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Studies related to plasma-wall interactions in ITER

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Summary

In the course of the ongoing project, our research was focused on the realisation of rhodium and molybdenum coated mirrors. The growing interest about the use of rhodium (Rh) as a material for the first mirrors in ITER (International Thermonuclear Experimental Reactor) and the necessity of using it as a thin film deposited on a polished substrate has raised the necessity of the development of a robust deposition technique for the preparation of high-reflectivity mirrors. A robust method, magnetron sputtering for depositing high quality films was successfully tested at the University of Basel. Amongst all investigated parameters (deposition rate, substrate temperature, metal substrate…), only the gas pressure during deposition was observed to have an influence on the optical properties of the film. Otherwise, the measured reflectivity is close to the reflectivity calculated from optical constants of pure rhodium. Storage of samples in air did not affect the reflectivity in contrast to molybdenum deposited mirrors.

The relevant size of mirrors for ITER will be around 30 cm diameter. Magnetron sputtering technique is an expensive technique to produce large rhodium mirrors due to the price of the target. Evaporation seems to be cheaper to produce these large-size mirrors. Rhodium and molybdenum mirrors were deposited by evaporation at the University of Basel.

In collaborations with groups from different Tokamak sites (TEXTOR, JET and DIII-D), the investigation of the erosion and deposition mechanisms affecting the optical reflectivity of such mirrors were carried out. Several exposures of rhodium and molybdenum coated mirrors under erosion-dominated conditions in TEXTOR demonstrated that in the case of high exposure temperature, a severe degradation of the optical properties of rhodium exposed mirrors appeared. Otherwise rhodium mirrors maintain their reflectivity in erosion condition. For molybdenum coated mirrors the reflectivity after exposure is similar as one of the exposed single-crystal molybdenum mirror, even for high exposure temperature.

Another part is the possible deterioration of mirrors's reflectivity as a result of erosion by ions and deposition of material eroded from the plasma facing components. In Basel, a new plasma source and an in-situ reflectometry measurement setup with 3 lasers has been developed. The first results on metallic mirrors (Molybdenum, Copper, Stainless Steel, Rhodium) are

presented here and analyses are ongoing. A more detailed plasma characterisation using Langmuir probe and mass spectrometer will be started.

A modification of JET is presently being prepared for installation in 2009, to bring operational experience in steady and transient conditions with ITER-like first wall and divertor materials, geometry and plasma parameters. One aspect of this change is that the reflectivity of metallic components is significantly higher than that of carbon fibre composite. Reflectivity measurements of JET sample tiles have been performed at the Univ of Basel, and these data are used within a simplified model of the JET vessel to predict additional contributions to quantitative spectroscopic measurements of e.g. Bremsstrahlung and impurity influx. The model is also applied in actual ITER geometry for comparison.

September 2009

1. Realization and tests of high quality rhodium coated mirrors by magnetron sputtering

1.1. Motivation

Due to its high reflectivity in the visible wavelength (Figure 1) range and its low sputtering yield, rhodium may be a good candidate material for first mirrors in ITER. However, the very high price of the raw material calls for using it in the form of a film deposited onto metallic substrates. Such film has to have a small grain structure to limit the surface roughening due to erosion (by charge exchange atom: CXA for example) and a high adhesion to the substrate. The development of a reliable technique for the preparation of high reflectivity rhodium films is therefore of the highest importance. This puts the stress on the necessity of using a vacuum deposition technique in fact deposition of rhodium films were performed by magnetron sputtering. Different deposition conditions like gas pressure, power applied to the target and temperature were investigated. The detailed optical characterizations are presented.

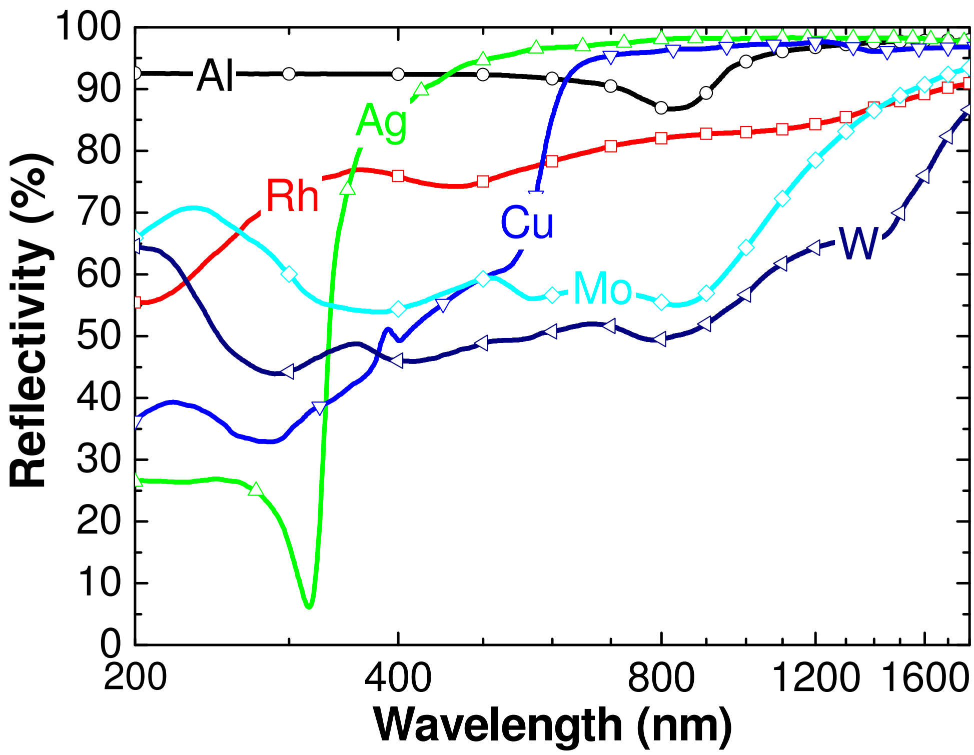


Figure 1: Spectral reflectance of Al, Ag, Rh, Cu, Mo and W calculated with the properties of the compounds from E. D. Palik, Handbook of Optical Constants of Solids, commonly used as reference.

1.2. Experimental technique

Deposition of rhodium was performed in a high vacuum chamber pumped down to a base pressure of about 2×10^{-4} Pa using a conventional pumping system. A water cooled magnetron was used with a pulsed-DC power supply. Argon, introduced through a mass flow controller (40 sccm), is used as sputter gas leading to a pressure of 0.6 Pa in the deposition chamber adjusted by a throttling value to the pumping system. The magnetron discharge current is equal to I = 0.11 A at the voltage U = -225 V. Depositions were carried out on silicon (100) substrates for surface analysis and on metallic substrates for optical measurements. Before deposition the metallic substrates (stainless steel 304L, molybdenum and copper) were polished first by abrasive SiC paper, then by diamond paste and finally by an alumina powder of 0.05 μm particle size to achieve roughness (Ra) ranging from 4 to 12 nm depending on the material. An in-situ cleaning was carried out before deposition with hydrogen plasma during 15 minutes. A bias of -50 V was applied on the substrates in order to remove any surface oxide or other impurities. The substrate faces the target with a distance of 5 centimetres. In addition, the substrate holder allows the deposition at elevated temperatures by means of resistive heating, and can also be electrically biased. The deposition rate was estimated by means of a quartz crystal microbalance (Inficon XTM). The typical deposition rate was 0.6 nm/s. After deposition, the samples were transferred from the high vacuum plasma chamber to the UHV XPS chamber without breaking the vacuum.

1.3. Experimental results

1.3.1. Characterizations of the film

First of all, it is important to note that no impurities (oxygen, carbon) were found in the films by XPS whatever the deposition conditions. After long term storage in air, no traces of oxidation are found on Rh-coated mirrors, the surface is only covered with adsorbed molecules (oxygen, carbon dioxide).

