# Progress in research and development of mirrors for ITER diagnostics

A. Litnovsky 1), V. Voitsenya 2), T. Sugie 3), G. De Temmerman 4), A.E. Costley 5) and A.J.H. Donné 6).

1) Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich, Partner in the Trilateral Euregio Cluster, Ass. EURATOM- FZ Jülich, D-52425 Jülich, Germany, a.litnovsky@fz-juelich.de;
2) IPP, NSC Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine,
3) Japan Atomic Energy Agency, Naka, Ibaraki, 311-0193, Japan,
4) EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK,
5) ITER Cadarache Joint Work Site, 13108, St Paul-Les-Durance Cedex, France,
6) FOM-Institute for Plasma Physics Rijnhuizen, Partner in the Trilateral Euregio Cluster, Association EURATOM - FOM, PO Box 1207, 3430 BE Nieuwegein, The Netherlands.

**Abstract**

All optical and laser diagnostic systems in ITER will use metallic mirrors as plasma viewing elements. In the harsh environment of ITER, the performance of mirrors will decrease mainly because of erosion of their surfaces and deposition of impurities. The deterioration of optical properties of diagnostic mirrors will directly affect the entire performance of the respective ITER diagnostics, possibly leading to their shutdown. Therefore, the R&D on mirrors is of crucial importance for ITER diagnostics. There is a coordinated worldwide research and development program supervised by the Specialists Working Group on first mirrors of the International Tokamak Physics Activity, Topical Group on Diagnostics. This paper provides an overview of new results in the field of the first mirrors, covering the manufacturing of ITER mirror prototypes, investigations of mitigation of deposition and mirror cleaning and the predictive modeling of mirror performance in ITER. The current status of research on beryllium deposition - a new critical area of mirror research, is given along with an outlook for the future activities.

## 1. Introduction

In ITER optical and laser diagnostic systems the first plasma-viewing element will be a mirror [1, 2]. Diagnostic mirrors have to operate in the harsh environment and preserve their optical properties under intensive plasma particle and radiation fluxes and neutron irradiation, by far superseding those in existing fusion devices [3]. The deterioration of the optical properties of mirrors in ITER under these conditions will inevitably hamper the performance of the corresponding diagnostic systems possibly resulting in their complete shutdown. Because of the high importance and acuteness of the problem, the coordinated worldwide research and development program has been initiated. This program is supervised and coordinated by the Specialists Working Group on first mirrors of the International Tokamak Physics Activity (ITPA), Topical Group (TG) on Diagnostics [4]. The R&D on first mirrors is recognized as a high-priority task of the ITPA TG on Diagnostics [5] and is also a topic of the IEA-ITPA Joint Experiments program (task DIAG-2).

To guide the R&D activity on the diagnostic mirrors the so-called Work plan on diagnostic mirrors (WP) is being developed. WP consists of six essential areas – tasks:

I. Performance of diagnostic mirrors under erosion- and deposition- dominated conditions: material choice;

II. Predictive modeling of the performance of diagnostic mirrors in ITER:

II.1. Modeling of the impact of the plasma and neutral environment on optical properties of diagnostic mirrors;

II.2. Modeling of irradiation effects and their impact on the optical characteristics of mirrors;

III. Mitigation of particle deposition onto mirror surfaces;

IV. Cleaning the diagnostic mirrors from deposits;

V. Tests of diagnostic mirrors in a neutron, gamma and x-ray environment;

VI. Engineering and manufacturing challenges for the first mirrors in ITER.

Each area (I-VI) is divided into the stages and each stage contains a number of the defined works – so called work packages. All the aforementioned tasks are to be fulfilled in parallel in a coherent way which allows for an efficient exchange and transfer of knowledge and provides the positive synergism in the solution of mirror issues. The ultimate goal of the work plan is to provide the baseline (generic) mirror solution for the various ITER diagnostics. The baseline mirror solution is the set of measures which must be undertaken in each specific diagnostic to ensure its endurance in ITER. The baseline solution is however, not a solution of a mirror problem in ITER. The "real" solution must be achieved for every particular diagnostic within the respective ITER-diagnostic cluster(s) or consortia. The review of the R&D on first mirrors was presented in [1]. Since then the efforts were intensified and many new results became available which are reviewed in this paper.

