litnovsky et al., J. Nucl. Mater., in press.
[3] V. Voitsenya et al., Plasma Dev. and Oper. 13, No.4 (2005) 291.
[4] V. Voitsenya et al., J. Nucl. Mater 290-293 (2001) 336.
[5] M. Lipa et al., Fus. Eng. and Design 81 (2006) 221.
[6] A. Litnovsky et al., Fus. Eng. and Design, in press.
[7] P. Wienhold et al., J.Nucl. Mater. 337–339 (2005) 1116.

[8] D. Rudakov, Rev. Sci. Instr. in press.
[9] K. Vukokov, Proc. of 33rd EPS Conf. P1-116.
[10] A. Kreter et al., Plasma Phys. and Contr. Fusion 48 (2006) 1401.
[11] W. Möller, W. Eckstein, Comp. Phys. Comm. 51 (1988) 355.
[12] G. De Temmerman et al., J. Nucl. Mater, in press.
[13] A.F. Bardamid et al., Plasma Dev. and Operations, Vol. 14, No.2 (2006) 159.
[14] D. Orlinsky et al. Probl. of At. Sci. and Techn., series Thermonuclear Fusion, vol.3, (2005) 3 (in Russian).
[15] B. Schweer et al, Fus. Sci. and Technology, Vol. 47, Nr. 2 (2005) 138.
[16] C.P.C. Wong et al., C. P. C. Wong, J. Nucl. Mater. 433 (1998) 258.
[17] Y. Zhou, Fus. Eng. and Design, in press.
[18] M. von Hellermann et al, IT/P1-26, these proceedings.
[19] K. Vukolov et al., Plasma Dev. And Operations. Vol. 12 (2004) 193.
[20] E. Mukhin, Plasma Dev. and Operations, in press.
[21] A. Costley, Fus. Eng. and Design 74 (2005) 109.
[22] A. Costley, Fus. Eng. and Design 55 (2001) 331.
[23] A. Rogov and K. Vukolov, Tech. Phys. Vol.51. No.4 (2006) 499.
[24] B. J. Brahms, Computational studies in tokamak equilibrium and transport, PhD thesis, Rijksuniviversiteit, Utrecht, the Netherlands, 1986.
[25] D. Reiter, J. Nucl. Mater. 196-198 (1992) 80.
[26] A. Kirschner et al., Nucl. Fusion, vol. 40, No. 5 (2000) 989.