The roughness of the film is an important issue for mirrors because of the associated loss of specular reflectance. For thick film (1.8 μm) deposited on molybdenum, no change of the roughness was observed before and after deposition (Ra = 4 nm). In this case the diffuse reflectivity measured with spectrophotometer is under one percent. No subsequent polishing after the Rh film deposition was thus necessary which has the advantage of simplifying the mirror preparation process.

SEM surface observations (Figure 2) show a flat surface with small crystallites. To investigate the structure of the film cross section observation were carried out on an Rh film deposited on a silicon wafer. For example, figure 3 shows a homogeneous rhodium film with dense columnar structure.. Some edges or tips of crystallites appeared on the surface, which means columnar grains tended to have highly faceted surfaces.

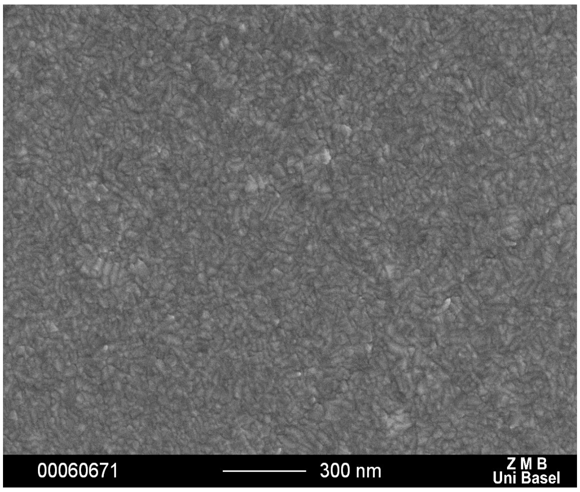


Figure 2: SEM observation of a rhodium film (1.8 μm thick) deposited on molybdenum. The roughness is Ra = 4 nm and the crystallite size is 9 nm.

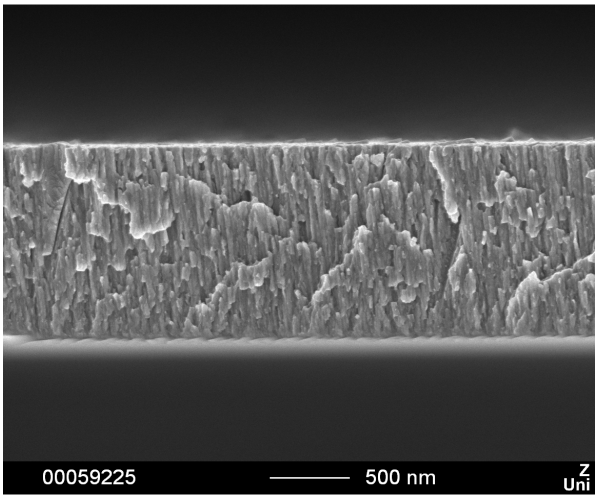


Figure 3: Cross sectional view of a rhodium film (1.2 μm thick) deposited on silicon.

Cross-section observations of deposited silicon in perpendicular view (Figure 4) show the free growth of the rhodium crystallites. The shapes of these columnar dendritic grains explain why on cross section observation, without free growth, these edges on the top surface appear. The growth process is typical for a case of infinite surface diffusion where new crystals are assumed to be nucleated periodically on the surfaces of the growing crystals. In this case, the growth rate is assumed to be the same on all crystal planes; which was demonstrated with XRD measurements (Figure 5). Nevertheless, the roughness is always rather low.

An important point concerning adhesion is the hardness of the coating. The nanohardness of the rhodium layer was measured for 1.7 μm thick layer deposited on molybdenum with a load of 3 mN. For this load the indenter penetration is only around 100 nm and the measured value is very high, 670 Vickers, in comparison to 180 Vickers for the normal bulk metal. That means the sputter layer has high dislocation density; this is also shown by the high values of the FWHM of XRD peaks even at low angle (Figure 5).

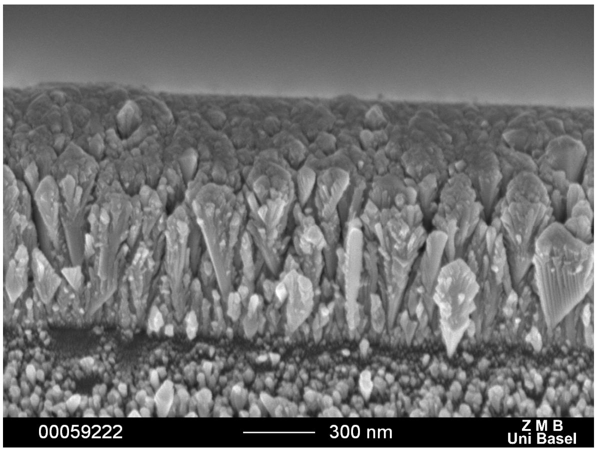


Figure 4: Perpendicular view of the deposited rhodium film in one side of the silicon substrate.

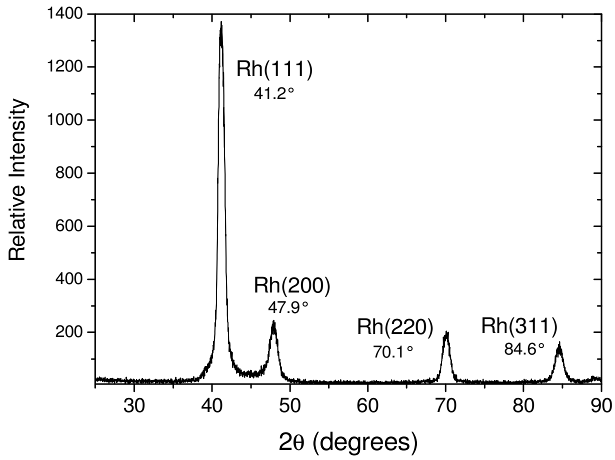


Figure 5: X-ray diffraction pattern of deposited rhodium film on silicon.

1.3.2. Reflectivity of rhodium mirror

Rhodium was deposited on stainless steel (304L), copper and molybdenum without any buffer layer. For all these layers the thickness is in a range of 1.2 to 1.9 μm. The total reflectivity, between 250 to 2500 nm (Figure 6) is plotted for these different substrates and is comparable to the reference. In all experiments the substrate does not influence the layer reflectivity.

For some laser diagnostics the polarisation of the light has an importance, for example for LIDAR the linearly polarised laser radiation will be aligned as incident s-polarisation. Different measurements were performed at a reflection angle of 40, 50, 60, 70 and 80°, for s and p polarizations and are plotted at 660 nm in figure 7. For a high incidence angle the s component of rhodium mirror has a higher reflectivity than p component. In the insert of figure 7 the reflectivity of this mirror measured at 40° for s and p polarisations and the reference is plotted.

All this optical characterizations done on 2 centimeters diameter sample are very encouraging. One mirror was deposited on a 4 centimeters square sample. The optical observations show a homogenous film on the whole surface. For mirrors with ITER-relevant sizes, the size of the magnetron target will of course have to be scaled up; however from the observations made here, there are a-priori no reason to foresee any technological limitations in the preparation of larger samples.

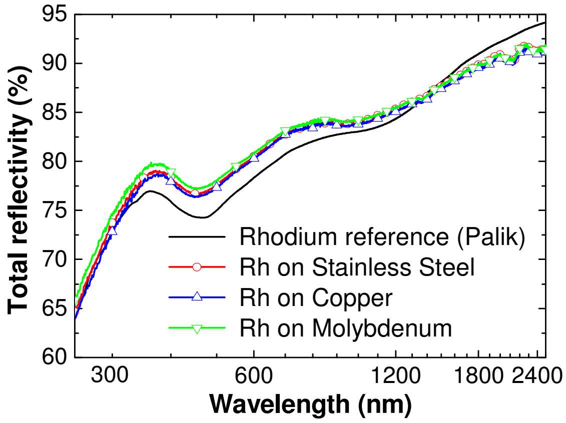


Figure 6: Total reflectivity of the rhodium layer measured with a spectrophotometer for different substrate.