## 2. Material choice: manufacturing of the large single-crystal mirrors

Two processes will have the most deteriorating effect on the mirror performance in ITER: erosion due to energetic particles and deposition of impurities [6]. Tokamak research [7] and laboratory studies [8] demonstrated the advantageous behavior of single-crystal materials under erosion-dominated conditions. However, the technological capability to manufacture the single-crystal mirrors of ITER-relevant size had to be demonstrated. Such an effort was initiated at the Kurchatov Institute (Moscow, Russian Federation) where single crystal molybdenum samples with diameters of 10 and 12 cm were grown by an active zone melting technique (Fig. 1).

The manufactured mirror samples will be polished and their optical properties will be tested afterwards both in the Russian Federation and in the EU. Furthermore, one manufactured sample is planned to be exposed in a tokamak plasma to test its robustness and performance under erosion-dominated conditions.


Figure 1. Large single crystal molybdenum mirror substrates

## 3. New techniques for mitigation of deposition

Several experiments were carried with the so-called periscope mirror system [9] to investigate the technique of blowing gas in front of the mirrors to protect their surfaces from degradation. In all the experiments the mirror system was introduced to the scrape-off layer (SOL) plasmas via the upper port using the limiter-lock material transport system [10] as it is shown in Fig. 2a. During the first experiment in the SOL plasmas of TEXTOR described in [9] the non-actively heated system without gas blow was exposed for NBI-heated, ohmic and ECR-heated discharges with a total plasma duration of 1050 seconds. After exposure, the first mirror was coated with ~0.5 μm thick carbonaceous deposit. At the same time, the second and third mirrors deeply in the periscope and remote from the plasma (Fig. 2b), were clean from any deposit. During the second exposure, the NBI-heated and ohmic discharges were made with a total plasma duration of ~ 500 seconds. Following the successful campaign at DIII-D with heated mirrors [11, 12] it was decided to heat the periscope up to the temperature of ~ 500$^{o}$C where the maximum of chemical erosion of carbon deposits by the D atoms and ions was observed for TEXTOR conditions [13]. This experiment however, did not lead to the success: the first mirror exposed to the plasma flux at elevated temperature did not reveal any measurable suppression of carbon deposition despite of the heating. The possible explanation for this result is that the impinging carbon flux was too strong compared to carbon removal efficiency by the chemical erosion. In the third exposure it was decided to blow deuterium gas into the periscope volume in addition of heating to increase the source of chemically reactive D atoms and if possible, to push plasmas away from the mirror surface. Forty four high-power identical repetitive NBI-heated discharges were made with Periscope system with a total duration of ~240 plasma seconds. After exposure, no visible deposition was observed on the surfaces of all three mirrors. The respective surface analyses did not reveal any impurities on the mirror surfaces. Moreover, optical measurements showed only negligible changes in the optical reflectivity of the exposed Periscope mirror (Fig 2d). Gas blow may be a promising technique for the protection of mirrors inside the long diagnostic ducts of ITER where several mirrors will be installed far away from plasma [14].

### 4. Progress in development of cleaning techniques

Significant progress was achieved in the development and application of the techniques for the mirror cleaning by a laser. The feasibility modeling assessment of cleaning of molybdenum and rhodium mirrors by a Nd-YAG laser system operating at 1064 nm with pulse duration of 140 ns and repetition rate 20 kHz was reported in [15].

