# Mirrors for ITER diagnostics: new R&D developments, assessment of the mirror lifetime and impact of the mirror failure on ITER performance

A. Litnovsky[1], V. Voitsenya[2], D. Thomas[3], M. Rubel[4], G. De Temmerman[5], L. Marot[6], K. Yu. Vukolov[7], I. Orlovskiy[7], W. Vliegenthart[8], Ch. Skinner[9], D. Johnson[9], V. Kotov[1], J.P.Coad[10], A. Widdowson[10], G. Vayakis[3], R. Boivin[11] ,T. Akiyama[12], N. Yoshida[13] and M. Joanny[14]
and the members of the ITPA Specialists Working Group on First Mirrors

[1] Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich, Partner in the Trilateral Euregio Cluster, Ass. EURATOM- FZ Jülich, D-52425 Jülich, Germany;
[2] IPP, NSC Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine;
[3] ITER Organization, Route de Vinon sur Verdon, 13115 Saint Paul Lez Durance, France;
[4] Alfven Laboratory, KTH, Association EURATOM-VR, 100 44 Stockholm, Sweden;
[5] FOM-Institute for Plasma Physics Rijnhuizen, Partner in the Trilateral Euregio Cluster, Association EURATOM - FOM, PO Box 1207, 3430 BE Nieuwegein, The Netherlands;
[6] Department of Physics, University of Basel, CH-4056 Basel, Switzerland;
[7] Nuclear Fusion Institute, Russian Research Center ‘Kurchatov Institute’, Kurchatov sq. 1’ 23182, Moscow, the Russian Federation;
[8] TNO, Schoemakerstraat 97, 2628 VK, Delft, The Netherlands;
[9] Princeton Plasma Physics Laboratory, Route 1 North, Princeton, NJ 08543, USA;
[10] Euratom / CCFE Association, Abingdon, OX14 3DB, United Kingdom;
[11] General Atomics, San Diego, CA 92186-5608, USA;
[12] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki-shi, Gifu 509-5292, Japan;
[13] Kyushu University, 6-1 Kasuga-kouen, Kasuga, Fukuoka, 816- 8580, Japan;
[14] CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France.

## Abstract

All optical and laser-based diagnostics in ITER will use mirrors as the first plasma-viewing component. In the harsh radiation and particle environment, optical properties of mirrors will degrade leading to the deteriorated operation of the entire respective mirror-based diagnostics. Prioritized R&D program is underway to ensure the most durable high-performance mirror solution. An analysis of newest developments in the area of first mirrors is presented in this contribution including an overview of the recent results of the mirror test at JET, progress on the laser and plasma cleaning of diagnostic mirrors and a new insight to predictive modeling. Based on these developments, an analytical assessment of the mirror lifetime is given. The combination of the proper mirror material, active and passive techniques for deposition mitigation and mirror cleaning may gain orders of magnitude increase of the mirror lifetime. The description of the risks of mirror failure and the possible consequences of mirror failure for ITER operation is provided.

## Introduction

Plasma-viewing first mirror is known to be the most vulnerable component of ITER optical and laser-based diagnostics. The optical reflectivity of mirror may degrade in the severe conditions of ITER operation, hampering the entire performance of corresponding diagnostics. A multi-area R&D program is established under the guidance and coordination of the Specialists Working Group on First mirrors of the ITPA TG on Diagnostics. The six critical directions are defined and addressed via the work plan (WP) of the coordinated R&D [1]. These directions are:

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. Mitigation of particle deposition onto mirror surfaces;

4. Cleaning diagnostic mirrors from deposits;
5. Tests of diagnostic mirrors in a neutron, gamma and x-ray environment;
6. Engineering and manufacturing challenges for first mirrors in ITER.

The aim of the work plan is to attain the longest time of high-performance mirror operation – the longest mirror lifetime. In our paper, we will concentrate on the analysis of the mirror lifetime discovering the influential factors and reviewing the ways to prolong it. We will also describe the risks of the mirror failure and its consequences for the ITER operation.

**Analysis of the current status of mirror R&D**

Naturally, the current understanding of the first mirror problem is based on the large knowledge base accumulated as a result of studies performed in the laboratory facilities and in tokamaks and dedicated modeling. Based on the results of these studies it is rather obvious that erosion of the mirror surface and the deposition of impurities are the environmental factors having the highest impact on the mirror reflectivity [2, 3].

