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DIAGNOSTIC MIRRORS FOR ITER: RESEARCH IN THE FRAME OF INTERNATIONAL TOKAMAK PHYSICS ACTIVITY

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Abstract

Mirrors will be used as first plasma-viewing elements in optical and laser-based diagnostics in ITER. Deterioration of the mirror performance due to e.g. sputtering of the mirror surface by plasma particles or deposition of impurities will hamper the entire performance of the affected diagnostic and thus affect ITER operation. Specialists Working Group on First Mirrors (FM SWG) in the Topical Group on Diagnostics of the International Tokamak Physics Activity (ITPA) plays an important role in finding solutions for diagnostic first mirrors.

Sound progress was achieved during the past decade of research on diagnostic mirrors for ITER. Single crystal (SC) rhodium (Rh) mirrors became available. SC rhodium and molybdenum (Mo) mirrors survived in conditions corresponding to ~ 200 cleaning cycles with a negligible degradation of reflectivity. These results are important for a mirror cleaning system which is presently under development. The cleaning system is based on sputtering of contaminants by plasma. Repetitive cleaning was tested on several mirror materials. Experiments comprised contamination/cleaning cycles. The reflectivity SC Mo and Rh mirrors has changed insignificantly after 80 cycles. First *in situ* cleaning using radiofrequency plasma was conducted in EAST tokamak with a mock-up plate of ITER Edge Thomson Scattering with five inserted mirrors. Contaminants from the mirrors were removed. Physics of cleaning discharge was studied both experimentally and by modeling.

Mirror contamination can also be mitigated by protecting diagnostic ducts. A Deposition Mitigation duct system was exposed in KSTAR. The real-time measurement of deposition in the diagnostic duct was pioneered during this experiment. Results evidenced the dominating effect of the wall conditioning and baking on contamination inside the duct. A baffled cassette with mirrors was exposed at the main wall of JET ILW for 23,6 plasma hours. No significant degradation of reflectivity was measured on mirrors located in the ducts.

Predictive modeling was further advanced. A model for the particle transport, deposition and erosion at the port-plug was used in selecting an optical layout of several ITER diagnostics.

These achievements contributed to the focusing of the first mirror research thus accelerating the diagnostic development. Modeling requires more efforts. Remaining crucial issues will be in a focus of the future work of the FM SWG.

1. INTRODUCTION AND MOTIVATION

Mirrors will be guiding plasma radiation towards the detecting systems in optical and laser-based ITER diagnostics. A so-called “first mirror” will be an optical element viewing ITER plasma directly. According to present estimates, first mirrors in the harsh ITER environment will mostly suffer from sputtering by energetic plasma particles and from deposition of plasma impurities onto the mirror surface [1, 2]. These processes will deteriorate the mirror performance and in turn, will hamper the entire performance of the affected diagnostic. As can be inferred from [3], several mirror-based diagnostic systems, as e.g. divertor Thomson scattering and impurity monitor will be required for the machine protection and basic control. The effect of a failure of such systems cannot be overestimated.

In order to address a crucial issue of the mirror lifetime, an extensive research program on diagnostic mirrors is underway under the scientific guidance of International Tokamak Physics Activity (ITPA), largely supported by ITER Organization and Domestic Agencies (DAs). The aim of the program is to detect and to investigate the processes affecting the mirror reflectivity, to estimate the risk of degradation and to find the ways of suppressing or eliminating these adverse processes. The Specialists Working Group on First Mirrors (FM SWG) in the Diagnostics Topical Group of the ITPA concentrates its efforts on finding solutions for diagnostic mirrors. Activities of the FM SWG are focused on five topics of the Work Plan [4] of the R&D on first mirrors:

1. Performance of diagnostic mirrors under erosion- and deposition-dominated conditions: material choice
2. Predictive modeling of the performance of diagnostic mirrors in ITER
3. Mirror surface recovery
4. Tests of diagnostic mirrors in a neutron, gamma and x-ray environment
5. Engineering and manufacturing challenges for first mirrors in ITER.

Addressing these directions via dedicated distributed tasks in a consistent and coherent way contributes to the so-called first mirror solution which is a set of measures to be applied to the mirror in order to prolong its high performance lifetime in ITER.

During a last decade since the latest FM overview [2], a significant progress was attained in all aforementioned topics of the WP. New achievements led to the significant, sometimes decisive changes in the research and development (R&D) on first mirrors. Among those findings are:

- Single crystal materials have proven their good optical performance under plasma-sputtering conditions and now are the prime materials for first mirrors
- In order to recover the mirror reflectivity, the *in situ* mirror cleaning system should be used. This system will be based on sputtering of the contaminants from the mirror surface by plasma
- The wall conditioning causes the most adverse effect to unprotected mirror systems. Mirror protection must be used whenever possible, to increase the lifetime.

Newest developments in the fulfillment of the Work Plan, contributing to improvements of the first mirror lifetime are described in this overview.

