Scientific report

Plasma-wall interaction studies related to fusion reactor materials

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Summary

In the course of the ongoing project, our research was focused on the investigation of the erosion and deposition mechanisms affecting the optical reflectivity of potential materials for ITER first mirrors both by active collaborations with groups from different Tokamak sites and by simulation in laboratory experiments in Basel.

Forschungzentrum Jülich, Germany - TEXTOR

At Forschungzentrum Jülich (Germany) studies were initiated by exposing polycrystalline molybdenum and tungsten mirrors in the erosion and deposition dominated zones in the scrape-off layer (SOL) plasma of TEXTOR. Recently, a comparative test of single crystalline and polycrystalline mirrors under erosion conditions showed the superiority of single crystalline mirrors in terms of homogeneous sputtering resulting in a very low deterioration of optical reflectivity. Such mirrors may have a sufficient lifetime under conditions where erosion is the dominating damaging effect.

Long-term exposure of mirrors made of different materials was performed in Tore-Supra (CEA Cadarache, France). The mirrors were installed on the first wall and open to the plasma, being submitted to bombardment of charge exchange neutrals during the Tokamak discharges and to helium ions during the conditioning glow discharge. It was found that a major part of mirror erosion is due to glow discharge, putting the stress on the necessity in ITER to protect the mirrors during conditioning discharges.

At CRPP-EPFL, mirror samples prepared from different materials (Mo, W, Si) have been installed on a specially designed manipulator that allows their insertion in the divertor floor region of TCV. A separate pumping system allows the mirrors to be easily inserted and retrieved following exposure without any requirement for a vacuum vessel vent. Samples are recessed behind the front surface of the graphite divertor floor tiles to avoid direct plasma impact. Under identical exposure conditions the mirror substrate can strongly influence the deposit thickness found on the sample: the carbon layer thickness on a Si sample is found to be five times higher than on a Mo substrate. This substrate dependent deposition efficiency may be of importance for the mirror material choice in ITER.

At JET, a comprehensive mirror test has been initiated within the framework of tritium retention studies. Mirrors from stainless steel and molybdenum are being exposed at various locations in the divertor (outer, inner and base) and on the first wall. Mirrors are exposed in the vicinity of quartz microbalances allowing monitoring on a shot by shot basis the erosion and deposition experienced by the mirrors. Besides its involvement in the experiment, our group was responsible for the design and installation of a spectrophotometer compatible with beryllium handling. This system will be used for optical measurements on mirrors exposed during the 2006 campaign.

In the laboratory in Basel, mirrors made from polycrystalline copper and stainless steel were exposed to low temperature deuterium plasma with controlled partial pressure of methane in the gas mixture. Under similar conditions markedly different erosion and deposition patterns are observed on different materials, showing the influence of the material itself on the erosion and deposition mechanisms.

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1. First mirror test in Tore Supra

Six metallic mirrors (2*Mo, 2*Cu, 2*Stainless steel) were exposed in Tore Supra for long term plasma exposure during the experimental campaign 2003-2004. One mirror of each material was kept out of the tokamak for reference measurement. The molybdenum samples were made from a single crystal with a 110 orientation. The stainless steel samples were made from a polycrystalline material similar to the AISI 316 steel. The chemical composition of this iron-based alloy is:, 16% chromium, 11% nickel, 3% molybdenum, less than 1% titanium and 0.04% oxygen. The high-purity polycrystalline copper samples were diamond polished.

The mirrors were located out of the equatorial plane and positioned 140 mm from the Last Closed Flux Surface (LCFS). The surfaces of the mirrors were oriented parallel to the toroidal direction (fig. 1).

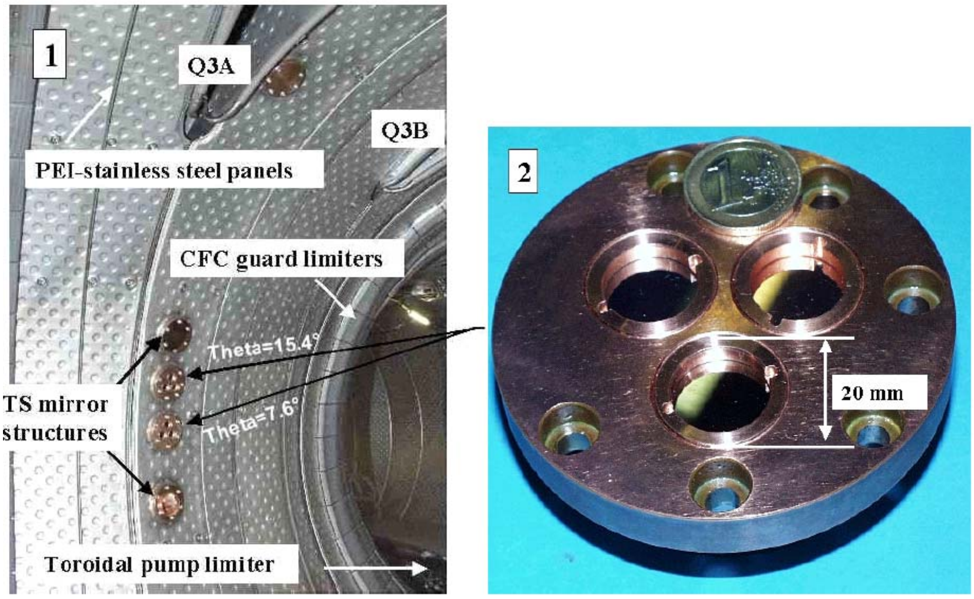

Figure 1: Mirrors locations in the vacuum vessel of Tore Supra.

Due to the active cooling of the first wall, the temperature of the mirrors never exceeded 150°C. During the experimental campaign, mirrors were submitted to roughly 1400 plasma pulses for a cumulated pulse length of about 26000 s (7h10).

Total and diffuse reflectivity of the mirrors were measured on the exposed and virgin samples by means of a spectrophotometer equipped with a 110mm diameter integrating sphere (Varian Cary 5) in the wavelength range 250-2500 nm (fig. 2) Specular reflectivity is obtained from the difference between the total and diffuse components.