Recently, a comprehensive First Mirror Test at JET has been carried out with test mirrors exposed in beryllium and carbon environment. 29 stainless steel and polycrystalline molybdenum mirrors retrieved from the torus after campaigns of 2005-2007. Mirrors were installed in separate channels of pan-pipe shaped cassettes (at different distances to plasma) which were placed on the outer wall in the midplane position and in the Mk-II HD divertor [4]. The essential results may be summarized as follows.

1. Reflectivity of all tested mirrors has been degraded.
2. No significant differences are noticed when the deposition on steel and Mo are compared.
3. Deuterium and carbon are the main elements detected on all mirror surfaces. In several cases (e.g. outer wall) the presence of beryllium is also found.
4. The deposition in channels in the divertor cassettes is pronounced at the very entrance. It sharply decreases with the distance from the plasma, $\lambda \sim$ 5-7 mm as shown in fig.1.

The optical properties of all mirrors have been significantly degraded mainly by carbon deposition. However, on the main chamber wall the layer growth rate is inhibited by CX-induced removal of deposits. These worrying findings show explicitly that much more efforts are required to prolong the mirror lifetime.

At the same time we need to assess the performance of mirrors in ITER environment which is primarily made by the predictive modeling. New modeling was made taking into account the fluxes, energy and angular distribution of particles and the simulation of the particle transport in the diagnostic duct including their reflection from the walls and re-erosion. Generic shapes of the diagnostic duct were assumed: cylindrical or conical tubes with different length to radius ratios L/R. The initial neutral particles in the model were produced due to surface and volume recombination of plasma ion and first wall sputtering. Their further transport was described using the EIRENE code [5] with prescribed steady-state plasma background. Plasma parameters outside the magnetic separatrix were taken from the series of the self-consistent B2-EIRENE (SOLPS4.3) runs[6]. Several ITER operation scenarios with different input power and gas puffing rates were considered. To model the first mirror sputtering, the reflection coefficients calculated by the TRIM code [7] were used. The estimated lifetime due to erosion of the Mo mirror in a duct with $L/R \geq 20$ is >10000 of full (400 s long) ITER discharges.

Modeling of impurity deposition involves large uncertainties in the data on the reflection and sticking factors and on erosion yields of the deposited films. To get the most conservative estimate, the 100% re-erosion of impurity atoms (C, Be) from the duct wall was assumed. The resulting mirror lifetime (assuming tolerable deposition thickness of 20 nm) was estimated to be only 8-1000 ITER discharges even for ducts with L/R=40. The large uncertainty in the calculated incident impurity fluxes gives no guarantee that erosion of the first mirrors can really take place in ITER. Therefore, the deposition on the mirrors should be treated as a most probable reason of mirror degradation. The highest estimated rate of C+Be deposition at L/R=40 is 0.001 nm/sec.

A possible way of further attenuation of the impurity fluxes is the installation of fins. The assumption of the full reflection of impurities from the duct walls significantly underestimates the mitigation. If the reflection coefficient R<1 is applied for impurity atoms, preliminary results show that factor of 1000 reduction of the incident impurity flux is possible even for R=0.9.

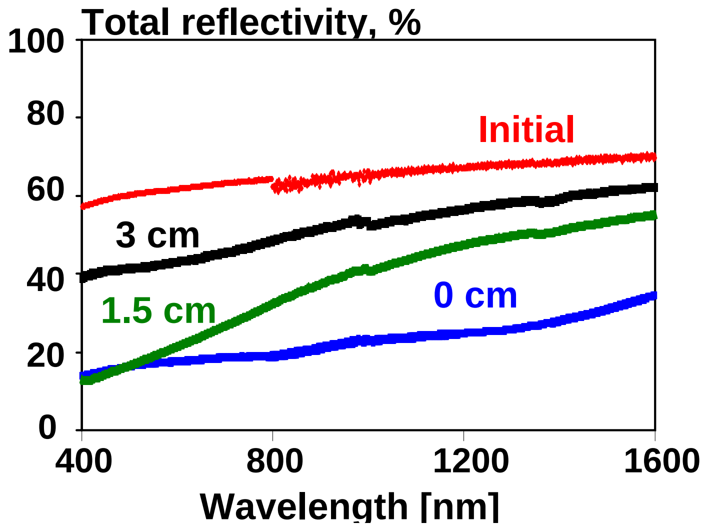


Figure 1. Reflectivity of mirrors from the divertor base located at the increasing distance from the plasma in channels. Shown is a distance from the entrance of the channel.

