Progress in Development of Deposition Prevention and Cleaning Techniques of In-vessel Optics in ITER

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Abstract. The lifetime of optical components unprotected from reactor grade plasmas may be very short due to contamination with carbon and beryllium-based materials eroded by plasma from beryllium walls and carbon tiles. Deposits result in a significant reduction of optical transmission. In addition, even rather thin and transparent deposits can dramatically change the shape of reflectance spectra owing to interference of reflected beams, especially for mirrors with rather low reflectivity, like W or Mo. Development of optics-cleaning and deposition-mitigating techniques is a key factor in the construction and operation of optical diagnostics in ITER. The most severe problem faces optical elements positioned in the divertor region. The latest achievements in protection of in-vessel optics are presented by example of deposition prevention/cleaning techniques for in-machine components of a Thomson scattering system in divertor. Careful consideration of well-known and novel protection approaches shows that neither of them provides guaranteed survivability of the first in-vessel optics in divertor. Only a set of mutually complementing prevention/cleaning techniques, that include special materials for mirrors and inhibition additives for plasma, is able to manage the challenging task. The essential issue, which needs to be addressed in the nearest future, is an extensive development of introduced techniques under experimental conditions (exposure time and contamination fluxes) similar to those expected in ITER.

1. Introduction

The problem of the protection and maintenance of optical units is faced in present-day fusion devices but is far more serious for the next-step burning plasma devices, such as ITER. All optical diagnostics for ITER are being designed and developed to be subjected to the severe environmental conditions. The lifetime of optical components unprotected from reactor grade plasmas will be very short because of contamination with carbon and beryllium-based materials eroded by plasma from beryllium walls and carbon tiles. Eroded wall materials will move around in the vacuum chamber and accumulate in the ducts equipped with the diagnostic optical elements. In addition to a significant reduction of optical transmission, even thin and transparent deposits can dramatically change the shape of reflectance spectra of rather low reflective mirrors, especially like W or Mo. Obviously, that development of optics-cleaning and deposition-mitigating techniques is a key factor in the construction and operation of optical diagnostics in ITER. The most severe problem faces every optical element positioned in the divertor region. It is apparent now, that neither of deposition prevention/cleaning techniques provide guaranteed protection of any in-vessel optics from environment. Only a set of techniques, specially selected for each optical surface, can manage the challenging task. Deposition flux on the first optical elements of a Thomson scattering (TS) system in the divertor and the required attenuation of the flux can be estimated from the following. The total flux of sublimated and sputtered carbon atoms from the carbon divertor targets can be up to 1.6×10^{-3} mol/s [1]. The main product of a divertor target erosion is methane (light hydrocarbons), which decomposes rather quickly into carbon-containing radicals. Most hydrocarbons will reach the divertor target again. Optics of the TS diagnostic in the divertor looks through a slot between divertor targets. Influx to a 20 mm wide slot is

then proportional to the ratio 20 mm/60 m (the total inner + outer divertor length in the toroidal direction is ~60 m):
1.6×10^{-3} mol/s × 6.022×10^{23} molecules/mol × 20 mm/60 m ~3.2×10^{17} C_xH_y molecules/s.
The hydrocarbon radicals can be subdivided into two types with low and high sticking coefficient. Low-adhering material sticks to surfaces after thousands of particle-wall collisions. This is the most dangerous material reaching optical surfaces even in long and narrow diagnostic ducts. Other hydrocarbons mainly adhering to the heated surfaces of divertor cassettes near the slot entrance would generate secondary radicals. Under secondary erosion of the a-C:H films nearby plasma the percentage of low-adhering particles is as much as 30%. Then the total flux of hydrocarbons with low sticking coefficient in the input of diagnostic duct may reach ~10^{17} C_xH_y molecules/s or ~10^{24} C_xH_y molecules carbon atoms for the action period of ~10^7 s. Practically all hydrocarbons penetrated through restricting inlets to extended diagnostic ducts will contaminate duct walls and optics (e.g., windows or mirrors). Assuming the contaminating flow is uniformly distributed, then up to 10% of total flux (i.e., a ratio mirror area/duct side surface) incident on the first collecting mirror of divertor TS or up to *~10^{23} C_xH_y molecules*. Thin hydrocarbon deposits, transparent in visible, can dramatically change the shape of reflectance spectra of mirrors owing to interference between beams reflected from the mirror surface and from the surface of deposits. An effect of the deposits of ~10 nm thick (or ~$5\cdot10^{16}$ Carbon atoms/cm^2 at ρ = 1 g/cm^3) may be tangible. For a first mirror of ~500 cm^2 a uniform 10 nm-thick deposit is equivalent to *~2.5×10^{19} carbon atoms*. Then, a required hydrocarbon flux attenuation along the 170 cm diagnostic duct to the first collecting mirror or along the 30 cm duct to the laser launcher is ~ *10^4*. These estimates show the vital necessity of deposition prevention and cleaning techniques. Similar thorough analysis for a tungsten divertor case is impossible at the moment due to lack of information about volatile Be or W compounds; however, the estimated deposition rate for first optics of divertor TS proves to be inferior to that for a tungsten divertor case.