2. PROGRESS IN THE RESEARCH AND DEVELOPMENT OF DIAGNOSTIC MIRRORS

2.1 Performance of diagnostic mirrors under erosion- and deposition-dominated conditions: material choice

Extensive studies of the mirror degradation in the existing tokamaks were made worldwide at an early stage of the first mirror R&D and the corresponding results are summarized in several reviews [5-10]. The overview of the results from JET is of paramount importance. The world's largest tokamak underwent the change of the first wall and divertor material and now operates with ITER relevant tungsten (W) – beryllium (Be) material mix.

The First Mirror Test (FMT) has been carried out in JET first in the presence of carbon wall and then during three campaigns with the ITER-like wall (JET-ILW) [10-13]. Diagnostic mirrors were installed both in the main chamber and in the divertor as it is shown in Fig. 1a. The following results are related to polycrystalline Mo mirrors exposed during: (i) the third ILW campaign (ILW3, 2015-2016, 23.33 plasma hours) and (ii) all three campaigns, i.e. ILW1-3: 2011-2016, measuring 63,52 plasma hours in total. Nine cassettes with 25 mirrors in total were retrieved: one large cassette with five mirrors from the main chamber exposed to ILW-3 only, four smaller cassettes with 10 mirrors from the divertor after exposure to ILW3 and another of set of four smaller cassettes with 10 mirrors exposed to ILW1-3. The examinations were performed by means of two spectrophotometers for total and diffuse reflectivity determination in the range 400-1600 and 300-2400 nm respectively. Elemental composition and distribution, surface analyses and microstructure were investigated using a number of surface diagnostics comprising optical, atomic force and electron microscopy and ion beam techniques: Nuclear Reaction Analysis (NRA), Heavy Ion Elastic-Recoil Detection Analysis (HIERDA) and Rutherford Backscattering Spectroscopy (RBS). Investigations have brought a number of key results.

(a). Graphs in Fig. 2a show reflectivity of mirrors from the main chamber wall. The total reflectivity of all mirrors has decreased by only 2%-3% from the initial value. All of them have a very thin modified layer (5-15 nm) containing deuterium (D), Be, carbon (C) and oxygen (O). This affected the optically active layer (15-20 nm on Mo) and lead to the increase of diffuse reflectivity. Neither W nor N have been found on the surface within detection limits.

(b). All mirrors from the divertor (inner, outer, base under the bulk W tile) lost reflectivity by 20-80%, as shown in Fig. 2b. This result confirms earlier findings and could be even expected, but there are significant differences in the surface state dependent on the location and exposure time.
(c). The thickest layers composed mainly of beryllium (Be) are in the outer divertor: 850 nm after ILW1-3.
(d). In addition to co-deposits, divertor mirrors are covered with metal dust: Be, Inconel and tungsten (W).
(e). Nitrogen (N), tungsten and nickel (Ni) are on all divertor mirrors. The highest N and W concentrations are in the inner divertor, while the content of Ni is the greatest in the outer.

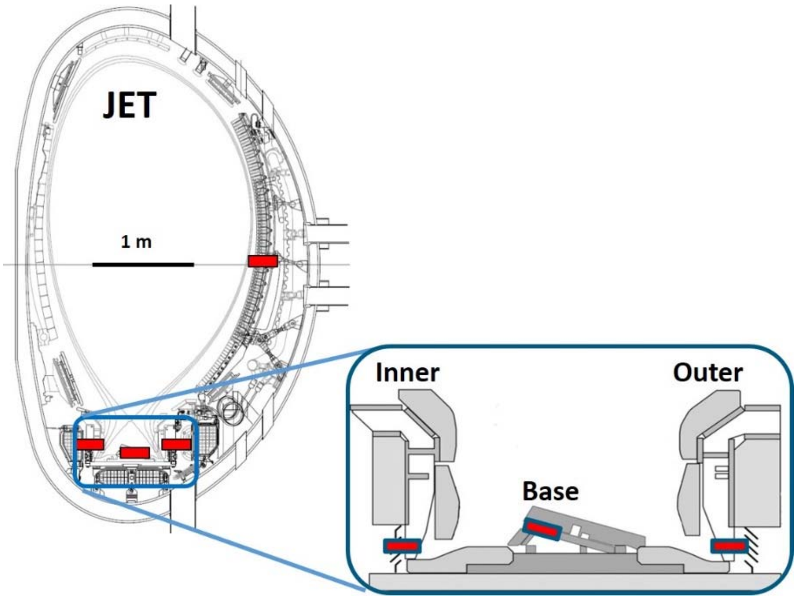

Fig. 1: Scheme of mirror locations in JET

Generally, all tests in the divertor performed during both JET-C and JET-ILW experimental campaigns consistently show that all mirrors, independently on the location completely lose reflectivity because of deposition. The growth rate of such layers in JET-ILW is however, about 20 times smaller than that with carbon PFC. At the same time, main chamber mirrors placed deeper in the diagnostic ducts, have revealed only an insignificant change of the total and diffuse reflectivity.