For the molybdenum samples, a decrease of the total reflectivity is noticed on the whole spectrum. It is most pronounced in the UV region. The diffuse reflectivity is the same before and after exposure and remains very low. Since the diffuse reflectivity is linked to the roughness, it can be deduced that the roughness did not sensibly evolve during exposure which has been confirmed by roughness measurement using con-focal microscopy and AFM. Therefore, we can assume that the decrease in the total reflectivity is due to absorption of light in a deposited layer on the surface. XPS measurements showed presence of impurities like carbon, oxygen and boron.

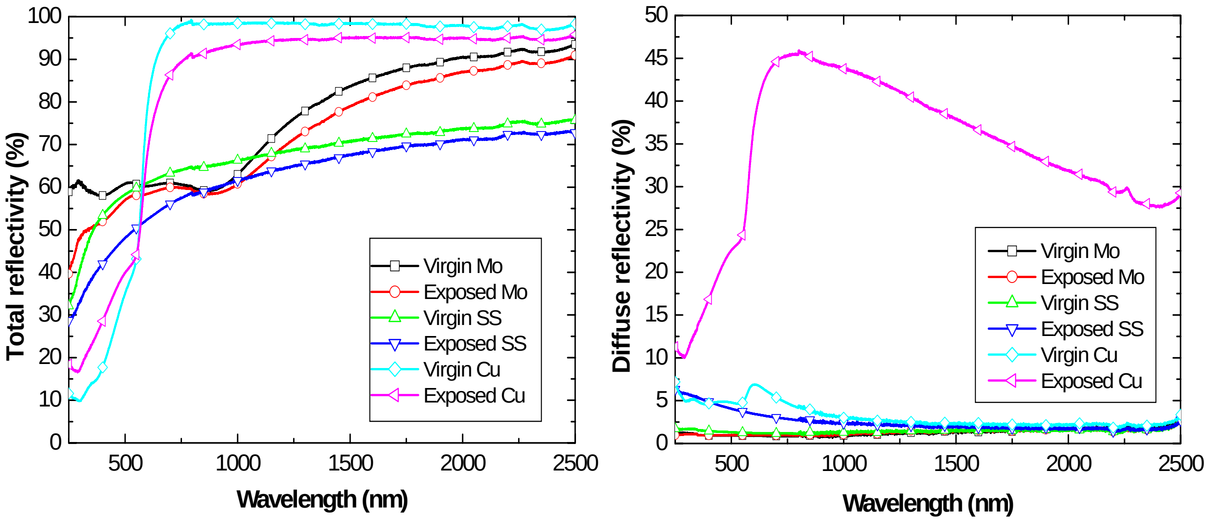

Figure 2: Total (a) and diffuse (b) reflectivity of samples exposed in Tore Supra.

For the stainless steel mirrors, both a decrease of the total reflectivity and an increase of the diffuse component (especially in the UV region) are noticed. AFM and con-focal microscopy measurements have shown a rise of the roughness. Again carbon and oxygen are found on the surface.

Results obtained for the copper mirrors are more surprising. First of all, it seems that the non-exposed mirror exhibits a much lower reflectivity than values found in the literature. Long-term storage in air and un-careful handling may have deteriorated the surface. As a consequence, values given here are not representative of what a well manufactured sample should be. The evolution of the diffuse reflectivity after plasma exposure, showing an extreme value of about 50% at 800 nm, is more difficult to understand. Even if the surface roughness has dramatically increased (according to AFM), the diffuse reflectivity is not expected to be so high. A possible explanation could be that, due either to the high roughness or to a problem with the flatness of the sample, part of the specular reflected beam hits the edge of the entrance port of the sphere and is integrated as part of the diffuse reflectivity.
In this experiment, mirrors surface was submitted both to erosion and to deposition, making very difficult the prediction of the mirror lifetime.

2. Exposure of metallic mirrors in the SOL of TEXTOR

2.1. Exposure of large polycrystalline molybdenum mirrors in the erosion and deposition dominated area in the SOL of TEXTOR

Large polycrystalline molybdenum mirrors have been exposed in the Scrape-Off Layer (SOL) of TEXTOR. Mirrors were placed on an inclined target holder (20° to the toroidal direction). Fig. 3 shows the experimental setup and the appearance of one sample exposed in the erosion dominated zone.

The mirror is partly protected by an aluminium bar creating a shadowed zone (according to the field lines) and a reference zone (under the bar) affected neither by erosion nor deposition. A small mirror is placed for comparison at the rear side of the target holder perpendicular to the toroidal direction. The target holder is placed in the SOL plasma because in this area particles energy and fluences are of the same order of magnitude of those expected in ITER.

In the first experiment the edge of the mirror closest to the plasma was kept at a distance of 8 mm from the LCFS (Last Closed Flux Surface) which is an erosion dominated zone in TEXTOR. It was exposed to 30 neutral beam heated plasma pulses with a total exposure time of 197 s. For the second experiment the closest edge of the mirror to the plasma was kept at a distance of 25 mm from the LCFS, so in a deposition dominated zone. It was submitted to 58 (partially neutral beam heated) discharges for a total exposure time of 312 s.

