Deposition mitigation and in-vessel optics recovery in ITER

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Abstract. According to recent experiments in plasma fusion machines, the contamination of optical elements under deposition-dominated conditions in ITER will result in fast degradation of their optical characteristics. The development of deposition-mitigation techniques is an important part of R&D program of ITER optical diagnostics. The paper describes the approaches to be used for the recovery of first optical elements of the Divertor Thomson scattering (DTS) diagnostics involving plasma cleaning and laser ablation. The long-term laser cleaning efficiency under continuous deposition of Al and W was studied for fused silica and alumina windows. The laser-induced damage threshold was expected to decrease by about the factor of three in highly contaminated areas and up to six times in the case of contamination with dust particles as compared to clean windows. The implementation of the laser cleaning technique for DTS diagnostics in ITER is discussed. Another technique, shown to be efficient for removal of metal and metal oxide deposits, is plasma treatment. The physical aspects of plasma cleaning based on capacitively coupled (CC) RF discharge are considered with the focus on the ITER-specific requirements to the system. Ion energy distribution and flux density in capacitively coupled RF discharge were measured as function of RF frequency and power. The grounded sheath voltage was found to be nearly constant at different discharge frequencies and absorbed power. The frequency dependence of effective sputtering yield of Be and Mo is presented for Ne and He plasma discharges.

1. Introduction

The laser ablation is considered to be the one of the promising techniques for remote recovery of diagnostic mirrors [1] and windows [2]. The laser pulse parameters used in the technique are chosen to be efficient for deposits removal remaining safe for the optical surface. For laser diagnostics, using high power laser irradiation, however, the laser-induced damage threshold (LIDT) becomes the crucial characteristics of optical elements and must be studied under the conditions simulating those in fusion machines. Among factors affecting LIDT, neutron, ionizing radiation and surface contamination have been previously reported for quartz glass and Al₂O₃ diagnostic windows. Neutron irradiation up to a fluence of 10¹⁹ neutrons/cm² was shown in [3] to have a minor effect on the sapphire laser resistance. The ionizing radiation in-beam and accumulated dose effects were found to be also negligible for sapphire windows, while KU1 quartz glass becomes less vulnerable to laser-induced damage with dose increasing [4]. The deposition of metal film, in contrast, was shown to result in dramatic decrease of LIDT of KU1 quartz glass material [5]. For the gold layer of 5 nm a
decrease in threshold by orders of magnitude was observed. For thicker deposits LIDT was found to be higher, which was connected with limited capability of the thin gold layer to remove the heat generated during the laser pulse.

The results from [5] evidence for the risk of breakdown of the laser windows if solid metal film was previously formed on the surface. These conditions, however, are irrelevant for plasma diagnostics working continuously in the course of tokamak operation providing the nonstop cleaning of laser window by the diagnostic laser beam. In this case the film grows until the balance is reached between deposition rate and laser-induced ablation rate. The sensitivity of the optical element to laser damage, depending on steady-state deposition thickness, can be characterized by the probability of damage as a function of laser beam intensity, similarly to that of pure material [6]. Therefore, LIDT of transparent optical elements in ITER should be checked with the account taken not only of laser parameters, such as spot size and pulse length [7], but also of the expected contamination making the elements vulnerable to reduced damage threshold. In the paper, the laser resistance of the potential materials for diagnostic windows under the simultaneous deposition and removal of aluminum and tungsten is considered along with experimental simulation of window performance located in deposition-dominated area.

Another technique to be used in ITER for remote mirror recovery is plasma cleaning. It was shown to be efficient for protection against hydrocarbon, metal [8, 9] and metal oxide deposits [10]. The capacitively coupled (CC) RF discharge generated between two planar electrodes, one of which is the diagnostic mirror, is considered as the most robust plasma source under severe ITER conditions with the limited maintenance access. The implementation of CC RF discharge for in-situ recovery of the in-vessel mirrors is widely discussed at the moment. Different working gases (Ar, Ne, D₂, He), mirror materials (Mo, Rh, ZrO₂/Ag etc.) and geometries are considered to meet ITER-specific requirements to the system. Cleaning of Mo and Rh mirrors in Ar plasma of 13.6 MHz CC discharge is reported in [8, 12], the recovery of Mo mirrors in Ne and D₂ plasmas generated at a frequency of 81.3 MHz is presented in [13]. The feasibility of CC RF discharge application under ITER magnetic field is also the matter of study over the last years [13].