Studied layers were amorphous carbon deposits of different thickness: 10 nm, 100 nm, 1 μm and 10 μm. According to the modeling calculations, the complete removal of the carbon deposit was possible for sufficiently thick films and was problematic for the layers having the thickness of order of 10 nm. The problem of removal of thin deposits relieves however, by assuming non-ideal thermal contact of the metal substrate and the deposit: it is still possible to reach the ablation temperature of carbon without damaging the substrate material. Removal of extremely thin films with a thickness of 1-5 nm is nevertheless a problem, since the damage threshold for a film and for a substrate material are nearly the same under these conditions. These findings will be assessed by a direct test of laser cleaning on mirrors that have been exposed in a tokamak environment under deposition-dominated conditions.

### 5. Modeling of the mirror performance in ITER

The first complete modeling results of the performance of the first mirror of US-lead core MSE diagnostic recently became available [16]. The plasma background for the first wall was taken from existing modeling runs for a standard ITER operating scenario with 100 MW input power in the SOL. Modeling was made for the Be wall coating with W-CFC armor of the divertor. The specially created transport code was used to simulate particle fluxes of deuterium, tritium, tungsten and beryllium impinging on the surface of the first mirrors. In this attempt the state-of-art geometry of the diagnostic duct of ITER core MSE diagnostic was taken into account. Introduction of the duct geometry resulted in a significant reduction of the particle fluxes impinging on the surface of the first mirrors.