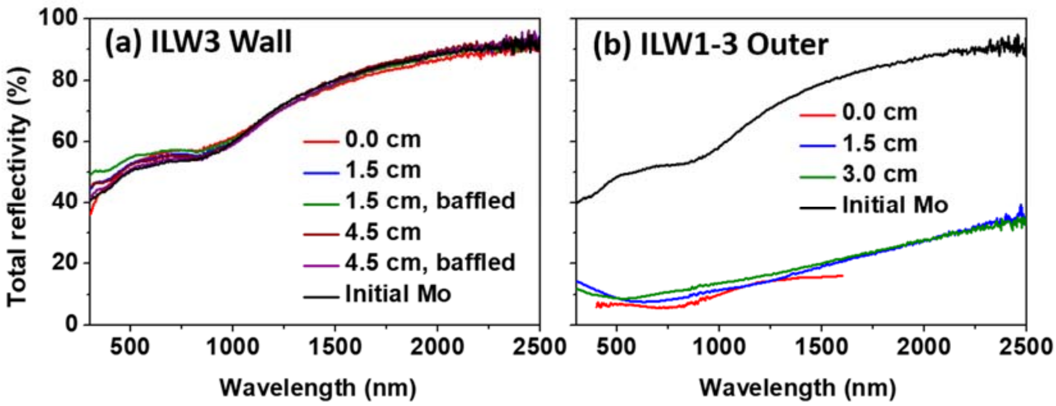

Fig. 2: Total reflectivity of mirrors exposed: (a) on the main chamber in ILW3, (b) in the divertor during ILW1-3. Numbers denote a distance from the entrance of the cassette in cm in the depth of a diagnostic duct.

Studies at JET were performed largely using polycrystalline molybdenum mirrors (PC Mo). Meanwhile, conducted studies have revealed the decisive advantages of the single-crystal molybdenum (SC Mo) in fusion environment [14-16]. The current mirror material research is therefore, was re-focused on finding the material compatible with mirror cleaning system used for mirror recovery – topic 3 in the Work Plan of the first mirror R&D. Progress in the mirror recovery is described in details in the chapter 2.3.

2.2. Predictive modeling of the performance of diagnostic first mirrors in ITER

A 3D numerical model was developed for simulation of particles incident to the recessed main chamber port-plugs in ITER during the stationary nominal power operation [17, 21]. The calculations have indicated a high probability of the net erosion conditions on the port-plug faces: the ratio of the eroding to the depositing flux of Be is always larger than one and can reach 12 on the upper port. Approximate models were devised to obtain the "worst case" estimates of impurity fluxes on the first mirrors which face the plasma directly [19]. However, those models are believed to be yet not accurate enough for reliable predictions of the surface composition changes in the mirror ducts. The main reason is the lack of an adequate description of the particle sticking in multi-component layers exposed to energetic particles. Therefore, the modeling is presently used primarily for the coarse prediction of effects on mirrors.

The results of the modelling were applied for the design of the Hα diagnostics. Fluxes of neutral deuterium (D), tritium (T) and beryllium on the first mirror of Hα diagnostics in the equatorial ports 11 and 12 were calculated [21]. Only stationary operation of ITER were modelled, no transients were considered. Modeling predictions foresee the erosion-dominated conditions at the surface of the first mirror of Hα system. The maximum estimated erosion rate is about 100 nm/year for a single crystal molybdenum mirror. Single crystal mirrors under these conditions will keep their optical properties under plasma sputtering. The deposition-dominated area is located on the edges of the mirror shadowed from direct plasma impact. The maximum deposition rate in worst-case scenario is about ~900 nm/year. The contaminated edges of the mirror do not play a role since the light collection area is entirely under erosion-dominated conditions for the selected field-of-view. Therefore, it might be unnecessary to operate the mirror cleaning system for suppression of deposition on the first mirror of Hα diagnostics [21]. The mirror surface recovery techniques, including mirror cleaning system will however yet be installed in order to ensure mirror operation in case of accidents (e.g. water leaks) which likely cause the first mirror contamination and deteriorate the optical reflectivity. Significant effort is concentrated on development of the mirror recovery techniques as a reader may infer from the following chapter.

2.3. Mirror surface recovery

2.3.1. Finding an optimum single crystal orientation and repetitive cleaning of single crystal mirrors

An adverse impact of impurity deposition in part illustrated in Fig. 2b can be so significant, that the reflectivity of affected mirror may become lost completely [6]. Techniques for so-called mirror surface recovery (MSR) are therefore under intensive development. These techniques comprise:

- Active mirror recovery by e.g. cleaning of mirrors,
- Passive techniques aimed at suppressing the mirror contamination by e.g. shutters

and

- Technical assistance techniques for monitoring the mirror reflectivity.

It is decided that the cleaning of the mirrors must take place *in situ* in the corresponding diagnostic. Such a way of cleaning on one hand, helps to avoid a retraction of a complete ITER port plug usually containing several diagnostics, for a single mirror repair and/or replacement and thus saves time and efforts and minimizes risks of diagnostic damage during (de-)installation. On the other hand, the corresponding *in situ* mirror cleaning system is rather complex. Comparative studies performed in the frame of the ITPA allowed to sort out the main candidate mirror materials and cleaning techniques.

