First Optics in ITER:
Material Choice and Deposition Prevention/Cleaning Techniques

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Abstract. The problem of survival of front-end optical components in ITER has been discussed almost since the ITER project started. Nevertheless, up to now there is no solution guarantying operable state stability of all in-vessel optical components in ITER over a long period of time. This paper describes the state of affairs of the design of a first mirror unit supplied with a cleaning plasma discharge intended for operation within long and narrow diagnostic ducts where the main risk will be pollutions by CH deposits. Such conditions are expected in the vicinity of the first collecting mirror of the divertor Thomson Scattering system. We present here some recent results of the mirror material selection/ testing, matching plasma conditions appropriate for mirror treatment and results of the numerical simulation of plasma parameters of capacitively-coupled discharge constructed using a commercial CFD-ACE code.

1. Introduction

In recent years, the behavior of different mirrors has been studied in experiments modeling the behavior of diagnostic mirrors inside ITER. These mirrors have many requirements to meet. They should be resistant to sputtering by fast ions and neutrals, to temperature fluctuations, to neutron, gamma, X-ray and UV irradiation, robust against deposition of impurities and, finally, they should be manufactured from nonreactive materials. In fact, the mirrors in ITER can be divided into two types depending on whether they are expected to operate in erosion or deposition dominated conditions. Mirrors to be used under the deposition dominated conditions will undergo intensive contamination by products of the plasma-induced erosion of first-wall components and divertor tiles. The lifetime of mirrors in such an environment depends on the mirror design and mirror material. For instance, deposition-induced loss of reflectivity can be minimized by using high-reflectivity mirrors [1]. And while the deposits of contaminants are problematic for even this type of mirror, reducing their lifetime up to dozens of ITER working discharges, the survivability of mirrors with rather low reflectivity, such as W or Mo, is much worse when deposition dominates [1]. Since the replacement of first mirrors is expected to be a complex procedure, the development of optics-cleaning and deposition-mitigating techniques is a key factor in designing and operating of first mirrors used under the deposition-dominated conditions. The in-situ cleaning techniques considered are the chemical treatment/sputter of the mirror surface deposits in plasma cleaning discharges or in atomic/ion flows. For the use of such type of mirror surface treatment, the key factor in selecting the proper mirror materials, except high reflectivity, is their compatibility with cleaning techniques. Actually, the mirror should be resistant to plasma treatment in contrast to contaminant deposits. Therefore the paper is focused on:

{1} the design of mirrors which can withstand both severe environmental conditions in ITER and conditions of cleaning discharges,

{2} the development of prevention/cleaning techniques based on mirror treatment by plasma discharge or by atomic/ion flows.

2. High Reflective Mirrors Suited for Plasma Cleaning Treatment

We consider several possible designs of high reflective first mirror with Al or Ag reflective layer discriminated by transparent protection: 1) a thin transparent coating (for example Al_2O_3, ZrO_2); 2) a sapphire plate in front of mirror or sapphire plate with deposited reflective layer on the backside; 3) sapphire plate used like a window - physically separated from mirror. The key question for the use of sapphire is degradation of its transmission due to neutron, UV or gamma irradiation. The transmission degradation of thin (less than 1 μm) Al_2O_3 films can be ignored in contrast to the transmission of sapphire plate (of ~1 mm thick) that can be sensitive. Behavior varies for different wavelength ranges and should be considered for each case individually [2]. Design and manufacturability for the mirrors of type 1) looks much preferable although solutions 2) and 3) are valid solutions and also are planned to be investigated in the next step.

In the case of use of thin film mirror technology, a substrate choice becomes the major part of the mirror design. There are two main approaches to selecting material for the mirror substrate: metals (Mo, SS, Be) and nonmetals (Glass, Ceramic, Glassceramic, Si). For large scale mirrors, subjected to a sustained acceleration during disruptions or abnormal events the most important mechanical features are the minimized density ρ and maximized coefficient of elasticity E which minimize mirror weight and its deformation under gravity. The physical value characterizing that mirror property is the specific stiffness that is the ratio E/ρ. This parameter for Be and Si is 2-5 times larger than for all traditional mirror materials. The application of such mirror substrate can greatly facilitate the mirror design. The weight of mirrors with substrate from SS considered at the moment as a main applicant for ITER mirrors [3] has to be heavier 5-10 times than similar silicon mirrors. Silicon has also extremely high level of thermal stability determined as a relation of thermal expansion coefficient to thermal conductivity. In addition to a set of unique physical-chemical properties of silicon, the process of large scale silicon mirror manufacturing is well established. An additional very important feature of the first mirror material in ITER is stability of optical properties under neutron irradiation. The survivability of mirrors with Si substrate in ITER conditions was estimated for the conditions similar to that expected for the first mirror of TS in divertor *(photo of the the first mirror prototype see on FIG.1.).*