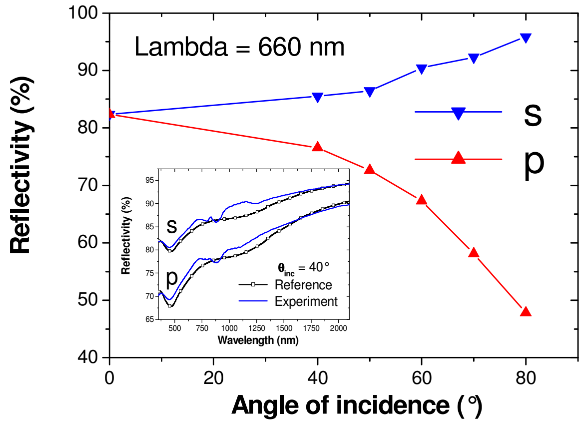


Figure 7: Reflectivity at 40, 50, 60, 70 and 80° for s and p polarizations at 660 nm. In the insert is plotted the reflectivity of this mirror measured at 40° for s and p polarisations and the reference.

1.4. Complementary experiments on rhodium mirrors

For all the listed experiments below no details are here presented but the references of published paper are available in the publication list.

The adhesion properties were evaluated using a CSM Micro Scratch instrument scratch tester with the collaboration of the University of Mulhouse (France).

It is well known that the substrate temperature during deposition affects the characteristics of the deposited film. Five substrate temperatures between room temperature (RT) and 550°C were investigated.

The influence of the gas pressure during the deposition process has also been studied in our set-up.

To investigate whether annealing cycles will have an effect on the mirror reflectivity and the thermal stresses between the reflecting layer and the mirror substrate; several experiments were carried out.

To ensure the reliability of these mirrors in a nuclear fusion environment it is necessary to determine their chemical stability and in particular the reactivity of rhodium towards typical impurities in a tokamak such as oxygen and carbon. Several depositions were performed with these impurities and were characterized.

2. Exposure of the rhodium and molybdenum coated mirrors in tokamak

2.1. Exposure of the rhodium and molybdenum coated mirrors in the SOL of TEXTOR

2.1.1. Experimental

Mirrors were exposed in the SOL (Scrape-off Layer) plasma of TEXTOR under erosion-dominated conditions in the same plasma environment. All three mirrors were placed in a row on the specially instrumented holder. Three mirrors have been exposed in TEXTOR in 2006 (figure 8) and were: single-crystal molybdenum mirror (a), rhodium mirror deposited by electro-deposition (c) and a rhodium mirror deposited by magnetron sputtering from Basel. A new exposure in 2007 was performed with three other mirrors: a rhodium coated polycrystalline molybdenum mirror from the University of Basel and rhodium coated polycrystalline molybdenum mirror from ENEA (Italy). In order to compare the sputtering rate of rhodium coated mirrors, a molybdenum coating mirror was also exposed in the same time. This molybdenum mirror was deposited on a molybdenum substrate, at the Univ. of Basel in the same set-up.

For ITER relevant size of mirrors will be around 40 cm diameter. Magnetron sputtering technique is an expensive technique to produce large rhodium mirrors due to the price of the target. Evaporation seems to be cheaper to produce this large size mirrors. One rhodium and molybdenum mirrors were deposited by evaporation at the University of Basel and were exposed in TEXTOR in 2008 as well as a single-crystal molybdenum mirror.

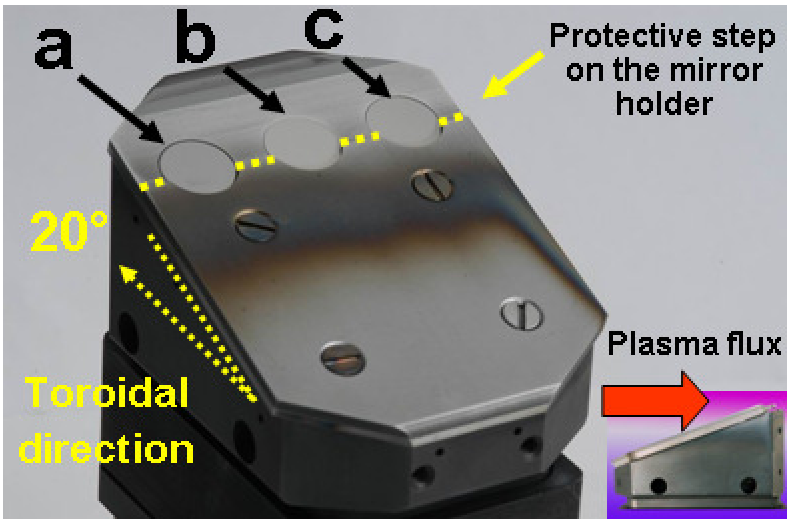


Figure 8: Holder with mirrors after exposure in the SOL plasma of TEXTOR. Single-crystal molybdenum mirror (a), rhodium mirror deposited by magnetron sputtering (b) and a rhodium mirror deposited by electro-deposition (c)

The experimental exposure conditions are summarized in the table below.

	2006	2007	2008
Fluence (ions/cm^2)	3.4x10^{20}	1.7x10^{20}	0.6x10^{20}
Mirror temperature (°C)	300 – 500	600 – 720	340 – 570
Uppermost edge of mirror holder temperature (°C)	1200	1300	870
Rhodium thickness eroded (nm)	440	700	100

Table 2: TEXTOR experiment exposure conditions

2.1.2. Optical characterisation

Reflectivity measurements were made at the same spots at the mirror's surfaces before and after exposure in TEXTOR (figure 9).

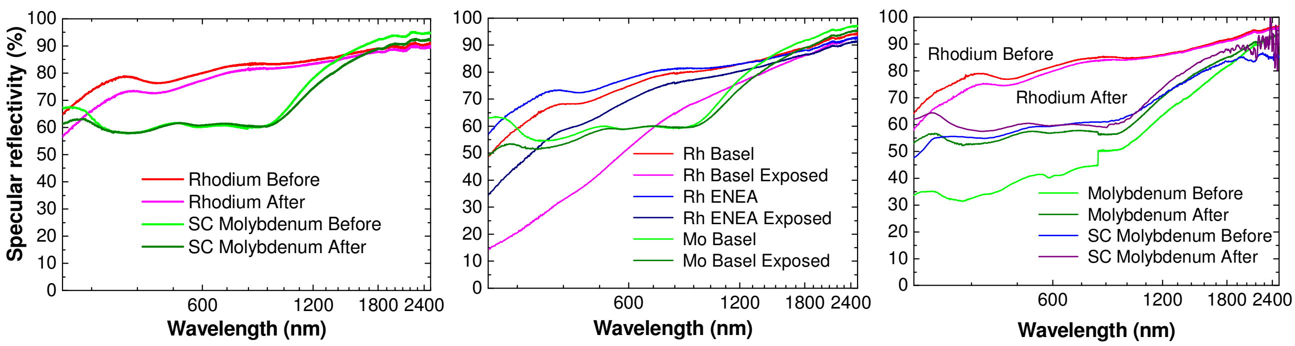


Figure 9: Specular reflectivity of the mirrors before and after exposure in TEXTOR in 2006 (left) 2007 (middle) and 2008 (right).

Exposure of rhodium coated mirrors under erosion-dominated conditions in the SOL of TEXTOR demonstrated that, in the case of high temperature exposure (2007) this led to a severe degradation of the optical properties of exposed mirrors. Otherwise these mirrors maintain their reflectivity after exposure. For molybdenum coated mirrors the reflectivity after exposure is similar as one of the exposed single-crystal molybdenum mirror, even for high exposure temperature.

2.2. Exposure of rhodium in JET

Four rhodium mirrors deposited in Basel are now in the JET Tokamak in Culham, (UK) and will be one year in the vessel. The mirrors are in 4 different positions in the JET vacuum vessel: divertor base, outer divertor, inner divertor and the main chamber wall (low field side). They will be retrieved in the second half of 2009 or beginning of 2010.