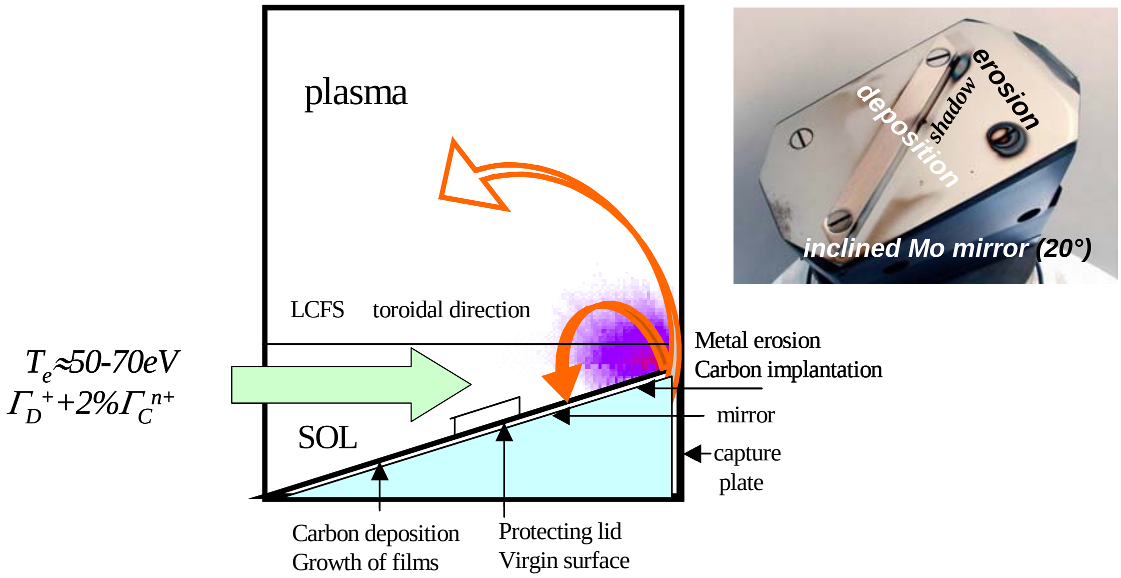

Figure 3: Schematic layout of the mirror exposure in TEXTOR and photograph of one sample exposed in the erosion dominated zone.

As seen in fig. 3, the part of the mirror closest to the plasma was submitted to erosion by plasma ions while parts further from the plasma were submitted to deposition of impurities.

Total and diffuse reflectivity was measured at about 50 locations on the mirror surfaces. Fig. 4 shows the results observed for the total reflectivity of the two mirrors. Before exposure the reflectivity stays below the reference values found in the literature. In the areas affected by net deposition of impurities, a drop of the reflectivity is noticed; it is most pronounced in the UV region and vanishes in the IR. Absorption of light in the deposited layer explains the behaviour in the UV region. Moreover reflectivity can significantly be affected by destructive and constructive interferences in thick deposits. Surprisingly, an increase of the reflectivity well beyond the reference values is noticed in the areas affected by net erosion. This increase was partly expected because of the cleaning procedure used on the mirrors before exposure. Indeed mirrors were rinsed in alcohol after polishing and the presence of an organic layer can be assumed before exposure, which can also explain the reflectivity values measured before exposure. During the first plasma pulses this layer was removed, plasma acting as a cleaning agent. But the fact to obtain reflectivity beyond the literature values is more difficult to understand and is still open for discussions.

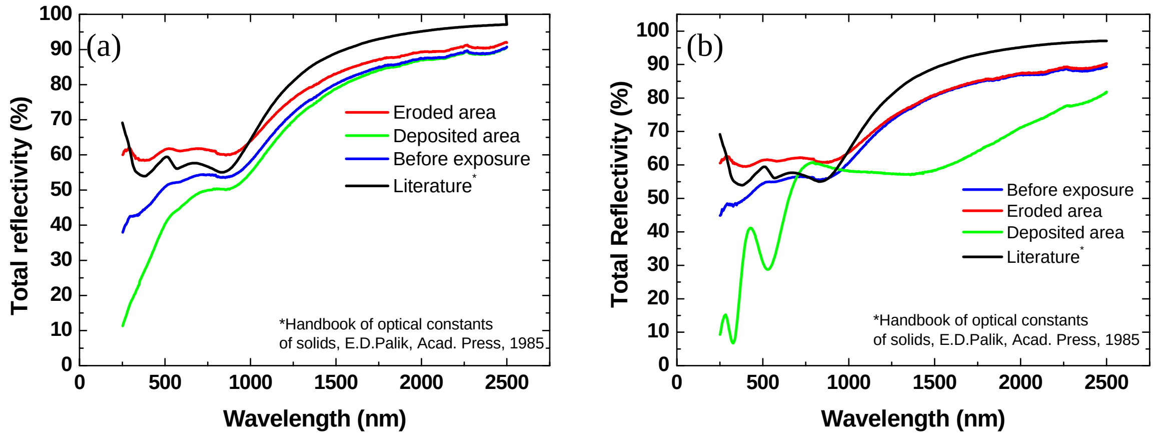

Figure 4: Total reflectivity against wavelength measured on different location on the surface of mirrors exposed (a) in the erosion dominated zone and (b) in the deposition dominated zone.

2.2. Comparative tests of single crystal and polycrystalline mirrors exposed in the SOL of TEXTOR under erosion conditions

2.2.1. Preparation and pre-characterisation of samples

Three mirrors were used in the experiment: polycrystalline molybdenum mirror, single crystal molybdenum [110] and single crystal tungsten mirror [111]. Single crystal samples were supplied by K. Vukolov from Kurchatov Institute, Moscow.

Pre-characterisation was made at the Institute of Physics (IfP) of the University of Basel. Total and diffuse reflectivity were measured by means of a spectrophotometer equipped with a 110 mm diameter sphere in the spectral range 250-2500 nm. Spectroscopic ellipsometry and polarization measurements were made in the range 300-800 nm for different angles of incidence (45°,55°,65°). Scanning Electron Microscopy (SEM) was used to study the morphology of the surface. Due to some problems during the preparation of the mirrors, a strong oxidation of the surface of the SC (single crystal) molybdenum mirror was found causing a drop of the total reflectivity down to 35 % (at 250 nm) against 65 % for a clean sample. Hydrogen glow discharge cleaning was applied in a preparation chamber at the IfP to test the possible recovery of the optical properties, fig. 5 shows the evolution of the reflectivity after the two 15 minutes cleaning. The plasma parameters of the discharge will be soon measured by means of a langmuir probe but the technique has shown a good efficiency for mirror cleaning.

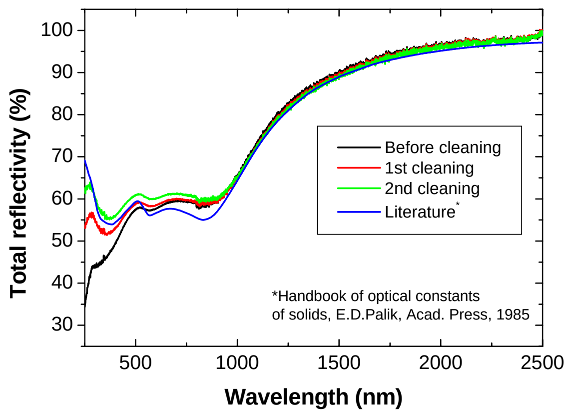

Figure 5: Evolution of the reflectivity of the single crystal mirror after the two 15 minutes cleaning in hydrogen glow discharge.