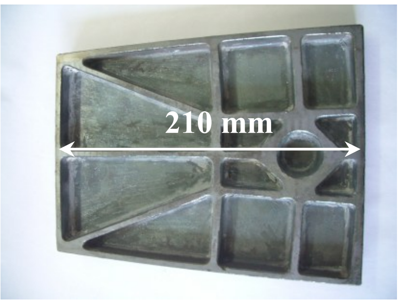

FIG.1 Backside of prototype of the first mirror silicon substrate.

Al and Ag mirrors on Si substrate, covered with Al_2O_3 or ZrO_2 film were subjected to neutron irradiation up to ~10^{23} n/m^2. 10^{23} n/m^2 is estimated to be total fluence for the entire period of ITER operation in the location of first mirror of TS in divertor. It was found that all types of mirror revealed no significant changes in reflectivity (see *FIG.2.*)

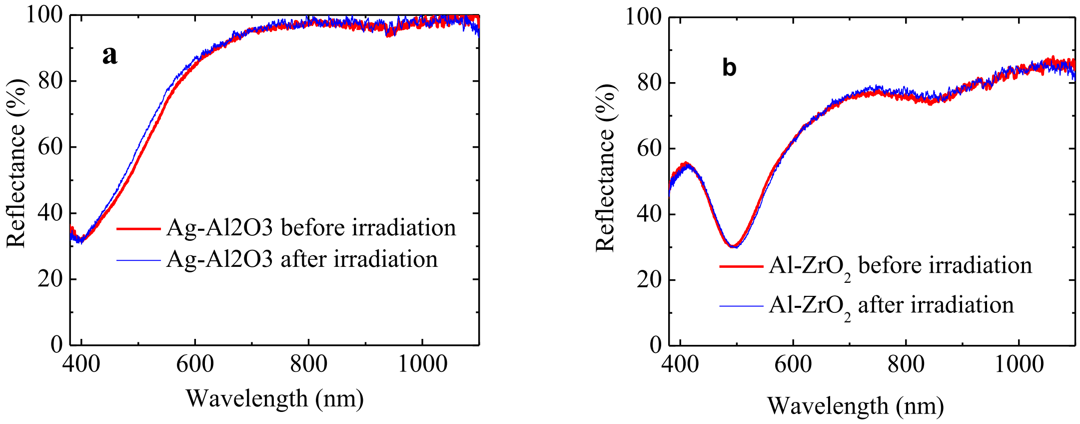

FIG.2. TS first mirror reflectivity before (thick line) and after (thin line) irradiation for silver reflection layer coated by Al_2O_3 (a) and for aluminum reflection layer coated by ZrO_2 (b).

Currently, we are testing Ag or Al mirrors protected with thin dielectric oxides Al_2O_3 or ZrO_2 from the point of their ability to work in both ITER-relevant and cleaning discharge conditions. To understand and predict the particular mechanisms of mirror surface degradation under plasma discharge and/or ion flow treatment and to define the criteria that can be used in the manufacturing process, we use the analyses of structure, morphology and chemical composition of all the layers of our mirror. Our testing experiments show that survivability of the mirrors coated with ZrO_2 film under deuterium ion bombardment with the impact energy of 50 eV strongly depends on technology of the mirror manufacturing. One of the patterns coated with ZrO_2 film *(see FIG.3.)* deposited on the Al substrate at room temperature, showed a lack of noticeable change in surface morphology after treatment of its surface by 50 eV D^+ ion flows regardless of which metallic sublayer, Al or Ag, was used [4], after exposure to fluence of $1 \cdot 10^{25}$ ions/m^2 or 10 hours of cleaning discharge. The observed absence of structural defects on the mirror surfaces coated with ZrO_2 films can probably be explained by the observed needle-like pores providing the molecular hydrogen transport outside and thus prevent hydrogen accumulation at the oxide-metal interfaces [5]. Similar films deposited in other conditions had marked degradation. The actual damage view of the defective mirror surface can be explained by structural irregularity caused by incipient crystallization. The mirrors coated with 200 nm Al_2O_3 film have undergone a rather fast degradation (200 nm thickness of the protective layer provides antireflection properties [1, 2] in the TS working range 1000–1064 nm). Nevertheless Al_2O_3 is one the main candidates for mirror protecting, but as a sapphire plate.