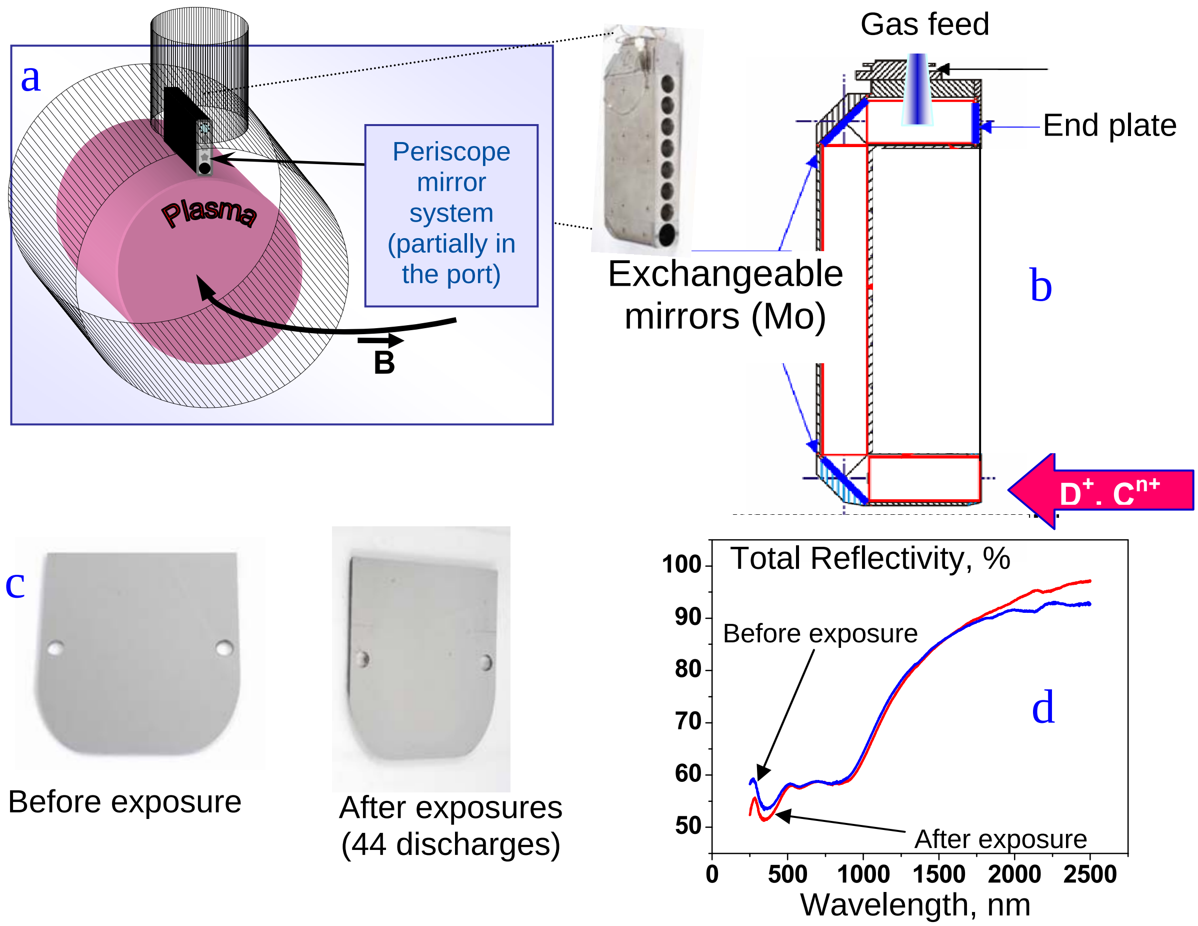


Figure 2. Details of the exposure of Periscope mirror system in TEXTOR: a) scheme of exposure; b) scheme of Periscope mirror system; c) photographs of first mirrors before and after exposure and d) evolution of the total reflectivity of the first mirrors before and after exposure, as measured at the center of the mirrors.

The results are summarized in table 1. It is clear from the table that the tungsten transport should not be an issue for a mirror. The fluxes of beryllium are rather small either. However, the presence of the Be deposits on a mirror represents an acute issue, as it will be discussed later in the paper. The special optical code was used afterwards to infer the optical reflectivity as a function of deposition on the mirror surface. As a result, the code predicted rather moderate change of the reflectivity of the first mirror of the ITER core MSE diagnostic. This finding however, may change significantly if the recently available value of reflectivity of deposited layers is implemented in the code. The measured reflectivity of Be deposits was significantly lower than that of handbook data [17].

Another approach was taken in the modeling effort at Forschungszentrum Jülich, Germany, EU. Here the activities were primarily concentrated on a better understanding of plasma and neutral background at the entrance of the diagnostic ports. A comprehensive modeling of mirror performance is planned for the next stage.

Table 1. Attenuation of the particle fluxes towards of the first mirror of the ITER core MSE system as modeled in [15]

| Particle type | Particle flux to the entrance of diagnostic module particles/($m^2$*s) | Resulting atom flux to the surface of the first mirror particles/($m^2$*s) | Reduction factor |
|---|---|---|---|
| D-T charge exchange atoms (full energy spectrum) | $7.21\times10^{20}$ | $3.96\times10^{18}$ | 182 |
| D-T charge exchange atoms (>10 eV spectrum) | $2.56\times10^{20}$ | $1.29\times10^{18}$ | 198 |
| D-T ions from plasma edge | $3.59\times10^{20}$ | $9.10\times10^{17}$ | 391 |
| He charge exchange atoms (full energy spectrum) | $6.50\times10^{17}$ | $4.26\times10^{15}$ | 153 |
| He charge exchange ions (from plasma edge) | $1.80\times10^{19}$ | $4.55\times10^{16}$ | 395 |
| Be ions (sputtered from Be wall) | $1.47\times10^{19}$ | $5.81\times10^{16}$ | 253 |
| W ions (sputtered from alternative W wall) | $8.71\times10^{16}$ | $2.68\times10^{13}$ | 3250 |

This, certainly slower approach nevertheless benefits from the use of more robust edge data. Presently, the plasma and particle environment was modeled for the full poloidal cross-section of ITER with a special emphasis put to the upper and midplane diagnostic ducts where ITER core Charge-eXchange Recombination Spectroscopy (CXRS) and the core Light Identification and Ranging (LIDAR) systems are located. In the modeling all charged states of deuterium, helium, carbon and beryllium were accounted. The full atomic package of EIRENE code including neutral-neutral collisions and radiation opacity was employed. The modeling runs were made for five specific conditions:

ITER with carbon first wall:

a) with a gas fueling via upper port at high rate;

b) with a gas fueling via upper port at nominal rate;

ITER with beryllium first wall:

c) with Be fully reflected from the walls;

d) with a gas fueling via upper port at nominal rate;

e) without gas fueling via upper port (pellet injection).