2.3. Exposure of rhodium in DIII-D

Two rhodium mirrors have been exposed in the new Midplane Material Evaluation System (MIMES) of DIII-D tokamak (San Diego, USA). Analyses will be carried out after deactivation period.

3. Role of carbon and tungsten impurities on the optical degradation of metallic mirrors

3.1. Motivation

The possible deterioration of mirror's reflectivity as a result of erosion by ions and deposition of material eroded from the plasma facing components represents a serious problem for the reliability of the spectroscopic signals for ITER. Dedicated experiments were initiated to compare the deposition and erosion patterns observed on different materials under similar conditions in laboratory experiments. For this, a new plasma source has been developed to provide clean deuterium plasma in our vacuum chamber. This source has been tested for different plasma conditions. Additionally, an in-situ reflectometry measurement setup with 3 lasers (with three wavelengths) has been developed and installed on the experimental chamber in order to monitor the evolution of the optical characteristics of mirrors exposed to this plasma source. Test of metallic mirrors (Molybdenum, Copper, Stainless Steel, Rhodium) with a deuterium plasma containing carbon and tungsten impurities are scheduled. The schematic view of the complete setup is plotted in figure 10.

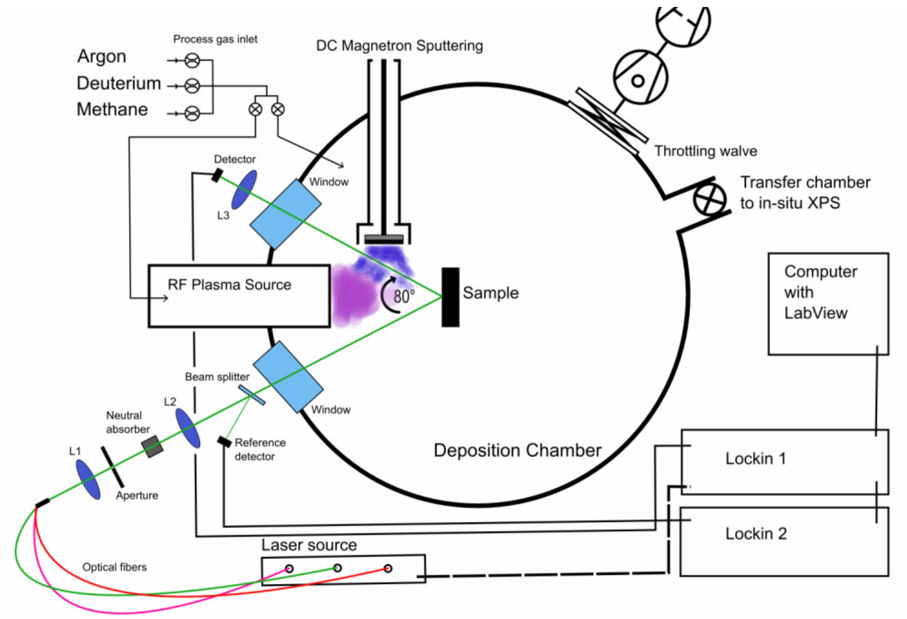


Figure 10: Setup for plasma exposure and reflectometry measurement.

3.2. Plasma source and laser reflectometry setup

A new plasma source has been designed and realized at the University (figure 11). The discharge in a Pyrex tube is generated through a matching network by a 13.56 MHz radio frequency excitation at typically power of 50 W. This excitation is coupled to the tube by a outer electrode acting as a surfatron. With this source it is possible to maintain the plasma in a large range of pressure: 8×10^{-4} to 2×10^{-1} mbar. No impurities are detected by XPS on a sample exposed to this plasma. Three different lasers (λ= 532, 670 and 905 nm) are used to measure the reflectivity of the sample during exposure. These three lasers are coupled through an optical fiber. As it is shown in figure 6, the laser beam is focused on the sample by optical components. The reflected beam leaves the high vacuum chamber through another glass window where he becomes focused again on a detector. For a reference signal, a beamsplitter is mounted in front of the entrance window to the chamber. The intensity of the reference signal and detected signal are measure using the lock-in technique to avoid experimental perturbations. The digital data are monitored and stored using a LabView program.

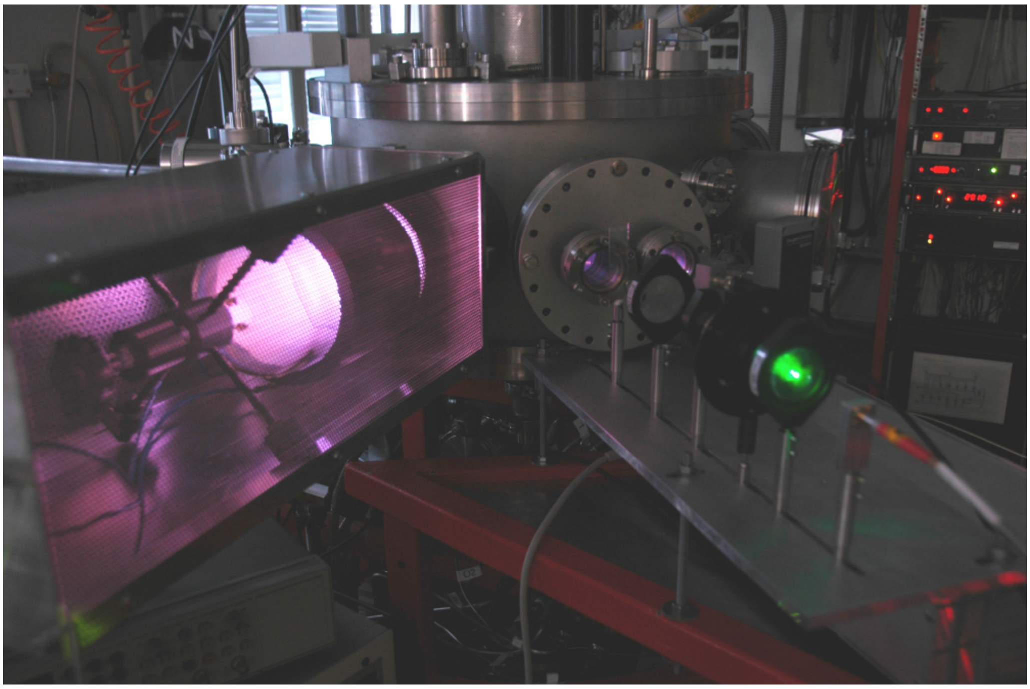


Figure 11 View of the laser reflectometry setup and the plasma source.

3.3. Mirrors exposures

Three different mirror materials were chosen for this experiment: poly-crystalline copper (Cu), stainless steel (SS) and single-crystal molybdenum (scMo). All these materials were exposed to four different plasma conditions: pure deuterium (D2), deuterium and tungsten (D2 + W), deuterium and 2.5% methane (D2 + CH4(2.5%)) and deuterium, 4.5% methane and tungsten

(D2 + CH4(4:5%) +W). Totally, twelve exposure runs were made. The denotations of the different samples are listed in Table 2.

Plasma	Copper	Stainless Steel	scMolybdenum
D_2	Cu1	SS1	scMo1
$D_2 + W$	Cu2	SS2	scMo2
$D_2 + CH_4(2.5\%)$	Cu3	SS3	scMo3
$D_2 + CH_4(4.5\%) + W$	Cu4	SS4	scMo4

Table 2: Exposed mirror materials and plasma conditions

The reflectivity does not change for Cu1 and SS1 while exposed to pure deuterium plasma. For scMo1 the reflectivity increases and stays constant after a total fluence of about 5.0×10^{18} ions/cm^2 (figure 12). This supports the assumption of a possible cleaning effect for scMo. The data shown in figure 8 for the materials Cu3, SS3 and scMo3 is quite similar with the spectral reflectivity (not shown here). For Cu3 and SS3 there is a small decrease in the reflectivity. For scMo3 there is a strong increase of the reflectivity, which increases even faster than for condition 1 (pure D2) and does not reach a steady-state after $1{:}5\times 10^{18}$ ions/cm^2. It is possible, that for longer exposure times, the reflectivity for scMo3 will reach a maximum and will also decrease due to the carbon impurities (see results for scMo4).

