EFFECT OF EXPOSURE INSIDE THE LHD VESSEL ON REFLECTANCE OF STAINLESS STEEL MIRRORS

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PACS: 52.55.Hc; 52.40.Hf

1. INTRODUCTION

The efficiency of in-vessel mirrors of diagnostic systems of a fusion reactor will depend both on the mirror material and on the mirror location inside the reactor vacuum vessel. Till recently the data necessary to predict the behavior under a fusion reactor environment of mirrors fabricated of different metals with different structure were obtained in simulation experiments only [1]. The first attempt to study the connection between the mirror location and modification of mirror optical properties was made two years ago for stainless steel mirror samples exposed inside the Large Helical Device (LHD) [2] during one experimental campaign. In this paper the main results obtained after investigation of samples taken out of LHD vessel are presented.

2. EXPERIMENTAL SETUP AND INITIAL DATA

Three mirrors of stainless steel type similar to 316 steel with size 20x10x1 mm were mechanically polished and cleansed in an ultrasound bath filled with acetone. The spectral reflectance at normal incidence of samples was measured in the wavelength range 200-700 nm, and afterward they were installed inside the LHD vacuum vessel as shown in Fig.1, where locations of these samples are indicated by numbers 1, 3, and 5. The samples were exposed during the whole 3rd campaign with main peculiarities of operating regimes described in [2]. It is seen that the samples were fixed at very different locations: #1 was positioned near the divertor region, #3 – close the plasma border, and #5 – quite deeply in the diagnostic port in the same poloidal cross section and in the same plane as #1 (central plane). After samples were removed from the vacuum vessel the reflectance was again measured in the same way, and the surface of samples were analyzed by several methods: Auger electron spectroscopy (AES), ion backscattering technique (RBS) using 1.5 MeV He^+ ion beam, scanning electron microscopy (SEM), profilometry, and ellipsometry at the wavelength 632.8 nm.

The 3rd LHD experimental campaign is characterized by the following peculiarities [2]: total number of main discharges 10^4, half with H_2 and half with He as working gas when plasma was heated by the ECH (~0.55 MW), ICRF (1.5 MW), and NBI (~4.5 MW) methods. Besides, glow discharge cleaning (two anodes) with total time ~2300 hrs was equally distributed between discharges with He and H_2 backgrounds. The maximal stored energy reached during the 3rd campaign was ~0.88 GW. In comparison to the 2nd LHD campaign the graphite tiles were installed in the divertor area in such a way that the plasma of divertor flows did interact with graphite targets only.

It was found that after exposure in LHD the reflectance of all samples has changed from the identical initial level. The change was not only in an absolute value but even in the opposite directions, as is seen from data in Fig.2. The reflectance of mirrors #1 and #5 dropped strongly as a result of appearance of the contaminating films, which could be easily seen in the white-dark photo of samples. From spectral dependence of reflectance (Fig.2) one can conclude that the film on the #5 sample is thicker than on the #1 sample. At the same time, the reflectance of sample #3 increased significantly (Fig.2). This latter fact we entail with not full cleaning of all three mirrors before they were installed inside the LHD vessel from contamination by some organic film appeared due to rinsing samples in an ultrasonic bath. The high level of reflectance for mirror sample #3 was supported by very high quality of surface as was supported by profilometry measurements and by analyzing the SEM photos.

The composition of the contaminating films that appeared on samples #1 and #5 was estimated using AES and RBS data. On the surface of #1 sample the deposited layer was found to consist mainly of C (~40 atomic %) and Fe (~40 atomic %) but on the #5 sample – the only contaminant registered was carbon (~90 atomic %) [2]. The surface of the sample #3 was free of carbon however a small trace of heavier metal, possibly, copper was registered by RBS.

The optical properties of film on sample #1 were measured by ellipsometry at the wavelength 632.8 nm within a simple approximation: a homogeneous film on the SS substrate. As the n and k values of the SS substrate the indices measured for the sample #3 were used. The refraction and extinction indices of the deposit found with such an approximation are n=2.5 and k=0.33, and the film thickness was estimated as ~26 nm. For sample #5 similar data could not be obtained because of very low reflectance at the wavelength of measurement (see Fig.2). To know more about properties of contaminating films on samples #1 and #5 and of the quality of mirror surface under the coatings, the cleaning of these films using the low temperature deuterium plasma was provided. The results of this experiment are presented in the next section.