For all the cases the full particle and energy distributions were calculated. In the modeling a further step was made to provide a conservative upper estimate of the mirror lifetime. For this purpose the test mirror was brought right to the entrance of the diagnostic duct, facing the plasma. The non-attenuated particle fluxes were impinging on the test mirror causing the net erosion of its surface or net deposition of impurities depending on the environmental plasma and particle conditions. It appeared that the first mirror of the core CXRS system is always under erosion-dominated conditions for carbon, with the erosion source being at least a factor of 4 stronger than the deposition one. The maximum erosion yield of carbon deposits reached 0.14 nm/sec.

For the mirror of the ITER core LIDAR system the situation is quite different: in all conditions the erosion source is at least an order of magnitude weaker than that in the upper port. The first mirror in a midplane port will be subject to deposition of carbon at a maximum rate of

0.016 nm/sec. It is difficult to make any conclusions on Be, since the eroding and depositing fluxes are nearly the same for all modeling runs. For the case without gas feeding via upper port, the conditions at the upper port are very similar to those at the equatorial one.

It should be noted however, that these calculations represent the conservative uppermost estimate. According to the table 1, the implementation of real duct geometry will likely decrease the particle fluxes significantly. Further efforts are concentrated on extending the code calculation grid inside the diagnostic ducts and making first runs to estimate the particle fluxes there.

## 6. New critical area of research: deposition of beryllium

Because of the choice of beryllium as a first wall material in the ITER main chamber, the SOL plasma may contain a significant fraction of beryllium. Experiments in PISCES-B at the University of California, San Diego, USA [18] have shown that even with a low fraction of beryllium ions in the plasma (0.1%) at plasma parameters relevant to ITER, a graphite target becomes coated with a beryllium layer that reduces its erosion by the plasma. Therefore not only carbon but also beryllium may be deposited on the first mirror surface. Unfortunately, this subject has received much less attention than the issue of carbon deposition.

It was assumed in [2] that if Be deposition was to occur on some mirrors the reflectivity of the coated mirror would turn to the reflectivity of pure Be for a film thickness higher than 20 nm. Recently detailed modelling of the effect of particle deposition on the reflectivity of the ITER MSE mirror has used a similar assumption [16]. From these calculations, a Be deposition rate of about 200 nm per year was derived for the mirror of ITER MSE diagnostic.

The effect of Be deposition on the reflectivity of metallic mirrors has been assessed experimentally in the PISCES-B device [19]. It was found that Be layers may exhibit high levels of porosity which makes their reflectivity much lower than the reflectivity of pure Be. Figure 3 shows the relative reflectivity measured on Mo mirrors after exposure. Evidently Be deposition reduces the relative reflectivity in the visible range.

Recently detailed investigations of the influence of the deposition conditions on the Be layer morphology have shown that the neutral pressure, the gas composition and the temperature during deposition had a strong influence on the morphology [20]. A low neutral pressure and temperature (below $150^{o}$C) tend to favour the formation of a dense layer whose reflectivity is expected to be closer to that of pure Be. On the other hand high neutral pressure (as it may be the case in the ITER divertor) favours the formation of porous layers with low reflectivity. In the studied parameter range, a substrate temperature of $300^{o}$C always causes the formation of a low reflectivity layer.

## 7. Summary

Significant progress was achieved in all fields of R&D on the first mirrors in the past two years. In particular, the large single crystal molybdenum samples of ITER-relevant sizes were successfully manufactured in the Russian Federation and are going to be tested in a tokamak environment. In a field of deposition mitigation techniques, the promising results were obtained with the gas blow in front of the mirror.