The discharge frequency is known to affect ion energy distribution (IED) function. The dependence was studied theoretically and numerically [14]. Within simple collisionless model, in low-frequency discharge the ions pass the sheath during the small part of RF cycle and therefore their energy is determined by instantaneous voltage at RF phase in which they enter the sheath [14] resulting in wide and bimodal IED. In high-frequency discharge the ions are accelerated in sheath during many RF cycles and their energy responds only to average sheath voltage. IED in this case tends to be monoenergetic. The collisions in near-electrode sheaths lead to broadening of IED. The effective sputtering yield with account taken of IED function may be quite different from that for mean ion energy. The selectivity of sputtering for a pair molybdenum-beryllium is considered in the paper for different frequencies of CC RF discharge.

2. Recovery of Diagnostic Windows by Laser Ablation

The ITER divertor Thomson scattering (DTS) diagnostics is one of those using high-power probing laser and the protective laser window. The window is to be located beneath the divertor cassettes at the distance ~ 500 mm from the plasma looking on the plasma through cassette gap. As a front-end element it will be subjected to deposition of metal (primarily Be and W) films as well as metal particles in solid and, possibly, liquid phases and simultaneous recovery by irradiation of Nd:YAG 1064 nm laser. The main issues to be addressed to ensure long-term window safety are:
i) The choice of window material
ii) Cleaning efficiency by the diagnostic laser irradiation
iii) Laser damage threshold of windows under continuous metal deposition

2.1. Experimental

The laser-induced breakdown was studied for KU-1 quartz glass 20X40X2 mm³ and Al₂O₃ 20X40X1 mm³ optically polished plates. The samples were mounted in the vacuum vessel at the angle of 60° to p-polarized laser beam to minimize in-vessel reflections (see Figure 1). The 50 cm focal lens was used for light focusing and the samples can be moved along the converging beam to vary the energy density of laser irradiation on the window surface. After each exposition of 10⁵ laser pulses the samples were shifted towards the focus until breakdown occurs. Laser damage was manually registered by monitoring the visible light emission. The energy of laser pulses was measured with laser power meter (see Figure 1).

Figure 1. Experimental scheme.

Q-switched Nd:YAG 1064 nm laser used for LIDT measurement operating at a pulse repetition rate 1-100 Hz with the parameters of a pulse: duration - 2 ns, energy - up to 2 J, has been developed for ITER DTS diagnostics. The laser is intrinsically multimode with a complex pattern of beam profile and hot spots in the pattern. To form the smooth, close-to Gaussian profile of the beam all measurements were performed in far field of laser irradiation. The inevitable drawback of this scheme is some instability of pulse energy in the far field. The energy fluctuations, however, were found to be no more than 10% with mean energy ~ 1 J at the samples location. The laser beam profile measured at various distances from the focus point in the absence of the sample windows showed insignificant deviation from Gaussian shape. The energy density in the maximum at the sample point normalized to the total pulse energy was taken for calculation of damage probability of the window.

To simulate surface contamination in the tokamak reactor the laser beam passing through the sample was focused on the metal – Al or W target (see Figure 1). Metal ablated or splashed by laser pulse from the target and re-deposited on the back surface of the sample was removed from the window by following pulses. Deposition rate was controlled by shifting the metal target 0.1-1 cm around the focus point. Depending on the target material two types of deposition were obtained – solid films of tungsten and aluminum droplets. Thickness of tungsten films was measured with spectroscopic ellipsometry by the side of the laser beam spot. The optical constants of dielectric substrate and the film had been determined separately and were fixed in the course of film thickness fitting at the following steps.

2.2. Damage thresholds and cleaning efficiency

In the case of nanosecond or longer-pulse laser irradiation, the damage behavior is primarily determined by surface or sub-surface defects – damage precursors. It does not exhibit a sharp threshold, but is rather characterized with the probability of damage increasing with irradiation intensity. The probability distribution depends on defects concentration and distribution of damage initiation fluences for the precursors and, at the same time, on the
experimental factors, such as beam profile pattern and laser intensity fluctuations. If the latter is the dominant one then probability distribution function must be identical for different sample types.

Figure 2 shows damage probability data for clean quartz glass KU-1 and Al₂O₃ windows. The experimental points in the figure are fitted with cumulative normal distribution function given by expression:

\[
\frac{1}{2} \left(1 + \text{erf}\left(\frac{E - \langle E \rangle}{\sigma \sqrt{2}}\right)\right)
\]

Where $\langle E \rangle$ is a mean damage fluence and $\sigma$ is a standard deviation of normal distribution.

The parameters values fitted for the best convergence are: $\langle E \rangle$ - 14.2 and 10.4 J/cm², $\sigma$ - 0.57 and 0.37 J/cm² for KU-1 and Al₂O₃ accordingly. One can notice that the ratio $\langle E \rangle / \sigma$ is close for two materials ~ 25 and 28. This might evidence that the probability distribution originates from the fluctuations of a maximal fluence in the laser beam and not from the surface defects distribution. In this case, however, the damage threshold should be attributed not to the lowest observed damage fluence but to $\langle E \rangle$ value.