In comparison with previous results [1, 8, 9] the newest modeling delivers two important messages. Erosion will likely be lesser problem than the deposition, outlining the important change in the overall R&D activities – the re-focusing of efforts towards the counteraction against the deposition.

Table 1. Particle flux attenuation factors along the cylindrical diagnostic duct in the equatorial port.

| L/R | 2 | 4 | 10 | 20 | 30 | 40 |
|---|---|---|---|---|---|---|
| Deposition | 3.2 | 4.7 | 9.0 | 16 | 23 | 29 |
| Erosion | 5.8 | 14 | 56 | 160 | 300 | 540 |

As for mirrors under erosion conditions, the efforts are now largely concentrated on the technical realization of the erosion-resistant mirrors of ITER-relevant size. The main candidates in this area are the single-crystal mirrors despite to known limitation on their available size [1]. Alternatively, the coated mirrors are proposed and the corresponding R&D is underway at ENEA and University of Milano (Italy) [10], Kurchatov Institute (Russia) and at the University of Basel [11]. The recent studies of coated mirrors under erosion conditions showed, that the Rh-coated mirrors preserved their reflectivity only in the IR range, whereas molybdenum coating on the tungsten substrate revealed a good resistance to erosion and the preservation of reflectivity in the IR and VIS ranges [12]. The R&D on the full-scale cooled concept of the coated mirror is ongoing [13].

The second important outcome is that now the inclusion of the generic duct geometry is started. As expected and shown for the selected diagnostic [14], this change tends to minimize the fluxes of particles expected at the mirrors (table 1), causing a positive impact on the mirror lifetime. Finally, the analysis of the newest modeling results yields to a rather explicit strategy of actions to be done to further decrease the particle fluxes towards the mirrors.

**Mirror surface recovery – a way to increase the mirror lifetime**

The present knowledge on the mirror issues for ITER diagnostics is advanced up to the level of clear understanding that only the set of measures simultaneously applied to the diagnostic mirrors may be the way of reaching the desired mirror solution. In particular, the so-called Mirror Surface Recovery (MSR) plays the key role in extending the mirror lifetime. The MSR consists from three stem parts:

A. Passive mitigation of the particle fluxes reaching the mirrors.

B. *In-situ* calibration of the mirrors

C. *In-situ* mirror cleaning.

A passive mitigation of deposition is a necessary step which is mainly provided by the special geometry of the diagnostic ducts, shaping of the duct material and the use of mechanical protection systems, like shutters. The progress on shutters is described for instance, in [15]. Luckily, the newest experimental results demonstrate the significant progress in the area of duct geometry and shaping. As an example, in LHD the new design of retroreflectors was introduced as shown in figure 2 [16]. Unlike the classical, open design the retroreflectors in LHD collected the light from the bending mirror acting as a protection of the retroreflector. The bending mirror itself was inclined at ~67$^{o}$ to impinging particle flux to increase the sputtering action. In addition the molybdenum fin structure was installed in the duct channel to mitigate the re-erosion of plasma impurities and sputtered duct material. Fins have earlier already demonstrated their efficiency in deposition mitigation [17]. After 3-months of exposure in LHD, no deposition has occurred on the retroreflector and on the mirror. The complete preservation of the reflectivity was attained in the contrast to the earlier results [18], where the heavy deposition dropped the reflectivity of a retroreflector. Definitely, this experience should be included in the coming analyses of the mirror lifetime.

*In-situ* calibration is an important area of the MSR, serving as monitoring tool to reveal the actual mirror performance and allowing making the decisions on both the mirror operation and the functionality of entire diagnostics. Calibration represents largely an engineering challenge, the most aspects of it can be found e.g. in [19].

*In-situ* mirror cleaning represents another, highly critical area of the mirror surface recovery. The mirror cleaning in the harsh ITER environment at the presence of magnetic field is an outstanding challenge. Based on the results of dedicated R&D, presently there are two main directions chosen for the further exploration: laser cleaning of diagnostic mirrors and cleaning of mirrors by the plasma.