2.2.2. Experimental conditions

The mirrors were placed in a row on a sample holder mounted on a test limiter and exposed in the Scrape-off layer (SOL) plasma of TEXTOR in erosion-dominated area. They were exposed to 36 neutral beam heated (NBI) deuterium discharges for a total exposure time of 210 s. Fig. 6 shows the sample holder with the mirrors after exposure.

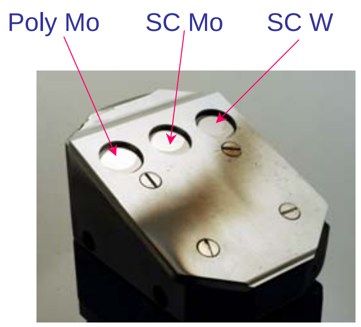

Figure 6: View of the mirrors on the sample holder after exposure.

2.2.3. Optical characterization and surface aspect of the mirrors after exposure

The reflectivity of the mirrors after exposure was measured at the same locations as before the exposure to plasma (fig. 7).

The total reflectivity of both mirrors did not change much due to erosion. Only a small decrease can be observed in the visible region of the spectrum. Things are different for the diffuse reflectivity. For the single crystal sample, it remains low (< 1.5 %). For the polycrystalline sample a drastic increase of the diffuse reflectivity can be observed especially in the UV-Visible (up to a value > 8.5 %).

The reason for this increase is likely due to the appearance of a so-called "step-structure" which is clearly seen in fig. 8.b. Indeed a polycrystalline material is composed of grains with different crystallographic orientations associated with different sputtering yields, when the surface is sputtered by plasma ions these grains start to be visible. This effect does not exist for a single crystal, as can be seen in fig. 8.a, where the surface of the single crystal mirror does not show any damage.

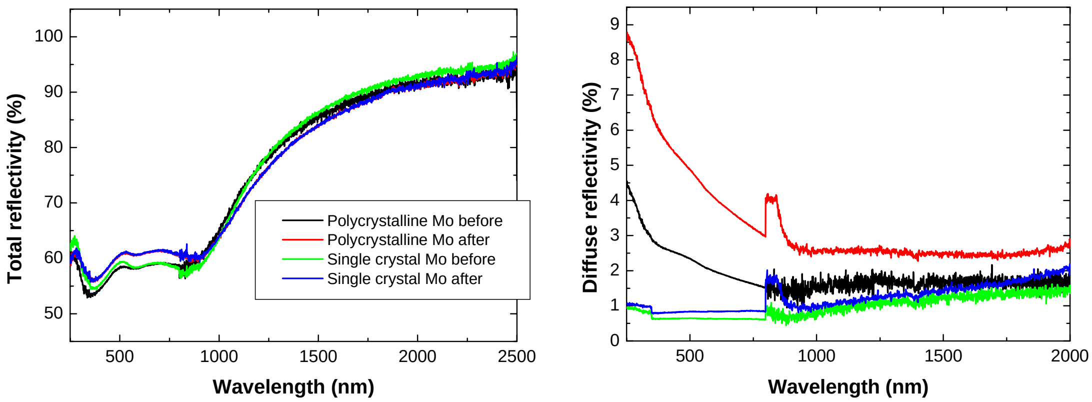

Figure 7: Total and diffuse reflectivity of the two molybdenum samples before and after exposure to TEXTOR plasma.

Given that the ion flux of the plasma in the region where the samples were exposed $2.4 \cdot 10^{18}$ ion.cm^{-2}.sec^{-1}, which is approximately 25000 times larger than expected for flux of charge exchange atoms on the first wall of ITER, the exposure time is therefore equivalent to about 1000 ITER shots.

In conclusion this experiment shows that single crystal mirrors exhibit a much longer lifetime at least in case erosion is the main damaging mechanism.

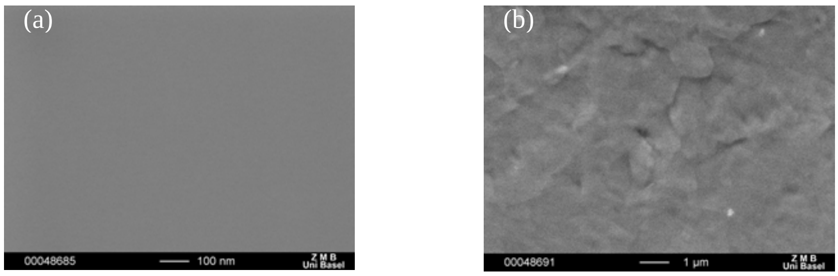

Figure 8: SEM pictures of (a) single crystal and (b) polycrystalline molybdenum mirrors after exposure (note the higher magnification used in fig. 4 (a).

3. Exposure of metallic mirrors in the divertor of TCV

3.1. Experimental programme

At TCV, mirrors made of polycrystalline molybdenum have been installed on a specially designed manipulator inserted from the bottom of the torus into the vessel floor which acts as a target region for a number of different diverted plasma configurations (fig. 9).

The manipulator allows samples to be exposed and retrieved without the need for a vacuum vessel vent. A large variety of magnetic equilibria are studied on TCV and the absence of any shutter system protecting the TCV samples means that most exposures are integrated across short campaign periods of 2-3 weeks, including helium glow discharge conditioning which is executed for 5 minutes between each tokamak discharge and for longer periods at the start of each operational day. The manipulator is electrically isolated from the torus and is thus maintained at the local floating potential established during glow discharge.