Mirrors will be cleaned in ITER using sputtering plasma discharge. This way of cleaning may ensure the removal of contaminants together with a part of the mirror material affected by impurity implantation. At the same time, such a technique represents a challenge for a mirror candidate material. Presently, based on results of both tokamak experiments and laboratory studies [14, 15] the single crystal mirrors are supposed to be employed in most of ITER diagnostics due to their ability to preserve the reflectivity under sputtering conditions. Series of plasma sputtering tests were made with single crystal materials in conditions expected in mirror cleaning system. For the first time, the single crystal rhodium (SC Rh) was used together with single crystal molybdenum (SC Mo) [22-24]. The experiments were performed in the PSI 2 linear plasma device [25] at Forschungszentrum Jülich GmbH. Single crystal Mo and Rh mirrors were placed in the holder and exposed to steady-state helium (He) plasma as shown in Fig. 3a. The mirror temperature was about 250ºC corresponding to that expected in ITER mirror cleaning system. The mirrors were biased, and the resulting ion energy was ~100 eV. During the experiments, the maximum total fluence of up to 4.0×10^{21} ion/cm^2 was attained.

Sputtering of mirrors was evaluated using the calibrated craters made by focused ion beam and by mass loss measurements. Single crystal molybdenum has lost 900 nm sputtered, whereas the single crystal rhodium has lost about 1900 nm. The removed material corresponded up to nearly 200 cleaning cycles in ITER for SC Rh.

Optical reflectivity was measured with the spectrophotometer before and after exposures and presented in Fig. 3b and Fig. 3c respectively. Only a minor degradation of specular reflectivity, not exceeding 8% at 250 nm for SC Mo were detected after ~100 equivalent mirror cleanings. For the SC Rh, the reflectivity change is ~ 7%, which demonstrates a decisive advantage of single crystal materials also with respect to mirror cleaning.

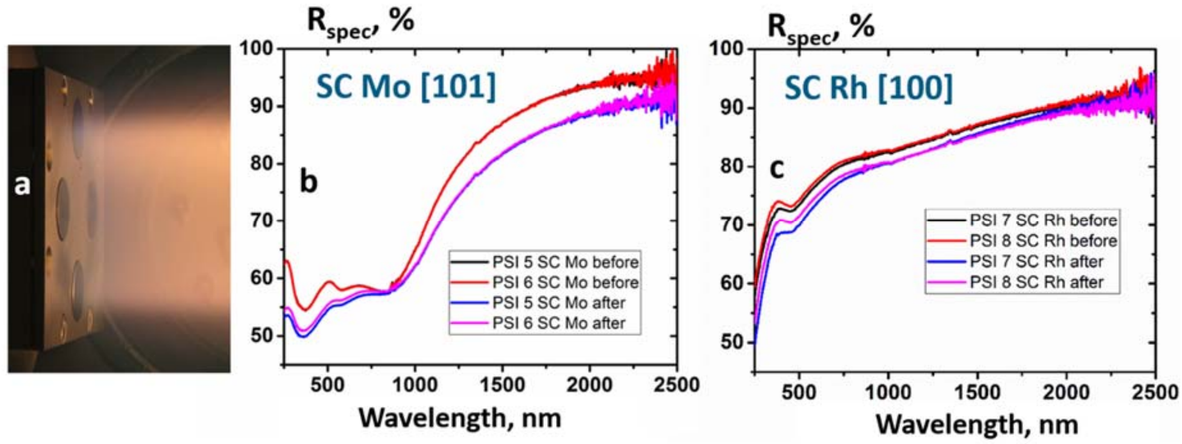

Figure 3. Sputtering of SC Mo and SC Rh mirrors in steady-state He plasmas: a) scheme of exposures and b) the specular reflectivity of SC Mo and c) SC Rh before and after sputtering.

The aforementioned progress attained in studies of mirror materials synergistically contributed to a further step towards the final feasibility test of the mirror cleaning system itself. The new radiofrequency-based cleaning system developed for the US-lead Upper Port Wide Angle Viewing System was capable for removing 10-20 nm of tungsten from the single crystal Mo mirror. No mirror damage has occurred after cleaning and the surface roughness of the mirror did not increase [26].