Recently, the dedicated attempt of laser cleaning of the mirrors exposed in JET with ytterbium laser (1052 nm) lead to the removal of deposits. The reflectivity was partly regained, but the surface became damaged by laser pulses [20]. These rather discouraging results from JET however, do not mean the termination of investigations on laser mirror cleaning. There are also optimistic expectations and the dedicated project on the laser-cleaning of the Be-contaminated mirrors is presently underway at the PPPL. Fiber optic coupling between laser and a remote scan head was demonstrated and makes this technology suited to ITER environment.

Plasma cleaning represents an alternative way to restore the reflectivity of mirrors. An intensive R&D has started several years ago. Promising results were shown for glow discharge cleaning of mirrors [21], however the application of glows for mirror cleaning in ITER is questionable. The efforts are largely concentrated on studies of the electron-cyclotron resonance (ECR) discharge which requires a magnetic field for its operation. The most recent results became available from FZJ where the cleaning of diagnostic molybdenum mirrors from carbon contaminants were studied using ECR-generated hydrogenic plasmas. Cleaning treatment was applied to the mirrors contaminated during experiments in TEXTOR and DIII-D tokamaks. Mirrors exposed in TEXTOR were contaminated with a hard amorphous carbon film, whereas the DIII-D mirrors were covered with a softer carbon deposit, providing a wide span of properties of the carbon deposits obtainable from tokamak experiments. The successful non-destructive cleaning of the tokamak soft amorphous carbon films using chemical erosion of carbon atoms by the hydrogenic atoms and ions was demonstrated. The highest attained cleaning rate was 0.7 nm/s. The reflectivity of cleaned mirrors was restored completely in the wavelength range of 250-2500 nm as shown in fig.3a.

However, hard amorphous tokamak deposits formed by energetic impurities usually have the carbide interface produced by carbon ions implanted and diffused into molybdenum substrate. The chemical removal of these carbides is proven to be ineffective. The least carbon removal efficiency corresponded to 0.001 nm/s as obtained by applying the biasing of ~-50V to the contaminated molybdenum mirror. Only with biasing the reflectivity of mirrors was recovered as shown in fig. 3b, in a similarity with results from TRIAM 1M [1] outlining the sputtering cleaning as the only option for reliable removal of contaminants. It should be noted, that even the least attainable removal rates are already comparable with the highest deposition rates expected in ITER [22].

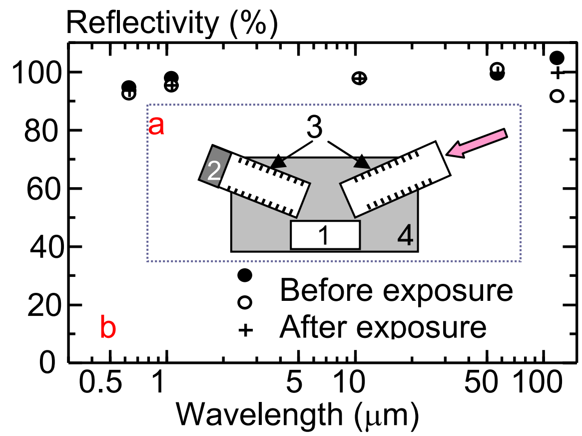


Fig.2. a) schematic of the new diagnostic duct for the retroreflector at LHD: 1) bending mirror, 2) flat mirror – a substitute of retroreflector, 3) diagnostic ducts with molybdenum fins and 4) the protecting housing. The direction of particle flux is shown with an arrow; b) dependence of the optical reflectivity on the wavelength for flat and bending mirrors before and after exposure in LHD.

**Mirror lifetime and the performance of ITER diagnostics**

In the last two chapters we will focus our analyses on the current understanding of risks of mirror failure. The first systematic study of the mirror lifetime, corresponding risks and an impact of mirror failure on ITER diagnostics was undertaken in [23]. Here we would like to share this preliminary analysis with wider fusion community by focusing on the essential details of this study.

In the analysis, 35 mirror-based diagnostics were assessed. The risks were divided into three categories: high, moderate and low. Several criteria were put as metrics for the risk evaluation:

1. Location of diagnostics: upper port: moderate, midplane port: low, divertor port: high;
2. Wavelength of operation: >2 um: low, 200 nm-2000 nm: moderate; <200 nm: high;
3. Solid angle of the mirror: <0.01 sr: low; 0.01-0.1 sr: moderate, > 0.1: high;

Fluxes to the mirrors were calculated using [24]. The resulting risk for the diagnostics was estimated considering all the corresponding risks above. The metric for the mirror failure was chosen as follows: the mirror was considered as out of operation when the deposits were formed at the surface of the mirror with a thickness of a quarter of a wavelength of this diagnostics. Simultaneously with mirror failure we understand the failure of the corresponding diagnostic. The detailed results are provided in [23]. Without going in much details, the lifetime estimates for ITER diagnostics vary largely being between 4-10 discharges and several thousands of ITER discharges.