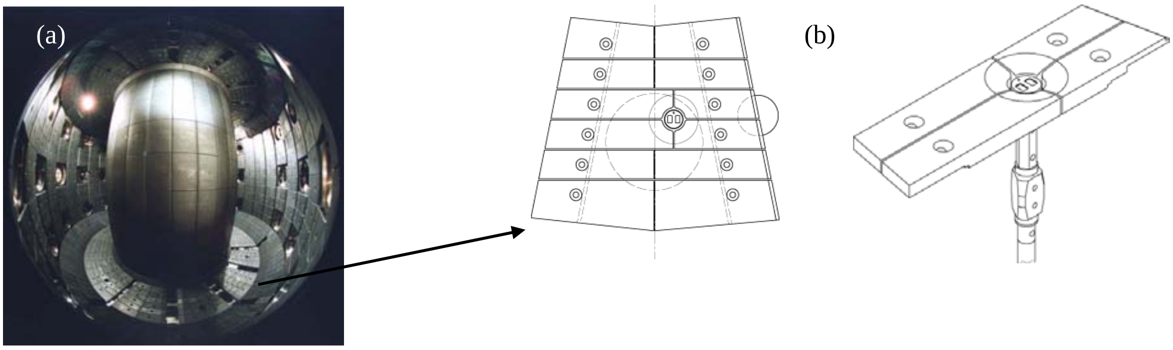

Figure 9: Inside view of the tokamak TCV with graphite tiles covered walls (a), and schematic drawings showing the installation of the sample manipulator in the divertor floor of TCV (b).

3.2. Main Results

Table 1 summarises the different materials tested, the experimental conditions (recessment distance, number of tokamak shots, glow discharge conditioning time etc.) and estimation of the deposited thickness. Evidently, only very thin layers have been found on the different samples, especially when high-Z materials (Mo, W) have been exposed. No difference in the carbon layer thickness was found when Mo and W were exposed simultaneously. There appears to be no correlation between the deposited thickness and the recess distance below the divertor target tiles, though the significance of this result must be gauged against the large differences in terms of plasma configurations and conditions (ohmic, H-mode, high power, low density electron cyclotron heated discharges, limiter, divertor etc.) characterising the different sample exposure periods. The most striking result is obtained when molybdenum and silicon samples are simultaneously exposed. The deposition rate on the Si sample is found to be much higher than on Mo, a phenomenon observed in two separate experiments. Since the exposure in pairs ensures that the samples experience nearly identical conditions, the only parameter which can play a role is the substrate material itself. It would therefore appear that the deposition efficiency on different substrates is quite different: carbon deposition on a high-Z material like Mo being less favourable than on Si.

Material	d(mm)	Nb of shots	Glow discharge (hrs)	Deposited thickness (nm)
Mo	15	323	33.44	4.7
Mo				
Mo	10	19	1.47	1
W				
Mo	50	214	21.54	0.9
W				
Mo	50	223	24.5	**1.3**
Si				**15.9**
Mo	50	820	90.5	**4**
Si				**24**

Table 1: Experimental condition of the mirror exposures in TCV. d is the distance between the sample surface and the front surface of the graphite divertor tiles.

The composition of the deposited layer has been investigated by XPS and SIMS, and found to be mainly deuterium and carbon, as expected given the use of deuterium as main plasma fuel and the extensive graphite coverage of the TCV first wall. However, in the current manipulator design, there is no possibility to measure the particle fluxes and energies the samples are submitted to.

4. First mirror tests in JET

4.1. Experimental setup

JET is the largest divertor tokamak, with an ITER relevant configuration; it can achieve plasma pulses of 20 s and has a unique beryllium environment. Mirror tests in JET aim at the study of surface properties changes (reflectivity, composition) of two different materials: polycrystalline molybdenum and stainless steel 316L. The First Mirror Test (FMT) is being made in the framework of the Tritium Retention Study (TRS) project.

Mirrors are mounted in stainless steel cassettes (fig. 10) with several channels and installed in different locations of JET. The cassettes are of a "pan-pipes" shape and are made of two detachable plates. The construction enables studies of deposition both inside the pan-pipes channels and on the mirror surface. Mirrors are blocks of 1*1*1 cm with a leg for an easier mounting.

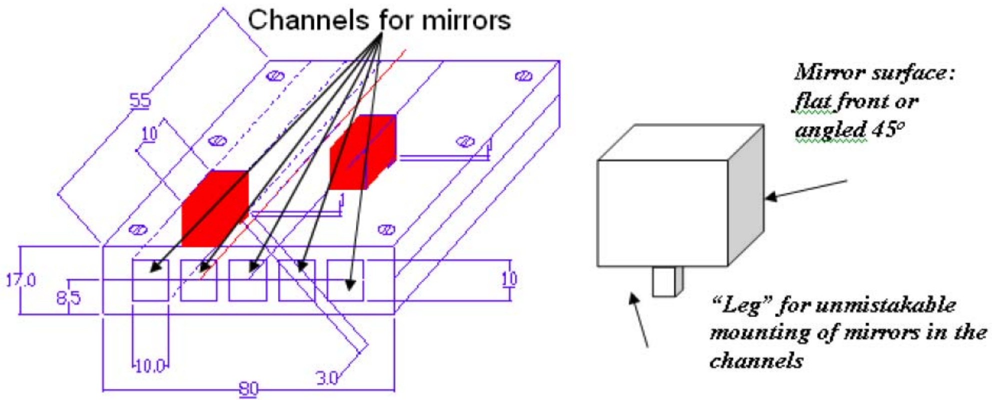

Figure 10: Schematic view of a cassette and a mirror block.

Fig. 11 shows the locations of mirrors and deposition monitors (quartz micro balance) in the divertor base and on the main chamber wall.

Optical pre-characterizations were made in Basel using UV-Vis-NIR spectrophotometer and spectroscopic ellipsometry. About 50 mirrors were measured (30 molybdenum and 20 stainless steel). If there was no difficulty to perform pre-characterization in Basel, the problem is totally different after exposure. The mirrors will be contaminated by beryllium and tritium during their exposure in the JET vacuum vessel. Post exposure reflectivity measurements thus require spectrophotometer equipment compatible with handling contaminated material. To overcome the non-negligible complications introduced by such requirement, special spectrometric equipment has been constructed at JET. Design and installation of the system were performed by our group.