An ability of cleaning system to remove the contaminants from the mirrors on a regular cyclic basis is of crucial importance for validation of mirror cleaning in ITER. The dedicated investigation was performed at the University of Basel. During this study, the ability of the cleaning system to recover the mirror reflectivity after repetitive "contamination – cleaning" cycles was tested. The impact of repetitive cleaning on mirrors was investigated on several types of mirrors: single crystal, nanocrystalline (NC) and polycrystalline Mo mirrors, SC and PC Rh mirrors[16]. The NC Mo film had a thickness of 2.4 µm. Up to 80 cycles were performed. One cycle consisted of one deposition of a contaminant layer: a 25 nm thick aluminum (Al)/W layer, comprising 90 at.% Al and 10 at.% W on one half of a mirror followed by a removal of contamination by plasma cleaning. The cleaning was performed with 60 MHz radiofrequency (RF)-stimulated argon plasma capacitively coupled (CCRF) to the mirrors and leading to a self-bias of -280 V. Measurements of total and diffuse reflectivity in the range of 250 - 2500 nm were performed using a spectrophotometer. Surface roughness was investigated with stylus profiler after 20, 34, 57 and 80 cycles. For PC and for NC molybdenum mirrors, a significant increase of the diffuse reflectivity of up to 50% (20% respectively) was detected at the 250 nm. At the same time, for the SC mirrors (Rh and Mo), the specular reflectivity only slightly decreased after 80 cleaning cycles with less than 5% variation while the diffuse reflectivity remained below 5%. The corresponding dependencies are presented in Fig. 4. Based on these results, it was confirmed that SC Rh and SC Mo were found to be the most promising materials for ITER mirrors. In the course of this study, the basic principle of the mirror cleaning system, which is a capability of cyclic removal of contaminants from the mirrors, was justified. Promising results on repetitive cleaning allowed making a further important step towards the realization of the first mirror cleaning system for ITER – a first *in situ* test of mirror cleaning system in a tokamak.

2.3.2. First-ever in situ cleaning in a tokamak

The first mirror (FM) *in situ* cleaning system was developed and tested in the Experimental Advanced Superconducting Tokamak (EAST), using the Material and Plasma Evaluation System which is usually employed for exposure of samples in the main chamber of EAST. EAST has an ITER-like magnetic field configuration which makes it an excellent platform for ITER mirror cleaning studies. Five mirror insets with a diameter of 25 mm, coated with NC Mo and contaminated with a 10 nm thick alumina (Al_2O_3) film acting as Be proxy [27] were inserted into the ITER edge Thomson Scattering (ETS) mock-up plate. The mockup plate with mirrors was introduced to the EAST chamber where the mirrors were cleaned with a RF neon (Ne) plasma applied to the ETS mock-up plate. ETS mock-up plate was positioned approximately in the center of the port flush with the first wall as shown in Fig. 5a. During the cleaning discharge, the EAST toroidal magnetic (B) field was kept at 1.7 T and the angle between the mirror surface and the B field was set to 5° and 20°, similar to what is expected in several ITER diagnostics.

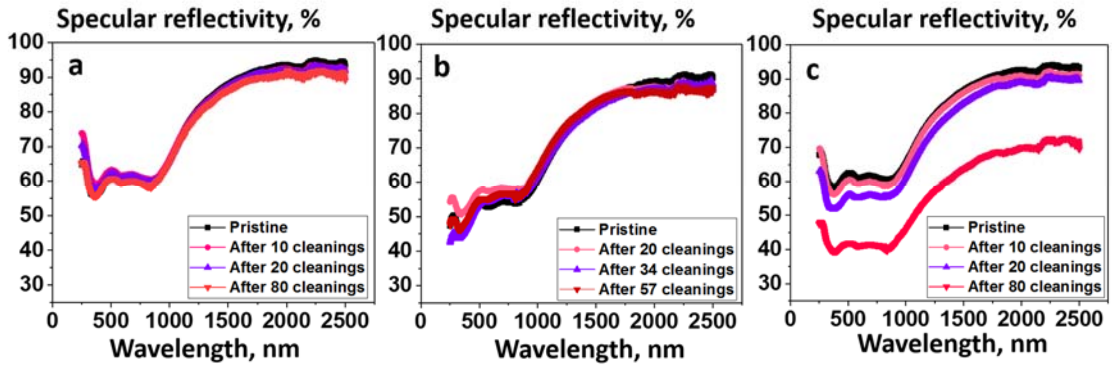

Figure 4. Specular reflectivity after repetitive contamination-cleaning samples: a) for SC Mo mirror, b) for nano-coated molybdenum mirror and c) for a polycrystalline Mo mirror.

It was demonstrated that neon (Ne) plasma at a large mirror can be successfully ignited and sustained for several hours with a B field of 1.7 T. The mirrors were successfully cleaned both at 5 and 20 degrees to toroidal field with a self-bias of - 20 V and - 80 V respectively for 0.5 hours. The presence of stainless steel remnants such as iron was observed on insets cleaned at 5°. This phenomenon is most likely caused by the long range re-deposition of sputtered material from the ETS plate. At larger angles (e.g. 20°), no iron re-deposition was observed. Total reflectivity measured with a spectrophotometer, was completely recovered for all insets cleaned in EAST except for the sample located at the edge of the ETS plate for 5° cleaning - due to plasma flux inhomogeneity in presence of high magnetic field. The corresponding evolution of the total reflectivity of cleaned mirrors is provided in Fig. 5b.