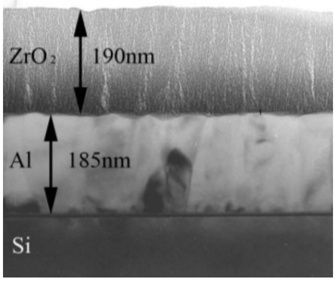

FIG.3. Cross section of the first mirror prototype with Al reflective layer protected by ZrO_2 film.

3. Deposition Prevention/Cleaning Techniques Based on Mirror Treatment by Plasma

Eligibility in ITER of all the known plasma-etching techniques, widely applied in the semiconductor and optical industry for thin film coating, is not as straightforward as it may seem [1]. Requirements for the plasma discharge for in-situ cleaning of in-vessel mirrors in ITER are rather demanding. The permanently existence of magnetic field of ITER superconducting coils and vacuum conditions determined by ITER vacuum impose restriction on the design of a plasma reactor for in-situ cleaning of optical components. The area of the mirror surface can reach thousands of square centimeters and along the mirror surface the cleaning conditions has to be uniform prevent mirror destruction. The concerned cleaning techniques are based on the chemical treatment/sputter of the optical surface deposits in cleaning discharges or in ion flows. The task of plasma cleaning technique preparation consists of two subtasks: plasma conditions appropriate for mirror cleaning from CH films and realization of cleaning plasma discharge in ITER conditions.

3.1. Plasma Conditions Adopted for Mirror Cleaning from CH Deposits

Reported earlier results of experiments [1] show that a-C:H film deposition is fully suppressed under the discharge in a CH_4/H_2 mixture with the addition of 10% N_2. Yet application of that very hopeful technique can be restricted, as any impurity additions in ITER can be opposed. Presently we are going to force the plasma treatment by combination with heating mirrors to temperature as high as 150-200ºC and a blow-off technique designed for reducing partial density of hydrocarbons or other pollutions inside diagnostic ducts in the vicinity of optical surfaces. The flow of deuterium directed along side of the protected mirror surface provides reduction of hydrocarbon concentration and can help to shift balance in chemical reactions to the transformation of hydrocarbon radicals to volatile species *(see FIG.4.).*

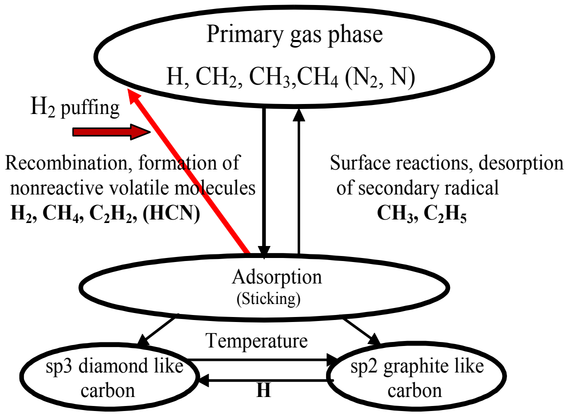

FIG.4. Diagram of the main chemical reactions processed in cleaning discharge and treated surface.