3. CLEANING OF MIRRORS #1 AND #5

The plasma was produced by an electron cyclotron resonance (ECR) discharge in deuterium in a double-mirror magnetic configuration with maximal magnetic field strength near 2 kG in magnetic mirrors and magnetron frequency 2.375 GHz [3]. It was shown earlier [1] that such plasma is very effective in cleaning the carbon film deposited on metallic surface.

The samples were fixed at the water-cooled holder centered along the device axis and brought into the discharge chamber through a vacuum shutter. The magnetic field lines cross samples along the surface normal. The electron density and temperature of plasma in the region of the holder position was near $6 \cdot 10^9$ cm^{-3} and 3-5 eV, correspondingly, according to measurements by electrostatic probes. Before and after cleaning of the contaminating film both samples were weighed within accuracy 20 mg. The cleaning procedure was carried out step by step, with regular *ex situ* control of the spectral reflectance in the wavelength range 220-650 nm. For these particular samples two regimes of film cleaning were applied: (i) without biasing the holder (like in [1]), i.e., when during first 130 for sample #1 and 140 min for sample #3 the ion energy was defined by the sheath potential only, e.g., not exceeded ~15 eV and thus the chemical erosion was the main mechanism of removing the carbon-based film; (ii) with biasing holder to –300 V, e.g., when starting from 130 min for #1 sample and from 140 min for #5 sample the ion energy much exceeded the threshold of the physical sputtering of carbon and any other contaminant material.

After 10-minute exposure during the (i)-cleaning regime the mirror #5 became of a violet color instead of initial dark-brown one, but the initial color returned back when cleaning was continued. The color of the sample #1 did not change significantly during practically whole time of cleaning.

The time dependences of reflectance recovering at two wavelengths for both samples are shown in Fig.3. These data demonstrate that the characteristics of films that appeared on these samples are very different. Namely, the film on the #5 sample was thicker (because the interference effects are seen) but softer than the film on the #1 sample. The rate of reflectance recovering by the #5 sample during the cleaning regime (i) was much faster in comparison to the #1 sample, however for both samples the recovering was stopped after about one hour cleaning time. For the #5 sample this "saturation" of mirror recovering (in the time interval 60-140 min) is probably due to full disappearance of the carbon film deposited inside the LHD vessel, and the remained film was the one connected with washing the sample in an ultrasound bath after the finish of polishing. This lowest contaminating layer was gradually disappearing, starting from the time 140 min. For the #1 sample the intermediate saturation level behaved in the way like the rest film consisted of not one but two layers: the upper which disappeared by ion bombardment during 130-145 min was probably the rest of the layer deposited in LHD, and the lower one which had the thickness and composition similar to the layer that maintained on the #5 sample due to washing in an ultrasound bath. The full recovering of the spectral reflectance was achieved for both samples after about 60 min bombardment by 300 eV energy ions.

4. DISCUSSION AND CONCLUSION

The data obtained at this stage of experiment demonstrate that the location of the mirror samples inside the LHD vacuum chamber is very important factor determining the rate of mirror degradation. The mirror #3 located close to the plasma confinement volume and quite distant from the divertor regions was cleaned from the contaminating film that appeared as a result of rinsing samples in the ultrasound acetone bath and profilometry and SEM data show that it saved the very smooth surface. Mirror #1, fixed close to the divertor region with graphite tiles as the divertor plates, became coated by the film of complicated composition. The thickness of deposited films found by AES and ellipsometry are not in agreement each other. Namely, according to AES the thickness was estimated as ~70 nm for #1 and ~700 nm for #5 but only ~26 nm from ellipsometry data for #1 sample. The carbon film thickness on the mirror #5, fixed deeply in the port, was much thicker according to optical measurement (Fig.2) and results of cleaning (Fig.3) however it could not be measured by ellipsometry, as was mentioned above.

The values of n and k indices found for deposit on sample #1 within the framework of the simple model (i.e., n=2.5, k=0.33) are in a quite good correspondence with values characteristic for a carbon film that was evaporated by an arc discharge between two graphite electrodes (n=2.6, k=0.35 [1]) but very different from indices measured for the film grown on the window of the JT-60U tokamak (n=1.8-2.0, k=0.17-0.15 [4]).

The resistance of deposited films to impact of low energy D ions is quite different as data of Fig.3 show. The cleaning process demonstrates that the film on the #1 sample was significantly harder than that on the sample #5. This is probably the result of high percentage of iron in the composition of the deposit. The SEM photos demonstrated that the film on the #5 sample was strongly inhomogeneous compare to the quite homogeneous film surface on the #1 sample.