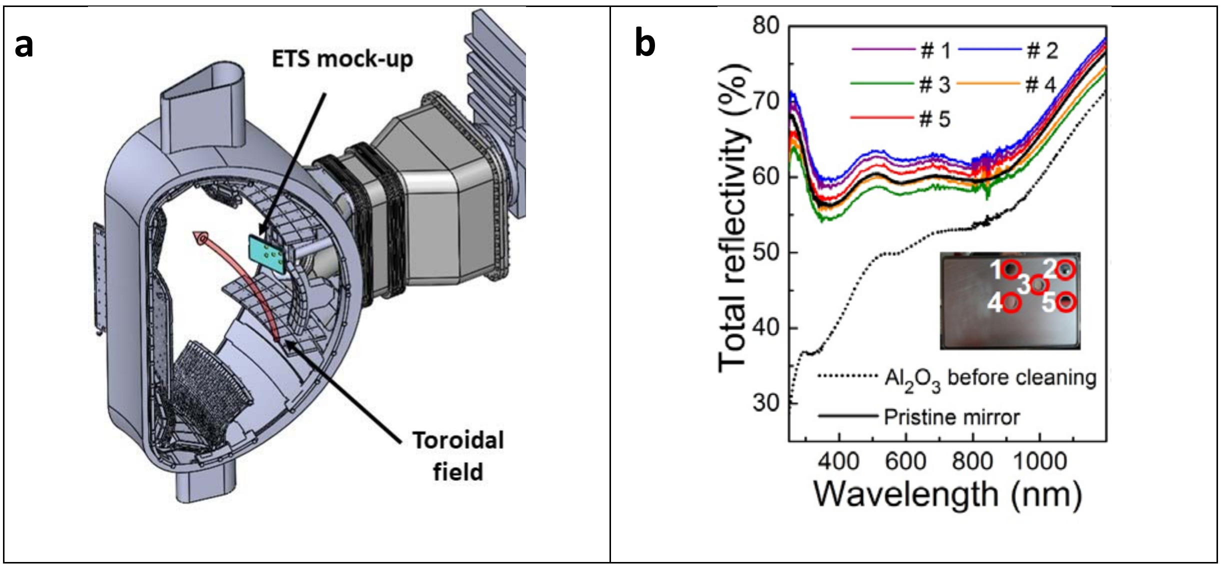

Figure 5. Experiment on in situ mirror cleaning in EAST: a) a scheme of the experiment, b) a view of the plate with mirror insets as exposed in EAST along with results of measurements of total reflectivity of five molybdenum polycrystalline mirrors 1-5 as a function of a wavelength. Note the completely decreased reflectivity of a mirror contaminated with Al_2O_3.

Generally, the cleaning rate was at least 40 times faster compared to that in the lab conditions without the magnetic field with the identical mirror insets and the same RF power. Further details of plasma cleaning in EAST are provided in [28]. Experiments with ITER-like first mirror unit mock-up are planned in EAST.

2.3.3. Understanding the physics of a cleaning discharge

Sound progress was attained not only in experimental investigations and test application of the mirror cleaning system but also in the physics understanding of the cleaning discharge. In particular, a comprehensive study of near-electrode sheath characteristics of capacitive-coupled radiofrequency discharge was performed for a wide range of noble gases: helium, neon, argon, krypton and xenon in order to find the optimum mirror cleaning regime [29]. Ion energy distribution function (IEDF) and ion flux (IF) on the powered electrode were measured as function of main cleaning discharge control parameters: RF power absorbed in the discharge, RF frequency and working gas pressure. It was shown that IEDF cannot be approximated by a mono-energetic distribution and needs to be used for sputtering rate calculation [29]. The ion flux was found to be strongly dependent on the applied RF frequency and on working gas type. According to these investigations, the effective sputtering rate of beryllium and tungsten was calculated and compared with that of molybdenum. The most effective Be sputtering is expected in helium discharge at frequency of 60-80 MHz while heavier gases are to be used for tungsten removal. It should be noted, that sputtering rates ratio Y_W/Y_{Mo} was found to be low <1. Therefore, W removal should be applied only if necessary at low frequency and with high absorbed RF power to minimize the impact on the mirror surface.

A significant attention is paid to the process of sputtered atoms re-deposition back to the mirror surface. However, the experimental studies of contamination transport and re-deposition are complicated as the process is strongly influenced by experiment geometry. For this reason, the Monte-Carlo code KITe is being developed [30] specifically for neutral particle transport in fusion applications. The code utilize sophisticated model for simulation of neutral particle collisions including realistic attractive-repulsive interaction potential and accounting for thermal velocities of gas atoms. In order to validate the code, the dedicated benchmarking experiment was made. The gold (Au) film was sputtered in the neon RF discharge at two pressures of 1 and 10 Pa. The resulting transport of sputtered Au atoms caused the deposition of Au on two collector plates. The distribution of deposited material was measured using the optical ellipsometry and Rutherford Backscattering Spectroscopy and modeled using KITe code. Experimental data on sputtered gold atoms and their transport in CCRF-discharge and dedicated modeling using KITe demonstrated a good agreement [30].