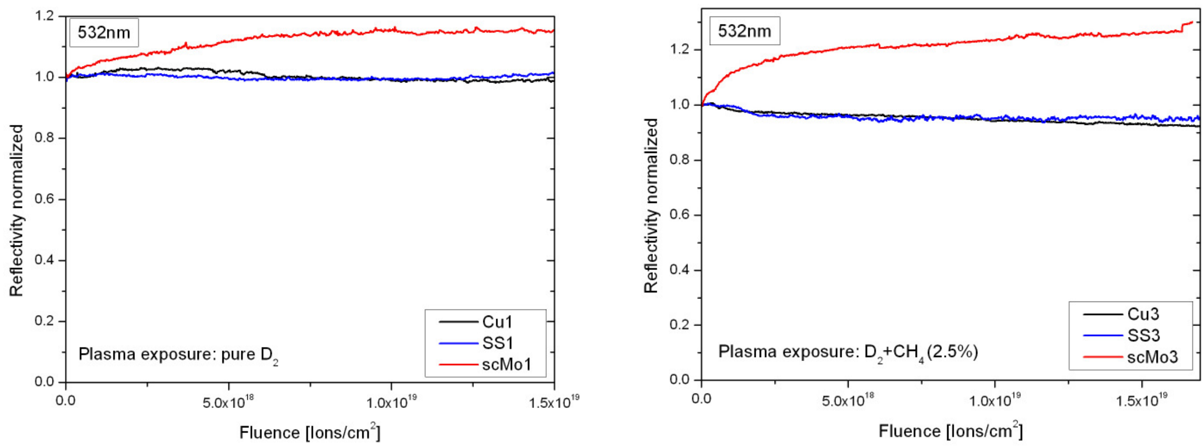


Figure 12: Change of the reflectivity for conditions 1 (left) and 3 (right). The curves are normalised to values for the start of the plasma

For plasma exposure using D2 +W, the results are plotted on the left in figure 9 for all three wavelengths. The reflectivity for scMo2 shows a smaller increase for longer wavelengths which is in agreement with the spectral reflectivity measurements (not shown here). For SS the reflectivity change is not very distinct for all wavelengths. Only for the 532nm-laser a small decrease can be observed at the beginning of the exposure. However, copper seems to be very sensitive to a deuterium plasma with tungsten. For all three wavelengths, the reflectivity for copper decreases strongly which is also the case for spectral reflectivity. Interestingly the reflectivity for copper does not decrease as fast as for a D2-plasma with 2.5% methane.

For SS and Cu, the reflectivity decreases very fast for the condition using 4.5% of methane in the plasma. In figure 13 it reaches nearly zero for the 500nm-laser data. Looking at the laser reflectometry data for Cu4, SS4 and scMo4 one can see that for longer wavelengths, the loss of specular reflectivity is not as dramatic as for shorter ones but it is still present. Several surface characterizations are now ongoing on these samples.

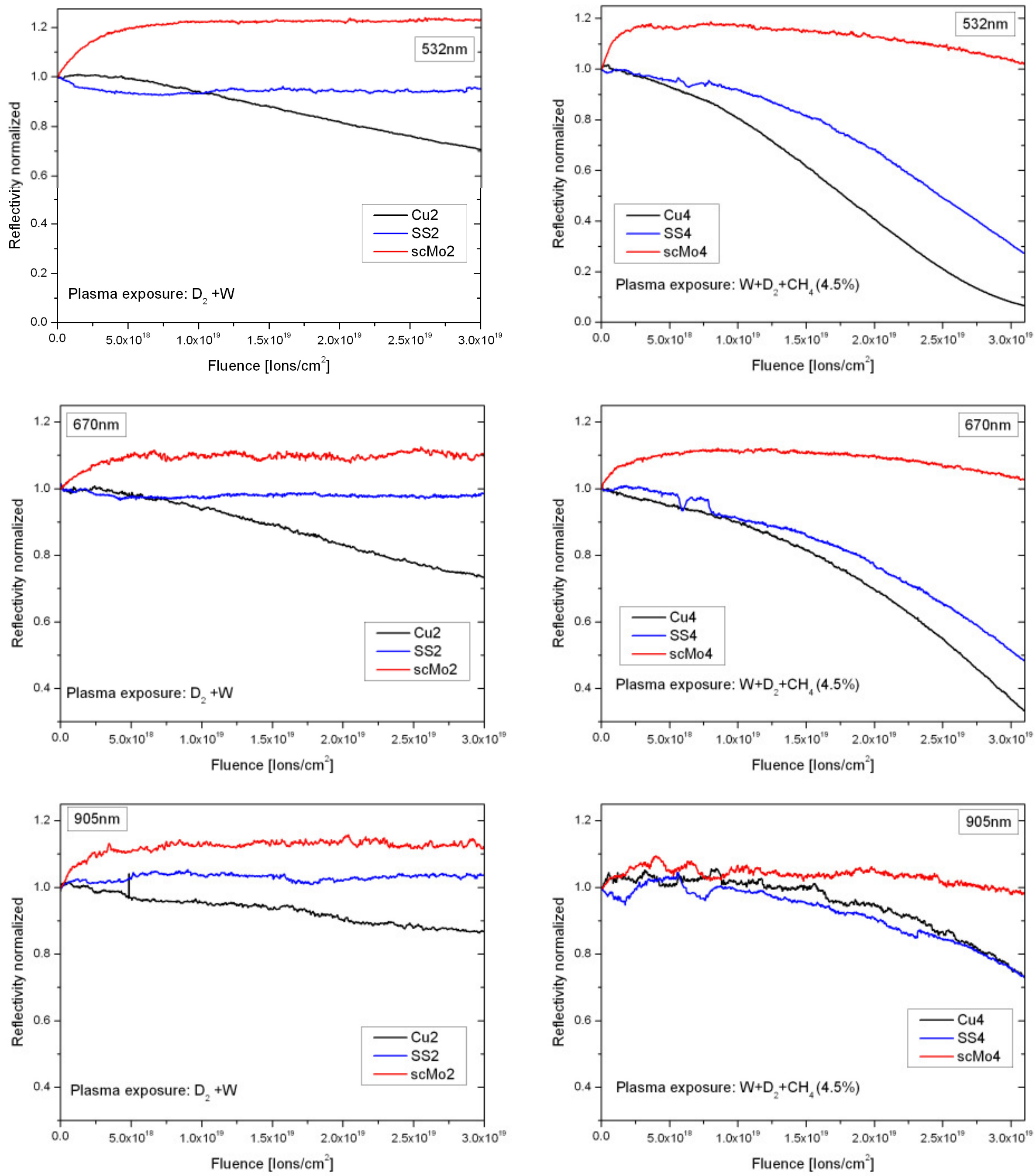


Figure 13: Change of the reflectivity for conditions 2 (left) and 4 (right). The curves are normalised to values for the start of the plasma

4. Optical measurements on JET tiles

4.1. Motivation

A modification of JET is presently being prepared for installation in 2009, to bring operational experience in steady and transient conditions with ITER-like first wall and divertor materials, geometry and plasma parameters. One aspect of this change is the reflectivity of metallic components is significantly higher than that of carbon fibre composite (CFC). Reflectivity measurements of JET sample tiles have been performed at the Univ of Basel, and these data are used within a simplified model of the JET vessel to predict additional contributions to quantitative spectroscopic measurements of e.g. bremsstrahlung and impurity influx. The model is also applied in actual ITER geometry for comparison.

4.2. Experimental

Measurements of the angular distribution of the light after reflection on a surface have been carried out on two different tiles. For the CFC inner wall guard limiter two directions have been measured: one called CFC // and the other called CFC ⊥. No difference was found for the Inconel tile; therefore we will not refer to any direction for this tile.