The main task is to prevent CH deposit formation on optical surfaces. For that the C_xH_y radicals adsorbed on the surfaces have to be transformed to volatile non-reactive species. It is suggested, that the concentration of hydrocarbons and dust in the vicinity of mirror will be reduced by specially organized puffing of deuterium. That puffing will assist hydrocarbons and dust removing from the bulk of the diagnostic duct. The discharge conditions determining relative intensity of deposition and erosion of a-C:H films are a key subject of the current research. Our recent experiments with mirrors exposed to CH_4/H_2 flowing discharge show that without any additional inhibitors the a-C:H film deposition is fully suppressed if hydrocarbon fraction in gas mixture is relatively small. The critical concentrations of CH_4 (at 20% of CH_4 conversion) corresponded to equal deposition and erosion rates of a-C:H film were thoroughly investigated in a hollow-cathode discharge with plasma parameters typical for such type a discharge [6]. The discharge had two separated areas strongly distinguished by plasma parameters, i.e., plasma of the hollow cathode with mean ion energy of 30-50 eV and the plasma of a positive column with ion energy of 1-5 eV. The main parameters of the discharge were: pressure of 18 Pa, gas flow rate of 7 m/s, mean dissipated energy per source gas molecule of about 15 eV. The main conclusions of the experiments are illustrated in *FIG.5* and *FIG.6* as measured rates of increasing/decreasing thickness of deposited films depending on the molar relation of CH_4 and H_2 in the hydrogen/methane flowing plasma. As seen from *FIGS. 5* and *6,* the deposition of a-C:H film on the mirror surface can be suppressed in the case the ratio of hydrocarbons flow to hydrogen flow is relatively small ($\leq$ 1% for the surfaces of the gas-flow glow discharge reactor plasma including both hollow cathode and positive column, and less than 5% for Si or Mo samples in the middle of positive column). Mass-spectrometer measurements of gas components in the plasma reactor output (see *FIG.5*) and simultaneous weighing of deposits on Si or Mo targets (see *FIG.6*) in the middle of positive column of the gas-flow glow discharge show that at the room temperature of target surface the erosion/deposition rate of a-CH film independent from the target materials [6]. At the first “carbon” stage of ITER operation [7, 8] the mixture of D/T/He neutrals cooled on the graphite targets can have from 3 to 10% [9] of hydrocarbons C_xH_y. Most of them will be deposited on the surfaces of divertor and particularly on the inner surfaces of diagnostic ducts. One way for hydrocarbon flow formation described in [1] supposes that up to 30% of hydrocarbons penetrating diagnostic duct is CH_3 with very low sticking ability. Just that impurity is the main component of deposited a-C:H films inside narrow and long diagnostic ducts. To decrease the diffusion flow of C_xH_y radicals (mainly CH_3) we suggested [1] to use the combination of a gas counter-flow and maximal extension of the duct wall surface. This applied technique can reduce the level of hydrocarbon content down to 1% or even much less, and consequently meets a requirement of the deposited film erosion in plasma cleaning discharges (see *FIG.5 and FIG.6*).

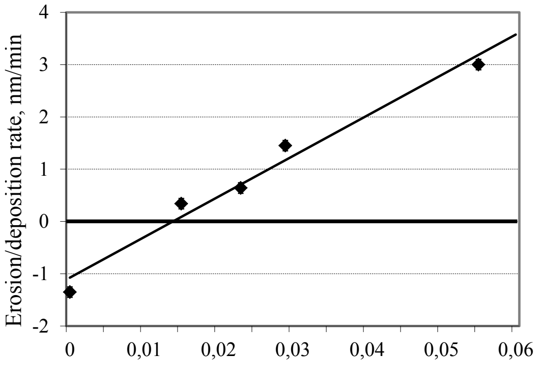

FIG.5. Plot of the erosion/deposition rate of a-C:H films on the surfaces (mainly quartz) of the gas-flow glow discharge reactor depending on the fraction of CH_4 in H_2/CH_4 gas mixture. The deposition rate was recalculated from CH_4 flow consumed on a-C:H deposit formation (assuming soft film formation with density of 1 g/cm^3) in the total discharge volume with surface area of ~300 cm^2.