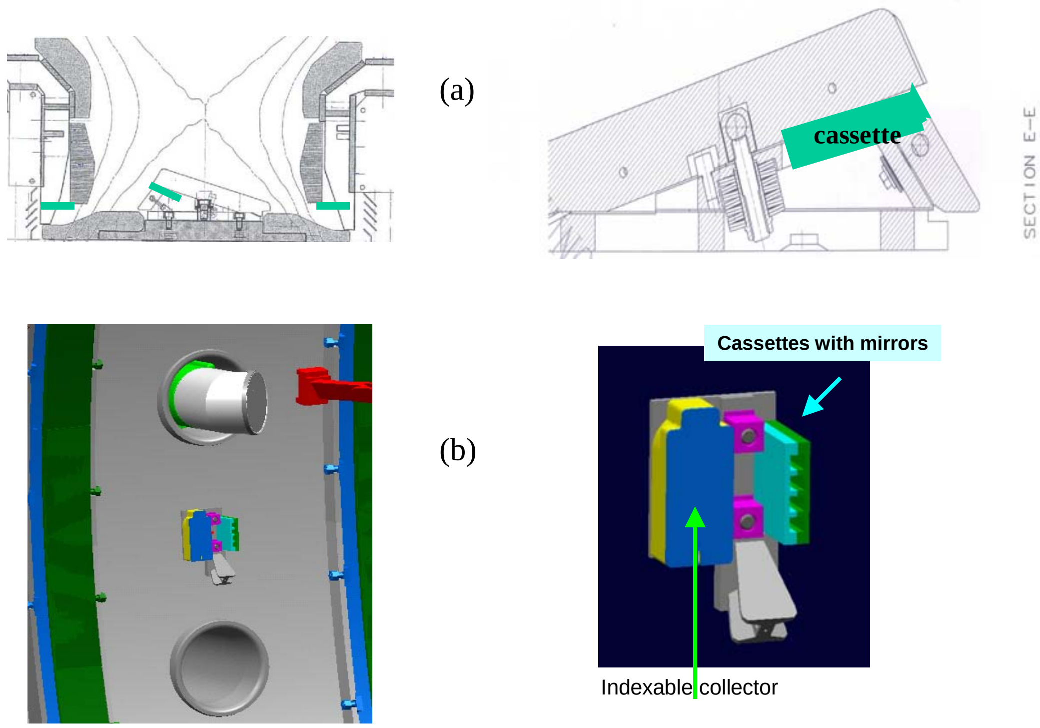

Figure 11: Mirrors locations in the divertor of JET (a) and on the main chamber wall (b).

4.2. Hardware components and installation

Such equipment must satisfy the following requirements: (i) the use of an integrating sphere which allows the measurement of both total and diffuse reflectivity (the specular reflectivity being calculated as the difference between these two values); (ii) wavelength range 350-1700 nm to cover the visible and near-infrared; (iii) physical separation of the integrating sphere and spectrometer to minimize the size of the glove box which must be constructed to enclose the contaminated mirrors. The following items have been chosen as the best compromise between safety and budgetary restrictions and the requirements for measurement range and accuracy:

- optical spectrometer with a 2048 pixel CCD (charge coupled device) detector and a 200µm entrance slit (350-1100 nm) ;
- optical spectrometer with a peltier cooled 256-element InGaAs diode array detector (900-1700 nm);
- 50 mm diameter integrating sphere coated with PTFE (*PolyTetra*-Fluoro Ethylene, i.e. Teflon®). A gloss trap coated with a black absorbing material is used to exclude specular reflection and measure only the diffuse reflectivity;
- 400 µm core diameter optical fibres.

Fig. 12 shows a picture of the hardware components before final installation in the glove box.

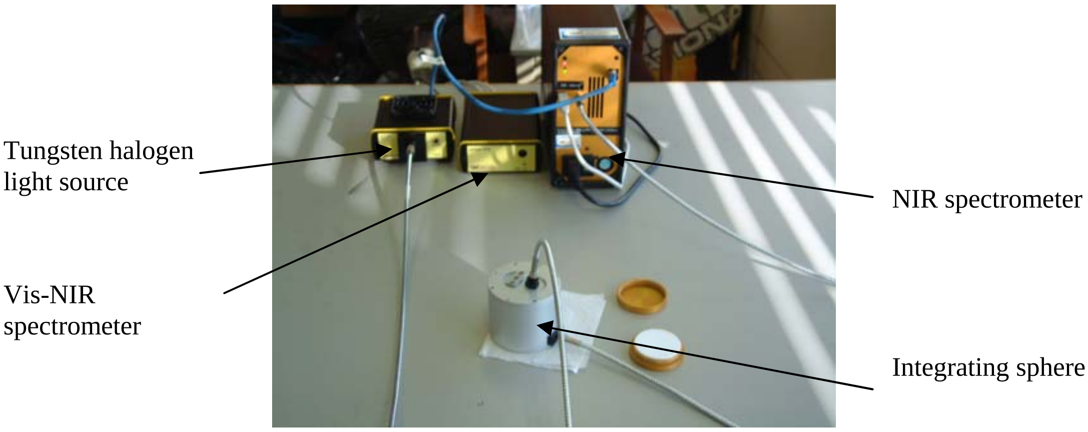

Figure 12: Hardware components of the measurements system installed at JET.

The equipment has been calibrated using samples whose reflectivity was measured both by the spectrophotometer and by ellipsometry in Basel. Results, presented, in fig. 13 are found to be in good agreement over the whole wavelength range.

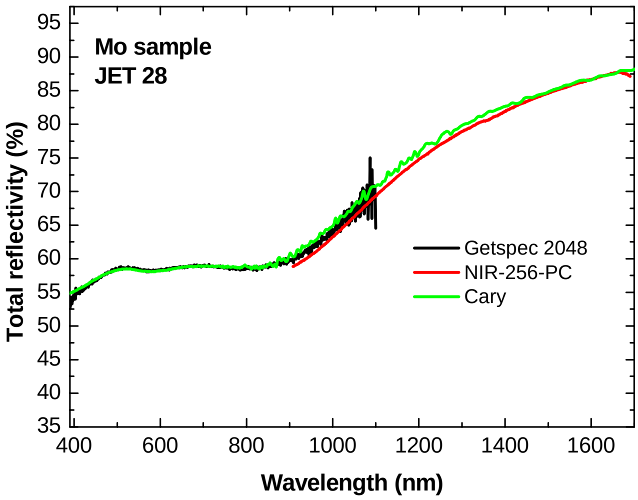

Figure 13: Comparison between a total reflectivity measurement made on a JET molybdenum sample with the setup installed at JET and with the spectrophotometer in Basel.