Plasma-based mirror cleaning system represents an active tool for the mirror surface recovery. Mirror degradation however, can also be minimized by using dedicated passive techniques like shutters and possibly, the shaped diagnostic ducts as described briefly in the next section.

2.3.4. *Passive protection of mirrors: on suppression of mirror contamination by duct geometry*

Earlier modeling results predict an effective suppression of sputtering and impurity fluxes attained by using specially shaped diagnostic ducts equipped with fins of baffles. It is expected to have the particles trapped by these fins on their way towards the mirror. The predicted suppression of sputtering and deposition can be very significant. For cylindrical diagnostic ducts of length L with a diameter of D, the attenuation factors for the particle fluxes can be as high as 10^3 and more for selected ITER scenarios and modeling assumptions, described in details in [19]. Implementation of fins leads to the further 3- to 10-fold reduction [19].Following these promising results the dedicated experiments with duct mirror systems are underway worldwide. Important results come from JET where the instrumented cassette containing both smooth and shaped (baffled) ducts was installed on the first wall and exposed. As it can be seen from the Fig. 2a. for the mirrors installed in the diagnostic ducts, the degradation of the reflectivity has essentially stopped. However, using the shaped ducts to suppress the mirror contamination as predicted in [21] did not exhibit decisive advantages of using baffles yet. Only minor changes in total reflectivity of mirrors installed in smooth and shaped ducts were detected, as shown in Fig. 2a. It must be noted however, that the mirrors in the cassette were not protected from contamination during conditioning discharges. There is a definite need in “clean” experiment with duct geometry using the mirrors protected with shutters during wall conditioning. The effect of wall conditioning can dominate the mirror contamination, as it was inferred after exposure of baffled duct system in TEXTOR [29] and directly measured in the experiment described in the next chapter.

2.3.5. Real-time measurements of mirror contamination in diagnostic ducts

For investigation of adverse processes degrading the mirror performance and for evaluation of duct efficiency, the real-time knowledge on deposition or erosion on the mirror surface is of paramount importance. A duct-based Deposition Mitigation (DeMi) system developed at the Ajou University was successfully installed and exposed in KSTAR tokamak [32]. The real-time measurement of deposition in the diagnostic duct was pioneered during the experiment. Pairs of calibrated quartz crystal microbalances (QCMs) were installed instead of mirrors inside of various diagnostic ducts. Whereas the first QCM 1 was measuring the mass change due to deposition of impurities at varying environmental temperature, the second unit QCM 2 was screened from any particle flux and thus was measuring the sole effect of environment temperature. The resulting difference between signals from QCM1 and QCM2 is therefore, the "pure" effect of particle deposition onto QCM1 acting as a mirror in this experiment. Mass gain due to impurity deposition on the QMB as a function of exposure time is shown in Fig.6 Measurements performed with QCMs resulted in the first-ever real time investigations of the prevailing adverse processes for the mirrors in a tokamak. The experimental data explicitly show the maximum mass gain is caused by the plasma wall conditioning with glow discharge cleaning (GDC) and baking.

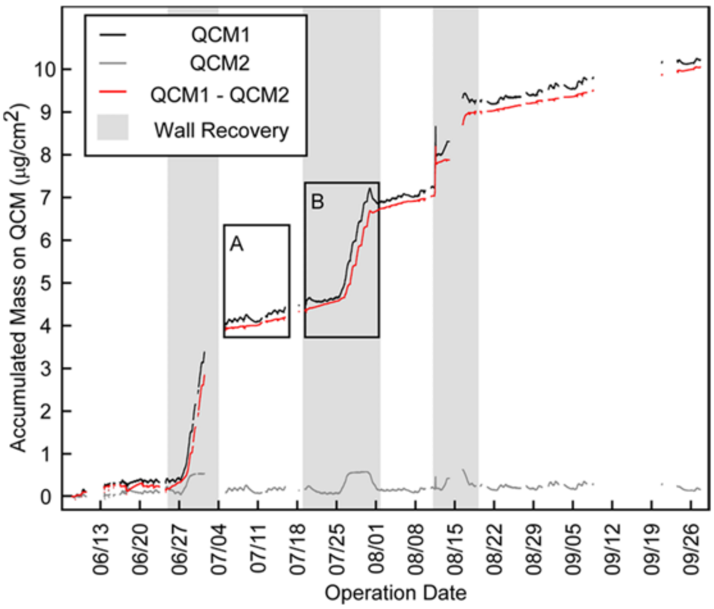

Figure 6. Result of real-time deposition measurement in the duct exposed in KSTAR tokamak. The net deposition signal is in red. Grey areas represent the wall conditioning comprising GDC and baking.