Measurements of the angular distribution of the scattered light were therefore thought to be useful to determine the influence of the reflection on the signal seen by a spectrometer looking in the direction of the tile. The basic idea was to fix the incident angle of the light (10° here) and to move the detector. Modifications of our system were made following these requirements.

A schematic drawing of the measurement set-up is represented in figure 14. Two optical spectrometers are used (MCS 501 and 511 Zeiss) for a measurement range of 350 – 1700 nm. They are connected to the detector by means of optical fibres. The light source is a halogen photo optic lamp (Osram Xenophot) with the following characteristics 150 W / 15V and 10.1 A. The incident angle is fixed at 10°. The intensity of the reflected light is measured for different angles (α) on the whole wavelength range. Due to the experimental construction it is not possible to measure angles lower than 10°.

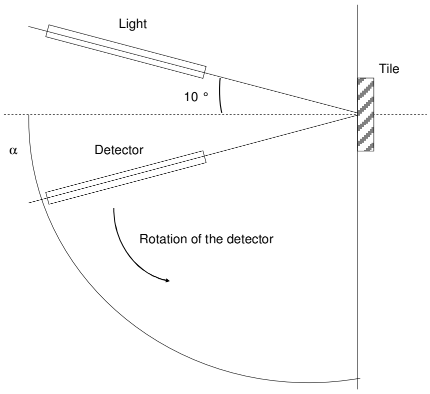


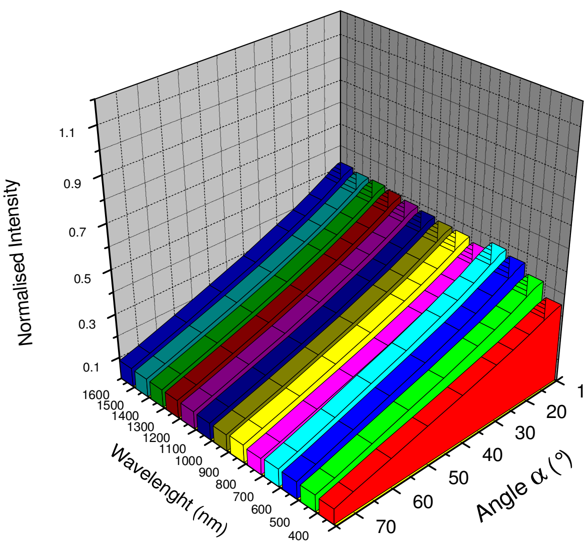
Figure 14: Scheme of the experimental set-up.

A reference plate is used to compare the measured values, it is made of Spectralon (PTFE: PolyTetra-Fluoro Ethylene, i.e. Teflon). This material has demonstrated the highest diffuse reflectance (UV-VIS-NIR) of any known material or coating. Its reflectance is generally >99% from 400 - 1500 nm, all the measured intensities have been corrected by the real reflectance for each wavelength. Moreover it shows a lambertian behaviour for the diffuse reflectivity i.e. the intensity I of the light reflected for an angle α is given by:

$$I(\alpha)=I(\alpha_0)\cos(\alpha)$$

with α_0 the incidence angle. In order to ease the comparison, the intensities measured when changing α are normalized to the intensity measured for the Spectralon at α=10°.

Figures 15 show a 3D representation of the measurements made for both tiles as a function of both the wavelength and the angle of measurement (α). In the right figure is represented the measured intensities for the CFC //, for the other direction the intensities are a slightly higher.



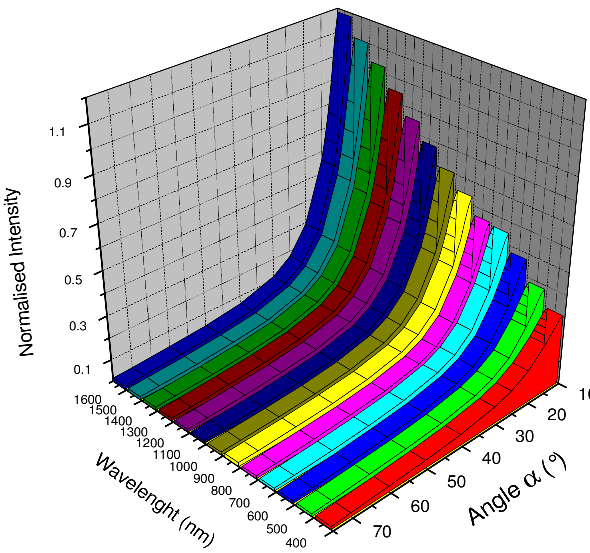


Figure 15: Intensity of the reflected light for the Inconel (left) and CFC // (right) tiles normalised by the Spectralon intensity at 10° for different wavelengths and measurement angles.

For easier reading, in figure 16, the normalized intensity is plotted as a function of the measurement angle for 1400 nm. The representation of the Lambert's law for the diffuse reflectivity is also given for comparison.

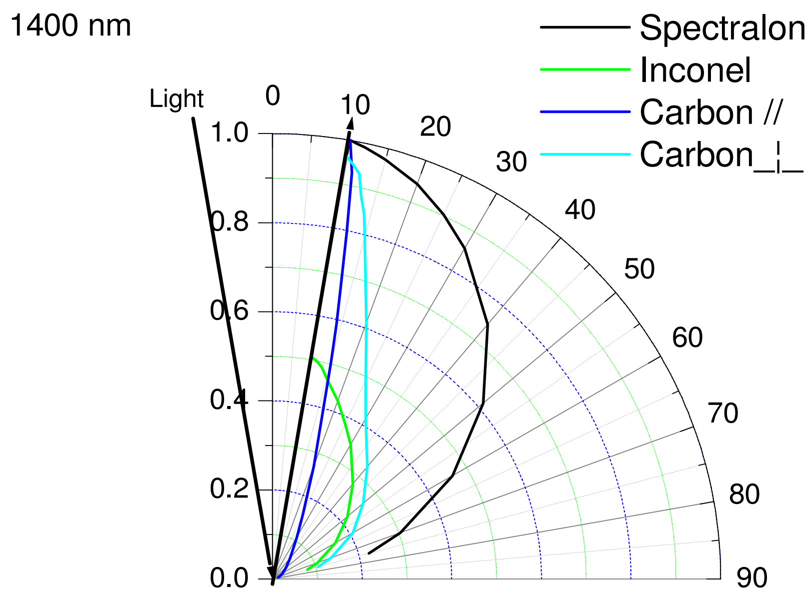


Figure 16: Intensity of the reflected light for the tiles normalised by the Spectralon intensity at 10° against measurement angle at 1400 nm.

4.3. Modelling

The most general method to characterize reflection is to measure the so-called bidirectional reflection distribution function, BRDF. Incident and reflected rays are parameterised in terms of polar coordinates θ and φ in a co-ordinate system defined by the reflective element. Using our data it is possible to simulate with different model the BRDF for the measured angles. A modelling code has been written at JET-EFDA Culham (UK) in the IDL language to simulate the effect of reflection on spectroscopic signals. The inside of the tokamak is represented by triangles, each associated with a reflectivity in the form of a BRDF. The first set of model results are for ITER bremsstrahlung at 500 nm, based on the density and temperature profiles of the high density 400 MW inductive scenario. In figure 17 simulated pictures are shown for a hypothetical wide angle camera equipped with a filter in the absence of reflection; including reflection; and of the reflected component only.