We should stress however, that this study was a first step in the more complex and more reliable assessment. Certainly, the metric for evaluation of the mirror lifetime must be updated, getting into account the known effects of deposition on the reflectivity [2, 3, 24]. A minute deposition of 20 nm of carbon or beryllium causes the drastic (tens of percent) drop of the reflectivity. Introduction of a new metrics to our study will likely decrease the mirror/diagnostic lifetime even further. However, there are several important factors mentioned in this paper, which were not yet included in the assessment [23] and which will be implemented in the near future:

1) Effect of the duct geometry, shaping and mechanical protection on suppression of particle fluxes towards the mirror;

2) Impact of the mirror cleaning on the extension of the mirror lifetime;

3) Use of active techniques of deposition mitigation and cleaning (e.g. gas blows).

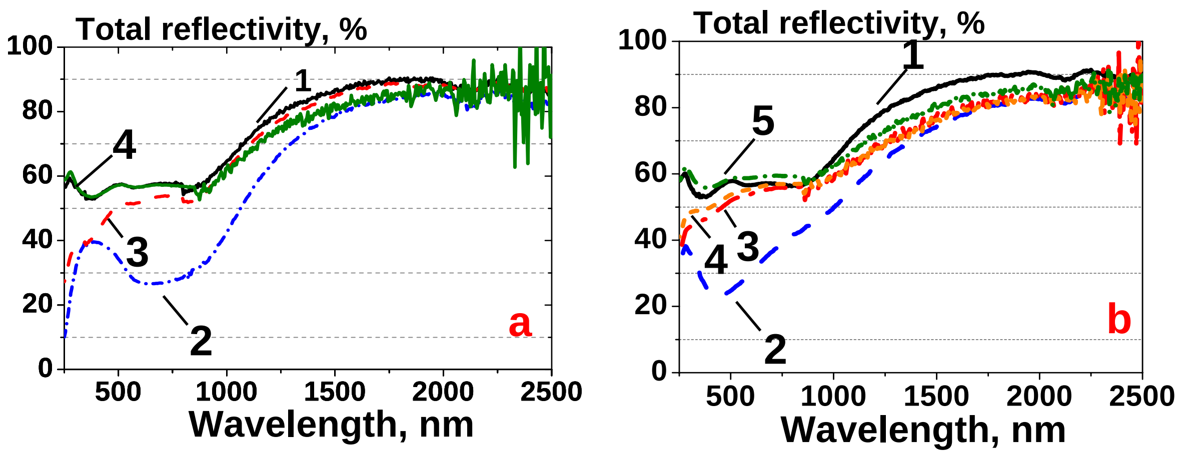


**Fig. 3.** Evolution of the total reflectivity after multiple cleaning treatments of mirrors contaminated in tokamaks: a) of the mirror with soft carbon film: 1) original clean mirror, 2) after deposition in the tokamak, 3) after10 minutes of cleaning and 4) after 30 minutes of cleaning and b) of the Mo mirror with a hard carbon film: 1) original clean mirror, 2) after deposition in the tokamak, 3) after 35 minutes cleaning without biasing, 4) after additional biasing for 45 minutes and 5) after additional to 3) biasing for 256 minutes.

A positive trend can be deduced from the recent results: the developed single crystal molybdenum mirrors when applied in erosion conditions, can withstand the particle erosion for several years of operation in ITER without any degradation of their optical performance [12]. Achieved removal rates for carbon deposits are generally already exceeding the predicted deposition rates. Application of shutters for the mirror protection may decrease the unnecessary exposure time leading to further prolongation of the mirror lifetime. In ITER diagnostics, these factors have to be implemented jointly, leading to the increase of the expected mirror lifetime by a factor of 100 and higher. On the other hand, there are several critical areas where only a moderate progress attained so far: the removal of the beryllium-containing mixed deposits and a practical application of cleaning techniques in ITER diagnostics.