Some of the optical windows presently used on JET for spectroscopic diagnostics are actually located at position relevant for future first mirrors in ITER. It is therefore expected that useful information might be gathered by measuring the transmission of such windows, which have been exposed to plasma for very long periods. A sample holder for transmission measurements has also therefore been included inside the glove box. A picture of the final setup is shown in fig. 14. Only the measurement units (i.e. the integrating sphere and transmission sample holder) are installed in the glove box. The connection to the spectrometers and the light source is made by means of optical fibres.

According to the present plan, some of the mirrors should be retrieved during the next shutdown in the summer 2006 (end of July). They will be replaced by new ones whilst the remaining mirrors will stay in the vacuum vessel and be exposed during the following campaigns.

After their retrieval from the torus, contamination level of the mirrors will be checked and they will be transferred to the measurement system where their reflectivity will be measured. After this step detailed surface analysis measurements will be made (SIMS, SEM,…).

Figure 14: Final set-up of the equipment with the measurement units (integrating sphere, transmission holder) installed in a glove box.

5. Influence of the mirror material choice on the erosion/deposition mechanisms affecting optical reflectivity

Recent results from long term exposure of mirrors in Tore Supra and from sample exposures in TCV seem to indicate that the mirror material itself can strongly affect the mechanism influencing the surface reflectivity. Such observation (if confirmed) could have potentially important consequences for the choice of mirror material to be installed in region of ITER where deposition of impurities is expected to be the main damaging effect (in the divertor for example). To investigate it further special experiments were initiated at the Institute of Physics (IfP).

5.1. Experimental setup

Mirrors from two different materials (stainless steel, copper) were exposed to deuterium/methane plasma with a controlled partial pressure of methane in the gas mixture. Reflectivity of the samples is followed in-situ during the plasma exposure using a laser reflectometer (λ=532 nm). A mass spectrometer is used to determine the gas composition.

Plasma ions are accelerated on the sample by applying on it a negative voltage of -210 V and a current of 50 mA. The mirrors are mounted on a water-cooled sample holder. Different methane contents in the deuterium/methane mixture have been used, the total pressure during the plasma exposure was kept constant at $1.5 \cdot 10^{-1}$ mbar. Let f_{CH_4} be the methane content in the plasma, as determined by the mass spectrometer. Simultaneously to the plasma exposure, reflectivity of s-polarized light is measured using a real time laser reflectometer (λ=532 nm). Plasma parameters ($n_e \cong 10^9$ cm^{-3} and T_e=13 eV) are measured by means of a Langmuir probe.

Two different materials were investigated: polycrystalline copper and stainless steel. They were prepared in IPP Kharkov, Ukraine. All samples were cut by an arc cutting in kerosene, washed by acetone and exposed to low energy ions (50 eV) of hydrogen ECR plasma during 20 min. Samples have dimensions of 22x22x4 mm.

5.2. Experimental results

Three different deuterium/methane mixtures were used: f_{CH_4}=0, f_{CH_4}=1.8 % and f_{CH_4}=3.5 %. The evolution of mirrors' specular reflectivity during plasma exposure is plotted in figure 15 as a function of the ion fluence, reflectivity levels have been normalized to ease the comparison.

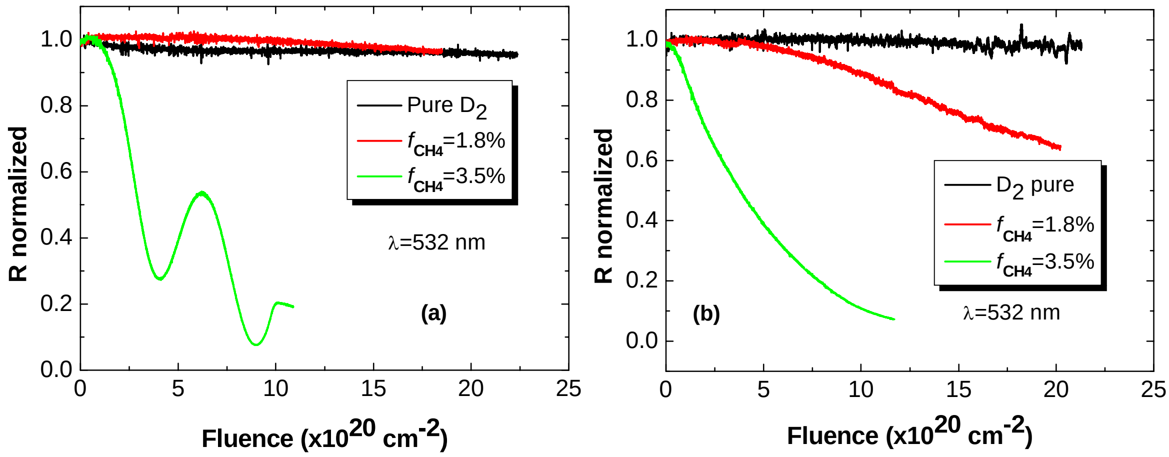

Figure 15: Real-time evolution of the reflectivity of (a) stainless steel and (b) copper mirrors during plasma exposure.

The behaviour of the reflectivity for both materials is quite different. For methane contents in the plasma lower than 3.5%, the reflectivity of the stainless steel mirrors (fig. 15.a) decreases very slowly with the ion fluence, with a final value of 0.96 after an ion fluence of $2 \cdot 10^{21}$ $ions.cm^{-2}$. For higher methane content, the evolution of the reflectivity shows constructive and destructive interferences typical of the growth of an amorphous hydrogenated carbon film. The presence of a carbon film was confirmed both by visual inspection of the sample and by EDX (Energy Dispersive X-ray) analysis. For copper (fig. 15.b), the degradation rate of the reflectivity is directly related to the carbon content in the plasma: the higher the carbon content is the faster the reflectivity decreases. For the highest methane content the reflectivity has almost dropped to zero for a fluence of 10^{21} $ions.cm^{-2}$. In all cases no carbon is detected by EDX analysis which indicates that copper is purely physically sputtered by the plasma ions.