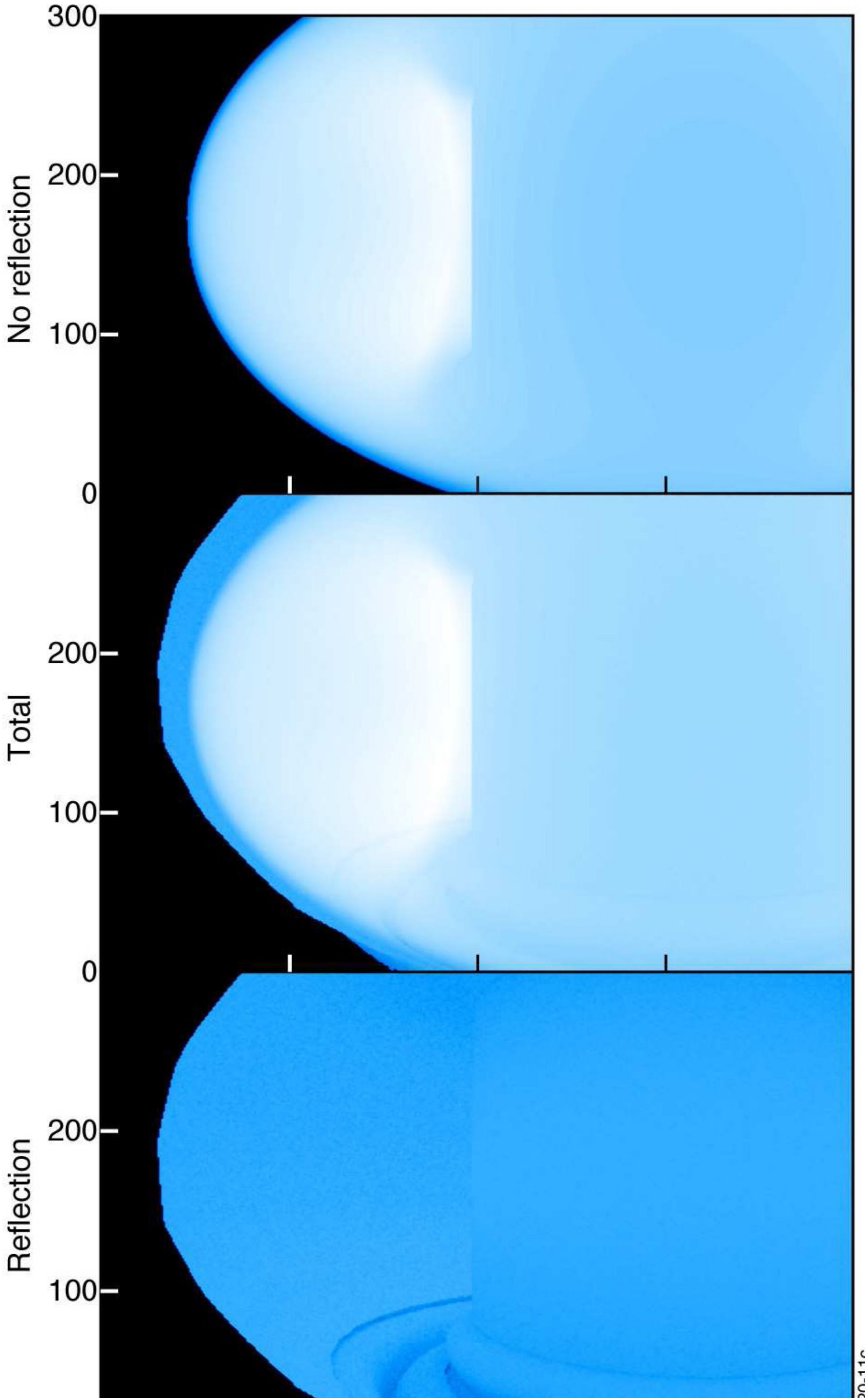


Figure 17: Simulated pictures of bremsstrahlung at 500 nm for based on the density and temperature profiles of the high density 400 MW inductive scenario in ITER-like geometry. Top: direct contribution. Middle: direct contribution plus reflected components. Bottom: Reflected component only. All wall elements have the reflectivity of the JET Inconel tiles. All three pictures are shown on the same normalized colour scale.

4.4. Improvement of the experimental measurements

The few number of measurements for the polar coordinates θ and only one φ lead to some difficulties for the fitting of the model. In order to improve this, new measurements on the same tiles as well as a tungsten coated tile were carried out at the Remote Sensing Laboratories, Department of Geography, University of Zurich. The tiles were measured in a darkroom for stray light minimization, with the addition of a 1000W brightness-stabilized (<0.05% rms) quartz tungsten halogen lamp (Oriel, type 6317), mounted on a separate adjustable stand. The wavelength range of the complete system is 400–2500nm. The setup is shown in figure 18. Due to the size of the sample, the motorised goniometer was not used and the detector was moved manually. Using this setup we measured only the principle plane i.e. 27 measurements per sample. The refinement of the model is now ongoing.

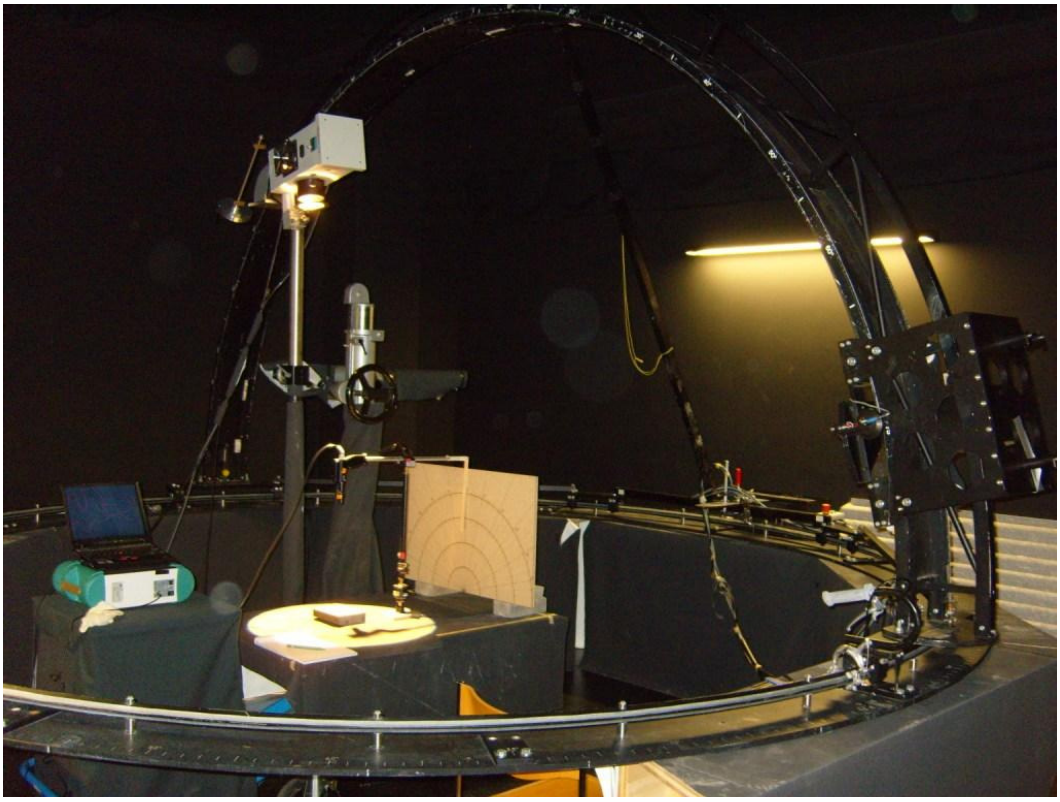


Figure 18: LAGOS, the laboratory goniometer system.

5. Publications

L. Marot, R. Steiner, G. De Temmerman, P. Oelhafen, **Reactivity of rhodium during co-deposition of rhodium and carbon**, J. Nucl. Mater. 390-391, (2009) 1135.

P. Sundelin, C. Schulz, V. Philipps, M. Rubel, G. Sergienko, L. Marot, **Nitrogen-assisted removal of deuterated carbon layers**, J. Nucl. Mater. 390-391, (2009) 647.

L. Marot, D. Mathys, G. De Temmerman and P. Oelhafen, **Characterization of sub-stoichiometric rhodium oxide deposited by magnetron sputtering**, Surf. Sci. 602 (2008) 3375.