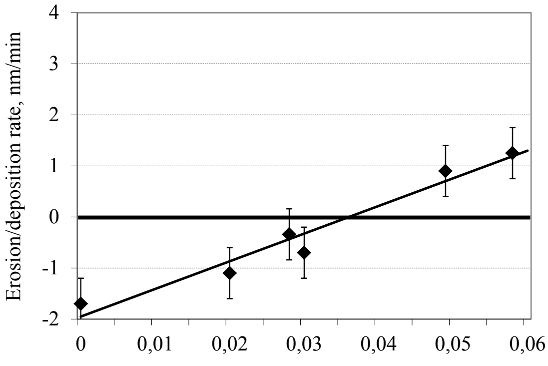

FIG.6. Plot of the erosion/deposition rate of α-CH films deposited on Si and Mo targets (irrespective of the target material) in the middle of positive column of gas-flow glow discharge depending on the fraction of CH_4 in H_2/CH_4 gas mixture. The erosion rate was recalculated from weighted hard a-C:H deposits with density of 1.8 g/cm^3.

3.2. Implementation of Cleaning Plasma Discharge in ITER Conditions

As an example of the first diagnostic mirror cleaning discharge we outline briefly a possible implementation of a cleaning discharge for the first mirror of the ITER divertor Thomson Scattering system. Currently, we consider a capacitively-coupled RF discharge as the main candidate for this purpose. The first collecting mirror has the role of one of the electrodes (the grounded one). The position of the first mirror with cleaning facilities is represented in *FIG.7.*

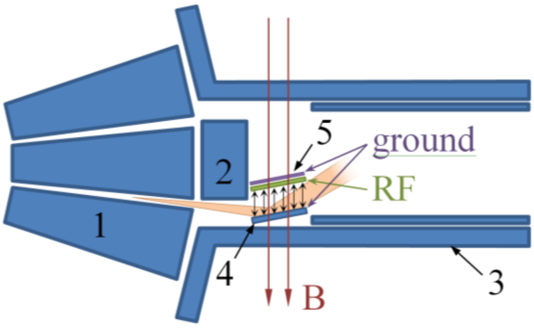

FIG.7. Layout of the first collecting mirror with cleaning discharge electrodes. 1) divertor cassettes, 2) neutron shield, 3) divertor port, 4) first collecting mirror, 5) second electrode of capacitively-coupled discharge

The main requirements of the cleaning discharge are as follows: all parameters should be uniform along all the treated surface, energy of major ions (like D^+, D_2^+, D_3^+) striking the mirror surface has to be less than 50-60 eV (see section 3.1); the current density on the mirror surface to the cleaned, in our experience, should be of 0.1 mA/cm^2; current density and ion energy impinging surface of second electrode of the capacitance discharge should be minimized. A numerical process to simulate plasma parameters of capacity-coupled plasma (CCP) has been constructed using a commercial CFD-ACE code [10] as the first step to designing a deposition prevention system in the vicinity of the first mirror of divertor TS. The simulator was tuned to reasonably predict the reactive ion etching rate behavior and used to investigate the effects of gas puffing rate and geometry of electrodes on the plasma operating variables and uniformity. The known disadvantage of CCP in oppose to ICP (inductively-coupled plasma) etcher is that RF power applied to the discharge determines both ionization processes in the plasma and bias potential over the sheath through which ions are accelerated and bombard the electrode surface. To separate these two processes the use of a two-frequency discharge is suggested [11]. In this way, the ion bombardment energy can be independently controlled by the RF power with the lower frequency while the plasma density can be adjusted by the RF power with the high frequency. The first results of the numerical experiments are presented in *FIG.8 and FIG.9*. The simulation was made for the following conditions: gas pressure was 10 Pa, electrodes were disks 100 mm in diameter, material of the mirror surface - sapphire (with known properties of the bulk material), discharge gap - 100 mm, RF power - 20-50 W. Variable parameter was RF frequency. In *FIG.8* frequency dependence of ion flux, applied voltage, and plasma potential, which determine the energy of ions impinging on the grounded electrode (mirror), are presented for 20 and 50 W RF power absorbed in the discharge. One can see that applied voltage decrease with frequency, while ion flux increases. These dependences give us ability to choose the optimal frequency 81.26 MHz. However, the plasma potential, which accelerates ions to the grounded electrode (mirror), is practically independent of power and frequency. It is a result of big difference of effective electrodes areas. To increase the energy of ions bombarded the mirror, its effective area should be decreased compared the power electrode. The ion flux distribution over the mirror is presented in *FIG.9.* The calculated flux inhomogeneity is less than 30 %. It is suggested that applying magnetic field can improve the homogeneity.