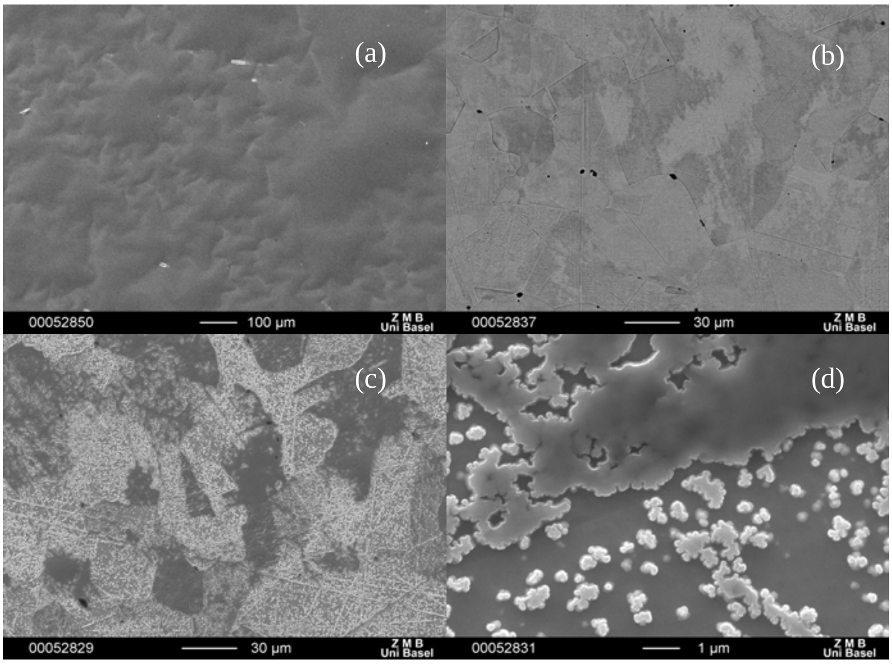

Figure 16: SEM pictures of (a) the carbon deposit found on the stainless steel sample exposed to f_{CH_4} = 3.5 %, of the copper sample exposed to (b) f_{CH_4} = 1.8 % and (c and d) 3.5 %. Figures 6.c and 6.d are pictures taken on the same spot but with different magnifications.

As evidenced by Scanning Electron Microscopy (SEM), the surface of the stainless steel mirrors exposed to plasma containing less than 1.8 % of methane remains undamaged and does not reveal the stepped structure typically found for polycrystalline samples exposed to high deuterium ion fluence. The deposit found on the sample exposed to the highest methane content has a very poor adhesion and can be peeled away very easily. As shown in fig. 16.a (and confirmed by measurement of the diffuse reflectivity) the film is very rough. The substrate below the deposit appears to be very flat and similar to a non-exposed surface.

The surface of the copper mirror exposed to pure deuterium plasma remains almost undamaged (SEM picture not shown here). As seen in fig. 16.b, the situation is different when the methane content in the plasma is increased. The different crystallographic grains start to be visible for f_{CH_4} =1.8 % and the effect is much more pronounced for f_{CH_4} =3.5 % (fig. 16.c). Figures 16.c and 16.d are pictures taken in the same area of the surface but with different magnifications. Beside the typical shape of the crystallographic grains, a lot of white spots are observed all over the surface. When zooming in (fig. 16.d), these spots appear to be micrometer-size agglomerates. But according to EDX there is no carbon on the surface, which means that these particles are made of copper and possibly come from prompt re-deposition of copper on the surface.

5.3. Implication for mirror material choice in ITER

From the results described above, it is seen that copper and stainless steel exhibit different behaviour towards simultaneous bombardment with carbon and deuterium ions. Copper is less sensitive to deposition but strongly sputtered by the plasma ions. The reflectivity is thus strongly affected as the surface roughness increases. On the opposite stainless steel appears to be much less sensitive to physical sputtering, but became coated when a sufficient carbon concentration in the plasma is reached. Since the samples have been exposed to similar plasma conditions, we can assume that the dominant parameter here is the substrate material itself. Up to now the mirror material was thought to have an influence only when erosion is the main damaging effect. But the results described here and observations made in TCV and Tore Supra tend to demonstrate that the substrate material may influence the deposition pattern observed. Further experiments are planned to determine the reason of such different behaviours in addition to numerical modelling using the Monte Carlo code Tridyn, but if confirmed they would have an influence on the choice for mirror material planned to be placed in deposition dominated region of ITER (in the divertor for example).

6. Publications

M. von Hellerman, M. de Bock, R. Jaspers, K. Jakubowska, R. Barnsley, C. Giroud, N.C. Hawkes, K.D. Zastrow, P. Lotte, R. Gianella, A. Malaquias, E. Rachlew, S. Tugarinov, A. Krasilnikov, A.Litnovsky, P. Wienhold, V. Philipps, P. Oelhafen, G. De Temmerman, L. Shmaenok, **Pilot experiments for the International Thermonuclear Experimental Reactor active beam spectroscopy diagnostic,** Review of Scientific Instruments, 75 (10), 3458

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7. Presentations

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Development of optical mirrors for analytical purposes in ITER, Seminar, March 2004, CRPP Lausanne, Switzerland.

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Influence of the material choice on the deposition/erosion mechanisms affecting optical reflectivity of metallic mirrors, Colloquium, March 2006, Forschungzentrum Jülich, Germany.

Influence of the material choice on the deposition/erosion mechanisms affecting optical reflectivity of metallic mirrors, 10^{th} ITPA meeting on diagnostics, April 2006, Moscow, Russia.

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8. Scientific collaborations

• Institut für Plasmaphysik, Forschungszentrum Jülich, Germany,
• Centre de Recherche en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne, Suisse,
• Alfvén Laboratory, Royal Institute of Technology, Stockholm, Sweden,
• Culham Science Centre, JET, Abingdon, England,
• Commisariat à l'Energie Atomique, centre de Cadarache, Saint Paul-lez-Durance, France
• Nuclear Fusion Institute, Russian Research Center 'Kurchatov Institute', Moscow, Russia,
• Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine,
• Centre for Energy Research, University of California at San Diego, San Diego, USA.

9. International activities in fusion research

• P. Oelhafen is guest member of the IEA TEXTOR executive committee.
• G. De Temmerman is member of the First Mirror Specialist Working Group of the ITPA Topical Group on Diagnostics.