![Figure 2. Damage probability of quartz glass and sapphire window. Left – pure windows, experimental points are fitted with cumulative normal distribution function. Right - windows under continuous tungsten deposition.](image)

Damage probability for KU-1 quartz glass and sapphire windows under continuous tungsten deposition is shown in Figure 2. The average deposition rate with the pulse repetition rate – 20 Hz was measured to be ~ 10 nm/min. The probability curves, in contrast to clear material, cannot be fitted with normal distribution function due to additional factors affecting the probability distribution. These may be variations in deposition rate or creation of damage precursors in the re-deposited material. As follows from Figure 2, the contamination of the surface with tungsten results in decrease of LIDT by about a factor of 3 – much less than can be expected from [5].

The metal eroded from the target per one pulse formed the deposit with a thickness of 0.1 Å - less than a monolayer of tungsten. Film growth in the course of continuous exposition results in gradual increase of its optical density and energy absorption until the evaporation rate becomes equal to deposition rate. Evolution of W layer on the surface of KU-1 window under the simultaneous deposition and removal of tungsten using laser irradiation 2 J/cm² can be seen in left part of Figure 3. This simulates the performance of DTS laser window to be located in deposition-dominated area in ITER. As follows from the figure, the film was growing over first hundreds of pulses but further exposition has no effect on a film thickness. The steady-state layer in the beam spot was found to be ~ 5 nm in thick forming almost transparent coating whereas material accumulated by the side of laser spot formed smooth well-reflective film. It should be noted that deposition rate of 10 nm/min exceeds that
expected even in highly contaminated areas of ITER including location of front-end laser window of DTS. Lower rates result in thinner film formation with roughly the linear dependence. For Be deposits one can also expect higher evaporation rate and therefore thinner films due to larger specific thermal capacity and saturated-vapor pressure of beryllium as compared to tungsten.

**Figure 3.** Left – Cleaning efficiency of quartz glass window under continuous W deposition. Right – damage probability of quartz glass windows under continuous sprinkle with aluminium droplets.

Among other factors affecting the laser resistance of diagnostic windows in ITER, one should foresee also the risk of contamination with macroscopic particles in either solid or liquid phases. This is of particular concern for the divertor diagnostics, which are expected to suffer from the dust, flaking off from the tiles due to plasma-surface interaction. The analysis of impurities transport in the diagnostic duct exposed in plasma gun facility QSPA-T reveal the presence of droplets, sprayed from aluminum target, at the far end of long and narrow duct. It was found that large droplets can undergo multiple reflections from the duct walls splashing into smaller fractions thus penetrating deep inside.

To simulate performance of a window subjected to the contamination with metal dust the tungsten target behind the window holder was replaced with aluminum one. Aluminum splashed from the target by focused laser beam re-deposited on the window surface primarily in liquid phase. The droplet size on the surface varied from several to hundreds of micrometers. As seen from right part of Figure 3, LIDT of KU-1 under these conditions is about 6 times as low as that of pure window. In the case when laser induced damage is driven by the absorbing defects on the surface the damage threshold depends on absorbing particle size [15]. Because of a large variation of aluminum droplet size, the experiment performed can be considered as a relevant simulation of possible dust deposition scenarios in ITER.

### 3. RF Discharge for In-situ Mirror Recovery

Following sections present the results of CC RF discharge characterization and discuss its implementation for cleaning the most common Mo mirrors from Be deposits. In symmetric discharge the effective areas of grounded and RF-biased electrodes are equal to each other resulting in equal near-electrode average sheath thicknesses and voltages. In case of RF powered mirror, however, grounded electrode surface expands by vacuum chamber walls area. Thus, the smaller (powered) electrode becomes biased negatively with respect to the larger (grounded) electrode, to keep zero DC current in the discharge. Ion flux, energy distribution and DC-bias were measured as a function of RF power and frequency. To measure IED, the grounded electrode was replaced with retarding field energy analyzer (RFEA). The IED on powered electrode was calculated as sum of IED measured by RFEA and DC bias measured by voltmeter. To measure ion current density, powered electrode was replaced with ion flux analyzer (IFA). The calibration of IFA was performed in Ne glow.
discharge. The discharge was driven through the DC-blocking capacitor by RF generator with variable frequency (10 kHz - 400 MHz) and maximum output power of 100 Watts. The distance between electrodes was 5 cm. The RF electrode 80 mm in diameter was shielded to prevent breakdown from backside and edges. The experiment was carried in Ne and He at pressure of 2 Pa, controlled with combined Pirani/ionization vacuum gauge. The RF power, applied to powered electrode, was measured by directional coupler and ADC.