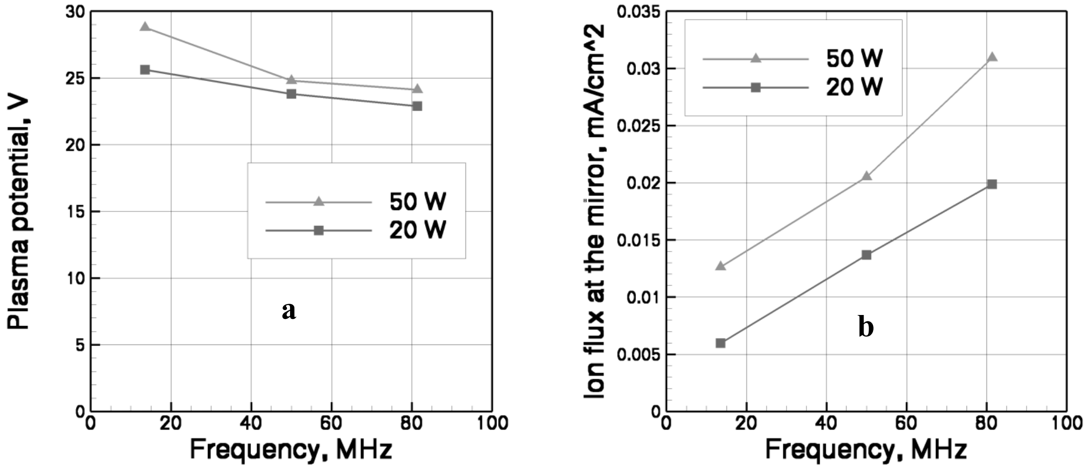

FIG.8. Frequency dependence of the plasma potential (a), and summary ion flux on the center of the grounded electrode (b) for different values of RF power absorbed in the discharge.

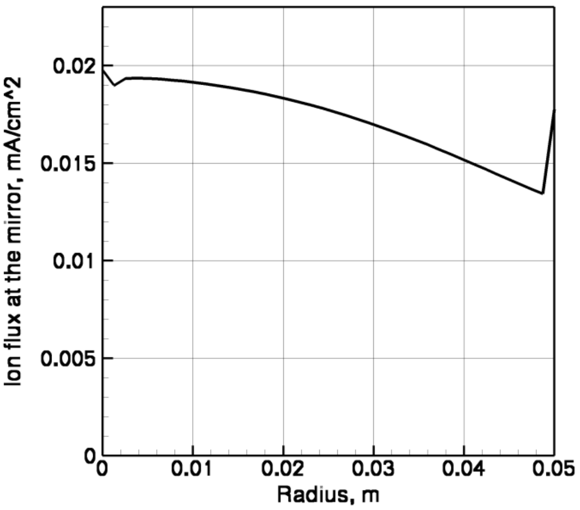

FIG.9. Distribution of H_2^+ *ion flux on surface of the grounded electrode. RF power absorbed in the discharge P=20W and frequency 81.26 MHz.*

4. Conclusion

The design of a first mirror unit supplied with a cleaning plasma discharge for ITER diagnostics has been developed. It is an extremely multi-aspect task and we try to consider all the key questions as well as to demonstrate the feasibility of their solutions. In the context of the design we select the mirror of light design with Si substrate, Al or Ag reflective layer protected by a thin ZrO_2 transparent film. The development of the mirror manufacturing process is going on and the first hopeful results are gained. It does not appear a final choice but currently it is adopted as a basis for the first mirror design of TS in divertor. A cleaning discharge is suggested to be used during working discharges of ITER. The rationale for such an approach is that it can prevent formation of CH films, which can be much more resistant to any treatment. As was shown in our experiments, the pressure condition in divertor port and expected concentration of CH radicals to be appropriate for such an approach. Implementation of a cleaning plasma discharge in ITER conditions is also a non-trivial task due to strong magnetic field and vacuum conditions determined by ITER operation. The commercial CFD code has been used for numerical simulation of plasma parameters of a capacitively-coupled discharge as a first step to designing a deposition prevention system in the vicinity of the first mirror of the divertor TS diagnostic. The simulator was tuned to predict the reactive ion etching behavior and has been used to investigate the effects of gas puffing rate and geometry of electrodes on the plasma operating variables and uniformity.

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