After finishing the cleaning procedure the reflectance spectral dependence of both mirrors became very close to what is shown in Fig.2 by squares as an example of typical SS mirror which was polished, rinsed in an ultrasound bath, and cleaned by low energy deuterium ions.

The mechanism which provided the cleaning of the sample #3 from the initial contaminating film and the maintenance of a high surface quality with corresponding high reflectance was not understood yet.

Basing on the above described results we can make the following conclusion:

The correct choice of mirror location inside the LHD vacuum chamber with graphite tiles protecting the vessel wall in the divertor area is a quite responsible problem. It is evident that the mirror fixed at the same position as the sample #3 will maintain its optical properties for a long period of LHD operation. Such mirrors can be used for observation of those parts of plasma or inner surfaces

(e.g., divertor plasma, divertor plates) that are not seen directly through the diagnostic ports.

In the case of inappropriate choice of the mirror position the cleaning of contaminating carbon-based deposit on the mirror surface can become a quite difficult problem because the biasing of the mirror holder to several hundred volts would be required.

The behavior of mirrors in conditions when the boronization procedure is planned to be used in future experiments would be very desirable.

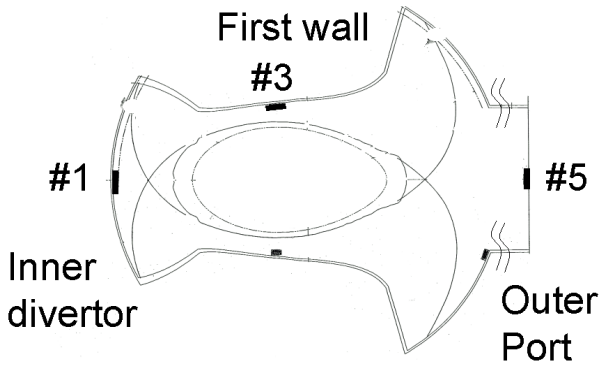

Fig.1. The scheme of locations of SS mirror samples inside the LHD vessel.

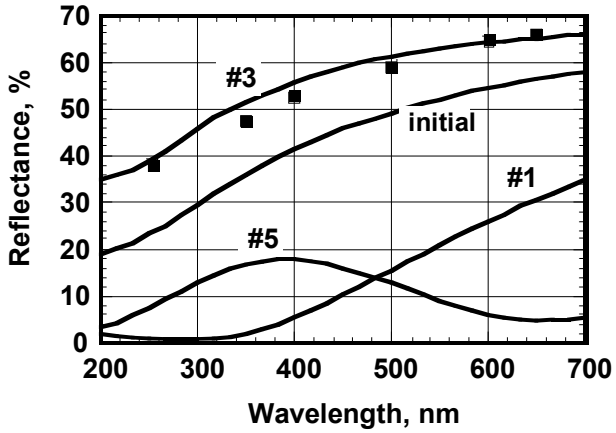

Fig. 2. Spectral reflectance of SS samples before (marked as "initial") and after exposure inside the LHD vessel (curves marked as #1, #3, and #5). Squares show the typical behavior of reflectance of a SS mirror subjected to cleaning by low temperature deuterium plasma after polishing and washing in an ultrasonic acetone bath.

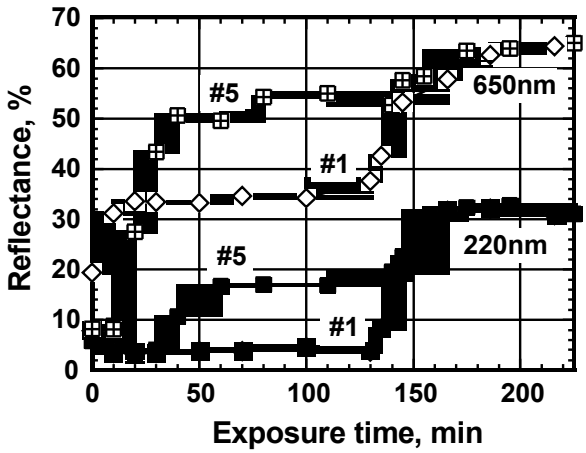

Fig.3. The recovery of reflectance (normal incidence, wavelengths 220 nm and 650 nm) of samples #1 and #5 due to deuterium ion bombardment. Up to t=130 min for sample #1 and up to t=140 min for sample #5 the sample holder was grounded, i.e., the energy of ions was <15eV. After that times the samples were exposed to ions accelerated to ~300 eV because of negatively biased holder.

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