**Impact of mirror failure on overall ITER performance**

In the subsequent analysis, the essential role is given to the importance of the particular ITER diagnostics to the ITER start-up, reaching advanced control and the successful performance evaluation. At present, ITER measurements are divided into three main categories [25] as shown in table 2. The diagnostics serving the category 1a are necessary for the machine control, whereas the diagnostics belonging to category 2b are necessary for the success of physics program at ITER at the later state of operation. A failure of 1a diagnostic would mean that ITER cannot be started. For the analyses, the diagnostics were divided into the primary ones, planned for measuring the particular parameter and their reserve diagnostic to measure this parameter when the primary diagnostic is out of operation. As can be seen, there are several cases (underlined in the table) where the both category 1a primary and backup diagnostics are based on mirrors meaning that a failure of their mirrors will indeed make the startup of ITER impossible. There are the possible ways to overcome this significant restriction:

1. By selecting the non-mirror based backup or primary diagnostics, when possible;
2. In case both diagnostics are mirror-based, making the backup channel for the measurement, significantly increasing its durability and minimizing the risk of failure even at the extent of compromising the measurement capabilities.

The work is ongoing studying the both suggested ways of handling this issue. It should be noted however, that the recent positive trends mentioned in this paper will most likely alleviate the severity of this problem in the near future.

Table 2. Plasma and first wall measurements required for ITER [25]

| Group 1a<br>Measurements for Machine protection and Basic Control | Group 1b<br>Measurements for Advanced Control | Group 2 Measurements for Performance Evaluation and Physics |
|---|---|---|
| Plasma shape and position,<br>Separatrix-wall gaps,<br>Gap between separatrixes<br>Plasma current,<br>Q(a), q(95%)<br>Loop voltage<br>Fusion power<br>Beta N=beta tor(aB/I)<br>Line-averaged electron density,<br>Impurity and D, T influx (divertor & main plasma)<br>Surface temperature: divertor and upper plates<br>Runaway electrons<br>Halo currents<br>Radiated power (main plasma, X-point, divertor)<br>Divertor detachment indicator<br>$J_{sat}$, $n_e$, $T_e$ at divertor plate<br>Disruption precursors<br>H/L mode indicator<br>$Z_{eff}$ (line averaged)<br>$n_T/n_D$ in plasma core<br>ELMs<br>Gas pressure (divertor and duct)<br>Gas composition (divertor and duct)<br>Dust | Neutron and alpha-source profile<br>Helium density profile (core)<br>Plasma rotation (poloidal and toroidal)<br>Current density profile (q-profile)<br>Electron temperature profile (core)<br>Electron density profile (core and edge)<br>Ion temperature profile (core)<br>Radiation power profile (core, X-point and divertor)<br>$Z_{eff}$ profile<br>Helium density (divertor)<br>Heat deposition profile (divertor)<br>Ionization front position in the divertor<br>Impurity density profiles<br>Neutral density between plasma and the first wall<br>$n_e$ of divertor plasma<br>$T_e$ of divertor plasma<br>Alpha particles loss<br>Low m/n MHD activity<br>Sawteeth<br>Net erosion (divertor plate)<br>Neutron fluence | Confined alpha-particles<br>TAE Modes, fishbones<br>$T_e$ profile (edge)<br>$N_e$, $T_e$ profiles (X-Point)<br>$T_i$ in the divertor<br>Plasma flow (divertor)<br>$n_T/n_D/n_H$ (edge)<br>$n_T/n_D/n_H$ (divertor)<br>$T_e$ fluctuations<br>$N_e$ fluctuations<br>Radial electric field and the field fluctuations<br>Edge turbulence<br>MHD activities in plasma core |

**Conclusions and outlook**

In this paper we analyzed the most recent achievements in the area of the coordinated R&D on diagnostic mirrors. The results of the intensive dedicated international joint efforts resulted to the significant progress, especially in the areas of predictive modeling and the deposition mitigation and cleaning. New modeling results essentially re-focused the entire R&D efforts towards counteracting the deposition on the mirror.

Current analyses show that for some of the ITER diagnostics, the lifetime of the first mirrors may be insufficient to meet maintenance interval targets. To prevent a potential impact on ITER operation, mitigating measures are being considered: in-situ protection, cleaning and replacement. However, an impressive progress made in the recent two years in all areas of the mirror R&D, delivers the sound optimism that these critical problems will be largely alleviated in the nearest future.

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