2.3.6. Gas purge in the baffled diagnostic duct – a gas shutter

Gas purge in the long and narrow diagnostic duct can be performed to suppress an adverse influx of impurities towards the diagnostic mirror. The impurity particles on their way towards the mirror collide with atoms of inert gas fed into the diagnostic duct, dissipate their energy in collisions and what is more important, lose their momentum towards the mirror. This concept is sometimes refereed as a "gas shutter" [33] following the pioneering experiments in TEXTOR with the Periscope mirror system equipped with a gas feed [34]. The concept of a gas shutter was further developed at KSTAR. Helium gas feed was performed in the baffled mirror cassette installed to KSTAR. In the course of the experiment, it was proven that the attainable helium pressure in the baffled duct can be as high as 1.9 Pa without any influence to the main chamber pressure of a tokamak [32]. Laboratory experiments performed with DeMi system have demonstrated 99% mitigation of impurity deposition of using argon gas shutter at the pressures exceeding 1.3 Pa [35]. Planned implementation of the DeMi system with a gas shutter into KSTAR therefore, will require the special duct geometry for confinement of an inert gas, such as specially shaped fins. A corresponding experiment is under preparation.

2.4. Engineering and manufacturing challenges for first mirrors in ITER

2.4.1. Development and testing of prototypes

The mentioned progress in first mirror R&D has triggered the intensive development of the real-size prototypes of the first mirror units and the corresponding mirror subsystems. These activities were mostly supported by DAs. Among others, the development of the shutter prototype for the ITER core Charge eXchange Recombination Spectroscopy revealed the remarkable progress. The prototype two-arm shutter driven pneumatically was developed, Fig. 7. This prototype was tested to slightly above 1,000,000 open-close cycles under vacuum at room temperature. The test lasted for 35 days, including overnight and weekend operation, comprising more than 830 operating hours. Mechanical properties of the shutter did not change over time and no leak was found with the detection limit of 1×10^{-7} Pa*l/second. As a response to changes of the CXRS core layout, a one-arm pneumatic shutter is under development, taking into account the results of the previous prototypes.

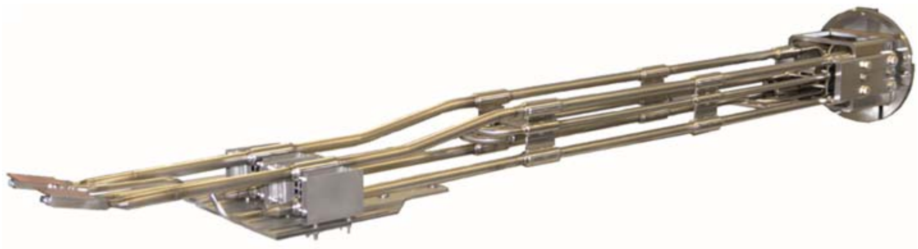

Fig. 7, A two-arm prototype pneumatic shutter for the core CXRS diagnostic

3. SUMMARY AND CONCLUSIONS

Since the last comprehensive FM review in 2009 [2], significant developments were made in all major directions of the Work Plan of the first mirror R&D. These developments have advanced the fusion scientists and engineers towards reaching the first mirror solution. The prime mirror materials for the first mirrors are expected to be single crystal molybdenum and rhodium. For the latter, significant progress towards availability was made recently. These materials survive the severe conditions both of regular plasma operation as well as of sputtering cleaning cycles. The cyclic cleaning has proven the sustainability of the optical reflectivity of single crystal mirrors towards sputtering. Practical tests on direct implementation into tokamak environment are underway and have already brought decisive results. There are modeling predictions that the geometry of baffled ducts may minimize the contamination of the mirror. However, a dedicated experiment with the baffled duct and protecting shutter is needed. A proper tool for such investigations was already developed – a duct mirror system with the real-time control over deposition, the DeMi.

Gained deeper understanding of the underlying physics allowed an improvement of parameters of the cleaning discharge efficiency increasing its applicability for ITER. At the same time, efforts were invested in the assessment of the particle environment in the vicinity of mirrors in ITER and in studying the prevailing processes: erosion or deposition on the mirror.

Improvements in design of the first mirror units and the corresponding components are very significant. As an example, a shutter mockup for the core CXRS system was capable of performing more than 10^6 cycles without degradation of its operational performance.

Aforementioned activities have enabled a significant progress in understanding, focusing efforts and discarding the non-feasible options. Such a focusing already sensibly accelerated the design of related diagnostics.

4. OUTLOOK

Significant progress was attained addressing all critical topics of the first mirror R&D. At the same time, there are areas where more efforts are to be invested. Among them is the predictive modeling of mirror performance in ITER. New models, although more realistic and accurate as compared with first modeling codes, are still lacking the necessary predictive capability and scalability on several important ITER diagnostics. In addition, crucially important tests in neutron and in accidental (e.g. in water leak / steam tests) environment are underway and yet to bring conclusive results. Addressing these tasks in the remaining critical areas of the R&D on diagnostic mirrors will be in focus of the Specialists Working Group on First Mirror in future.

DISCLAIMER

The views and opinions expressed herein do not necessarily reflect those of ITER Organization, the European Commission or the National Natural Science Foundation of China.

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