K.-D. Zastrow, S. R. Keatings, L. Marot, M. G. O'Mullane, G. de Temmerman, and JET-EFDA Contributors, **Modeling the effect of reflection from metallic walls on spectroscopic measurements**, Rev. Sci. Instrum. 79 (2008) 10F527.

L. Marot, G. Covarel, M.-H. Tuilier, R. Steiner, and P. Oelhafen, **Adhesion of rhodium films on metallic substrates**, Thin Solids Films 516 (2008) 7604.

L. Marot, G. De Temmerman, V. Thommen, D. Mathys and P. Oelhafen, **Characterization of magnetron sputtered rhodium films for reflective coatings**, Surf. Coat. Tech. 202 (2008) 2837.

A. Litnovsky, D.L. Rudakov, G. De Temmerman, P. Wienhold, V. Philipps, U. Samm, A.G. McLean, W.P. West, C.P.C. Wong, N.H. Brooks, J.G. Watkins, W.R. Wampler, P.C. Stangeby, J.A. Boedo, R.A. Moyer, S.L. Allen, M.E. Fenstermacher, M. Groth, C.J. Lasnier, R.L. Boivin, A.W. Leonard, A. Romanyuk, T. Hirai, G. Pintsuk, U. Breuer, A. Scholl, **First tests of diagnostic mirrors in a tokamak divertor: An overview of experiments in DIII-D**, Fusion Eng Des 83 (2008) 79.

L. Marot, G. De Temmerman, G. Covarel, A. Litnovsky, P. Oelhafen, **Rhodium-coated mirrors deposited by magnetron sputtering for fusion applications**, Rev Sci Instrum. 78 (2007) 103507.

G. De Temmerman, M. J. Baldwin, R. P. Doerner, D. Nishijima, R. Seraydarian, K. Schmid, F. Kost, Ch. Linsmeier, and L. Marot, **Beryllium deposition on International Thermonuclear Experimental Reactor first mirrors: Layer morphology and influence on mirror reflectivity,** J. Appl. Phys. 102, 083302 (2007).

G. De Temmerman, R.A. Pitts, V.S. Voitsenya, L. Marot, G. Veres, M. Maurer, and P. Oelhafen, **First mirror tests for ITER: influence of material choice on the erosion/deposition mechanisms affecting optical reflectivity,** J. Nucl. Mater. 363-365, 259 (2007).

M.J. Rubel, G. De Temmerman, G. Sergienko, P. Sundelin, B. Emmoth and V. Philipps, **Fuel removal from plasma-facing components by oxidation assisted techniques: an overview of surface morphology after exposure,** J. Nucl. Mater., 363-365, 877 (2007).

A. Litnovsky, P. Wienhold, V. Philipps, G. Sergienko, O. Schmitz, A. Kirschner, A. Kreter, S. Droste, U. Samm, Ph. Mertens, A.H. Donne, D. Rudakov, S. Allen, R. Boivin, A. McLean, P. Stangeby, W. West, C. Wong, M. Lipa, B. Schunke, G. De Temmerman, R. Pitts, MJ. Rubel, A. Costley, V.S. Voitsenya, K. Vukolov, P. Oelhafen, A. Romanyuk, **Diagnostic mirrors for**

ITER: a material choice and an impact of erosion and deposition on their performance, J. Nucl. Mater. 363-365, 1395 (2007).

D.L. Rudakov, J.A. Boedo, R.A. Moyer, A. Litnovsky, P. Wienhol, V. Philipps, S.L. Allen, M.E. Fenstermacher, M. Groth, C.J. Lasnier, R.L. Boivin, N.H. Brooks, A.W. Leonard, W.P. West, C.P.C. Wong, A.G. Mc Lean, P.C. Stangeby, G. De Temmerman, W.R. Wampler, J.G. Watkins, **First tests of molybdenum mirrors for ITER diagnostics in DIII-D divertor**, Rev. Sci. Instrum., 77 (2006) 10F126.

V.S. Voitsenya, A. Sagara, M. Lipa, G. De Temmerman, H. Zushi, V.N. Bondarenko, A.I. Belayeva, K.A. Slatin, Ch. Gil, V.G. Konovalov, N.I. Naidenkova, R.A. Pitts, I.V. Ryzhkov, B. Schunke, A.N. Shapoval, A.F. Stan, **The properties of contaminated films deposited on in-vessel mirrors in LHD, Tore Supra, TCV and TRIAM-1M**, Proc. of the 33rd EPS conference on Plasma Physics, June 19-23, Roma, Italy, P5-134 (2006).

M.J. Rubel, G. De Temmerman, J.P. Coad, J. Vince, J.R. Drake, F. Le Guern, A. Murari, R.A. Pitts, C. Walker and JET-EFDA contributors, **Mirror test for ITER at the JET tokamak,** Rev. Sci. Instrum., 77(2006) 063501.

6. Presentations

Coated mirrors for ITER, Seminar at the CRPP, EPFL, Lausanne 15th December 2008.

Molybdenum and rhodium mirrors deposited by evaporation technique, Oral presentation at the 15th ITPA (International Tokamak Physics Activity) Topical Group on Diagnostics Gandhinagar, India 17 – 21 November 2008.

Reactivity of rhodium during deposition with carbon and in oxygen plasma, Poster presentation at 18th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Toledo, Spain, May 26-30, 2008.

Nitrogen - assisted removal of deuterated carbon layers, Poster presentation at 18th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Toledo, Spain, May 26-30, 2008.

Plasma exposure of rhodium mirrors, Oral presentation at the 14th ITPA (International Tokamak Physics Activity) Topical Group on Diagnostics Lausanne, 14 – 18 April 2008.

Coated mirrors for ITER, Oral presentation at the 13th ITPA (International Tokamak Physics Activity) Topical Group on Diagnostics Chengdu, China, 29 October – 2 November 2007.

Rhodium coated mirrors deposited by magnetron sputtering for fusion applications, Poster presentation at the 8th International Symposium on Fusion Nuclear technology, Heidelberg Germany, 30 September – 5 October 2007.

Rhodium deposition by magnetron sputtering: a possible technique for the first mirror, Oral presentation, LIDAR Cluster meeting, video conference, 30th May 2007.

Rhodium coated mirrors deposited by magnetron sputtering for ITER diagnostics, Colloquium, Forschungzentrum Jülich, Germany, 8th May 2007.

Rhodium coated mirrors deposited by magnetron sputtering for first mirror, Oral presentation at the 12th ITPA meeting on diagnostics, Princeton, United State, 28th March 2007.

Material choice for ITER first mirrors: a short overview of the present studies, Seminar, July 2006, University of California at San Diego (UCSD), San Diego, USA.

7. Scientific collaborations

National collaborations

- Centre de Recherche en Physique des Plasmas (CRPP), Ecole Polytechnique Fédérale de Lausanne
- Centre de Recherche en Physique des Plasmas, PSI, Villigen, Switzerland
- Remote Sensing Laboratories, Department of Geography, University of Zurich

International collaborations

- Institut für Plasmaphysik, Forschungszentrum Jülich, Germany,
- 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,
- Laboratoire Mécanique, Matériaux et Procédés de Fabrication, 61 rue Albert Camus, Université de Haute-Alsace, F-68093 – Mulhouse Cedex, France,
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- Euratom / CIEMAT Fusion Association 28040 Madrid Spain.
- Forschungszentrum Karlsruhe, Institut fuer Reaktorsicherheit, Karlsruhe, Germany

8. International activities in fusion research

• P. Oelhafen is guest member of the IEA TEXTOR executive committee.

• L. Marot is member of the First Mirror Specialist Working Group of the ITPA Topical Group on Diagnostics (https://tec.ipp.kfa-juelich.de/mirrorswg/).

• L. Marot is member of the LIDAR Consortium Agreement (Consortium for the provision of the Core-LIDAR Thomson scattering system for ITER).