In the area of mirror cleaning, the feasibility studies of the laser cleaning of amorphous carbon deposit demonstrated the possibility of the complete removal of carbonaceous deposits with Nd-YAG laser operating at 1064 nm.

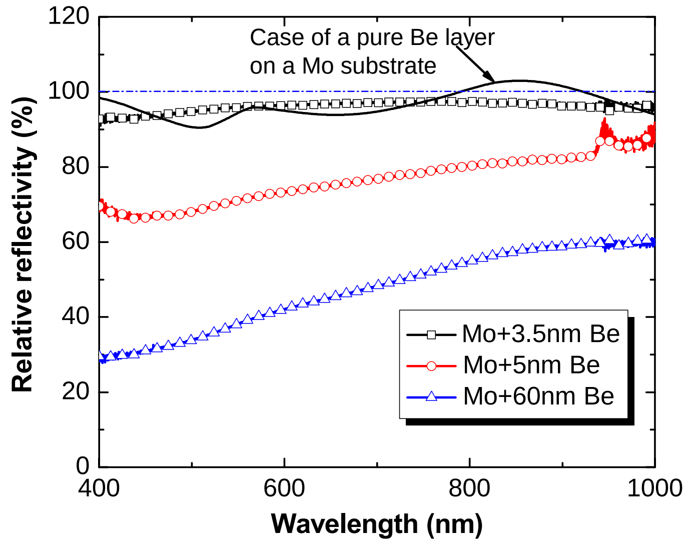


Figure 3. Relative reflectivity of Be deposits on molybdenum mirrors from [19]. The black line corresponds to the relative reflectivity of Be and Mo from [17] and corresponds to the reflectivity which should be measured if the mirror consisted of a perfectly smooth Be layer deposited on the polished substrate. The dashed line at 100% indicates the reference level corresponding to a non-exposed mirror.

The modeling efforts were continued and the first comprehensive predictive assessment demonstrated that the first mirror of the ITER core MSE system will be sufficiently protected during the working ITER discharges. However, recently available data on the reflectivity of deposited Be layers may significantly change these results. In another modeling effort the predictions of plasma and neutral background near the first wall was made. The results show that the first mirror of the ITER core CXRS diagnostic will be preferentially under erosion-dominated conditions. On a contrary, the first mirror of ITER core LIDAR system will be primarily deposited.

The first results of studies of Be deposits indicate that rather porous deposits are usually formed during plasma exposures under ITER-relevant conditions. The reflectivity of deposits is low which implies the necessity of cleaning.

The current research revealed clearly the critical areas, where the progress has to be achieved as soon as possible. The predictive modeling is one such an area, since it provides an estimate of the most important mirror parameter - its lifetime. The second critical area is the study of beryllium transport, deposition its mitigation and prevention. Here, the current R&D is on the critical path since the first data became available only recently, database on beryllium in fusion devices is very limited and knowledge on cleaning of beryllium-containing deposits from the mirrors is missing. Therefore an emphasis of the future research has to be concentrated on these two critical areas. It should be explicitly mentioned however, that only the proper funding will make feasible the further progress in the R&D on first mirrors including the necessary advances in the critical areas of research.

## 8. Outlook

Besides the concentrated activities in the two critical areas of an R&D on first mirrors, the future efforts will be applied to several particular tasks:

- Experimental and theoretical assessment of the performance of irradiated mirrors made from ITER candidate mirror materials;
- Optimization of the experimental database on first mirrors with the main concentration on the relevance of experimental conditions to those expected in ITER. This activity will include the necessary but previously missing experiments in ITER-relevant conditions;
- Joint work with diagnostic designers on the implementation of mirror concepts in design of the respective ITER diagnostics, including the deposition mitigation, cleaning and in-situ mirror calibration schemes;
- Joint work with industry on manufacturing the mirrors, optimization of manufacturing technology for fusion purposes and tests of industrial mirrors in tokamak environment.

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