3.1. Ion flux parameters as a function of RF frequency and power

Ion energy and flux at the powered electrode as a function of discharge frequency in Ne and He discharges are shown in Figure 4.

![Figure 4 Ion energy and flux as a function of frequency in Ne(left) and He (right) discharges for RF power of 15 W, P=2 Pa.](image)

As seen from figure, flux density on powered electrode reveal different tendencies in Ne and He discharges while DC bias decreases for both gases as frequency increases, in accordance with [16]. At the same time, the grounded sheath voltage remains almost constant at approximately 27-30 eV (see Figure 5). The ratio $U_{RF}/U_{Grounded} \approx (S_G/S_{RF})^{1/2}$ [14] (where $S$ is the electrode effective area) is not expected to depend on frequency or power. The reduction of DC bias means that higher frequency results in smaller effective area of grounded electrode, i.e. symmetrization of the discharge. The power, absorbed in the discharge, is sum of power, absorbed in both sheaths, and power, which is required for ionization/recombination balance: $P=I(2E_{gnd}+U_{bias}+W)$, where $I$ is total ion flux, $E_{gnd}$ is the voltage drop at the grounded sheath, $U_{bias}$ is DC bias and $W$ is the ionization energy of working gas atoms. Since $E_{gnd}$ and $W$ are constant and DC bias decreases at higher frequencies, the total ion flux should increase to keep the discharge power balance.

![Figure 5. Evolution of IED at the grounded electrode with a frequency. RF power - 15 W, pressure - 2 Pa. Left – neon, right – helium.](image)
The frequency and power dependence of the IED at the grounded electrode is shown in Figure 5 and Figure 6. In accordance with [14, 16], higher frequency corresponds to narrower main peak of IED with the reduction of low energy wing. The bimodal shape of IED is limited RFEA energy resolution of 2 eV and is not resolved.

For cleaning efficiency of CC RF discharge the effective sputtering yield is given by:

\[ \gamma_{\text{eff}} = \frac{\int_{E_{\text{min}}}^{E_{\text{max}}} \gamma(E) \, dE}{\int_{E_{\text{min}}}^{E_{\text{max}}} \text{IED}(E) \, dE}, \]

where \( \gamma(E) \) is the sputtering yield of contamination material taken from [17]. Figure 7 shows the effective sputtering yields of Be and a most common mirror material – Mo - along with their ratio, which characterize sputtering selectivity in the “mirror-contamination” system. The latter is an important characteristic of a cleaning process indicating the capability to remove deposits without affecting the mirror surface. As follows from Figure 7, higher sputtering rate of Be can be achieved in Ne gas at low frequencies. If the cleaning procedure is not supposed to be time limited, high-frequency discharge in He atmosphere appears to be preferable from the point of view of mirror surface safety.

4. Conclusions

The performance of laser windows as front-end elements of laser diagnostics was studied under the conditions simulating the deposition-dominated environment inside vacuum vessel of fusion reactors. LIDT of KU-1 quartz glass as a potential material for laser windows is shown to be \( \sim \) 1.5 times as high as that of Al2O3 for clean windows and under the continuous deposition of tungsten. This makes fused silica glass KU-1 more preferable material for front-end laser windows. One might expect the decrease of LIDT by about the factor of three in highly contaminated areas and up to six times – down to \( \sim \) 2 J/cm2 in the case of
contamination with dust particles. The obtained values of damage thresholds are exceed irradiation fluences expected for the first laser window of DTS diagnostics assuming the laser beam diameter ~ 1.5 cm and Brewster angle of incidence. Cleaning efficiency of fused silica windows under the simultaneous W deposition reveals good stability without any trend of quartz window degradation. Further experiments are needed, however, to check the feasibility of the technique for the recovery of the window with previously deposited tungsten or Be layer.

Ion flux and energy distribution have been measured as a function of a frequency and RF power in capacitively-coupled RF discharge. It was shown that the discharge frequency has a strong influence on both IED function and ion flux and, as a result, on sputtering efficiency and selectivity. The trade-off between sputtering rate and selectivity is an important factor affecting the cleaning system efficiency. The optimal regime should be chosen individually, taking into account external conditions, cleaning periodicity, and mirror design for each particular diagnostics. The impact of magnetic field on the discharge parameters is also a matter of following study. Along with discharge symmetrization, one can expect the distortion of IED function and Incident Angle Distribution (IAD) function in the magnetic field due to formation of magnetic pre-sheath.

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