2. Deposition Prevention and Cleaning Techniques

To prevent, reduce and/or mitigate a pollution influence on mirror reflectance spectra the following approaches are used: heating up to 150 - 200 ºC; mechanical protective appliances like shutters or mechanisms for replacement of worn-out components, and novel approaches, such as a proper selection of optical component materials or methods based on reduction of partial density of hydrocarbons or other pollutions inside diagnostic ducts in the vicinity of optical surfaces. Two cleaning approaches — laser cleaning and plasma cleaning — are known. Cleaning efficiency of various techniques may markedly differ and depend on the time period of application, i.e. during/between deposition processes. The cleaning approaches are rather sophisticated and require further development.

2.1. Routine Protective Techniques

Mechanical Protective Appliances (Shutters): The most risky objects for divertor TS diagnostic are plasma-facing optical components (e.g., laser launcher and the first collecting mirrors). Unfortunately, extremely long plasma discharges require a longer performance of unprotected in-vacuum optics, and a high repetition rate (up to 100 Hz) excludes the using of mechanical appliances during inter-pulse periods. An analysis of current technical solutions and a choice of driving units for protective devices is now one of the crucial tasks. Preliminary survey is based on ITER technical documentation [2] and involves an operating experience of existing prototypes in modern tokamaks. At the moment we have designed a basic version of a remote-control mechanism with a cardan driver similar to the used in JET [3]. Strong magnetic field in a divertor port makes it difficult to position an electromagnetic driver inside ITER vacuum chamber. Consequently, in the basic version an electromagnetic driver is placed outside the vacuum and transmits rotation via rotary drive feedthroughs [3]. The long distance of ~10 m from the driver to the divertor cassette area is the main limitation of the solution. Another approach involving a current loop in strong magnetic field (up to 5 T) or pneumatic drive like in [4] looks more optimal and practically feasible. The final decision on appropriateness of driver types (possibly a set of some different types) requires detailed designing and demonstration.

Heating: Hydrocarbon deposition prevention technique utilizing the temperature of ~200 ºC, at which chemical erosion of carbon films by hydrogen atoms prevail over deposition [5] was successfully tested in modern tokamaks [6] and laboratory experiments [7]. The technique is very promising, but for a successful operation demands the following be considered:

- Thin (1-10 nm) hydrocarbon-containing films [1] generated at the initial stage of the mirror operation (even without long-term hydrocarbon deposition), modify the reflective mirror characteristics. Then, the method has to be used in parallel with a reduction of partial density of hydrocarbons in the vicinity of the heated optical surfaces (see below).
- Atomic hydrogen is a key element in the thermal erosion process [5]. However, due to surface association of atomic H its density decreases in the long and narrow diagnostic ducts and may become insufficient for cleaning via thermal erosion.
- Deposition suppression is observed for low-energy CH-radicals. In the case of contacts with ions of 30-100 eV the heated surfaces are contaminated only slightly slower than without heating [1].
- Thermal gradients along protected surface activate thermal diffusion [1] of secondary radicals (formed on the surface but not condensed) directed to the area of high temperature. The phenomenon requires special consideration, such as a protection of large-aperture mirrors or windows by uniform thermal field which is technically challenging.
- Radiation effects (X-ray as a first step) on the chemical modification of heated metal mirrors at ITER environments also need special consideration [9].

For laser-irradiated optical elements, the heating technique should be used with special precautions, such as the increasing of temperature decreases the laser damage threshold [10].

The heating technique is profitable for decreasing of hydrocarbon deposition rate, yet it does not protect from complex deposits containing Be, W, etc.

Laser cleaning: Cleaning technique based on laser ablation of thin films and dust particles is well-known and used extensively in many technological applications [11]. The main mechanism of laser cleaning (removal of particles and/or deposited films) is the fast thermal expansion [12] leading to mechanical tensions and/or inertial force occurrence. Laser cleaning takes place if these forces exceed the adhesion forces. The deposit detachment occurs during the falling edge of laser pulse, and therefore, during pulsed cooling down.

The inertial forces due to pulsed thermal expansions are the basic mechanism of removing *particles or small pieces* of deposits. Pulsed laser irradiation virtually homogenously heats metal particles of under-micron size and rather small dielectric particles. Direction of laser irradiation for such particles is practically unimportant, as opposed to particles of rather large scale or low thermal conductivity, where thermal energy concentrates in a thin irradiated deposit layer. For large particles, a shift of mass center and, consequently, inertia force arises when the particle heating occurs from the side of a surface to be cleaned. It is typical for surfaces of transparent media irradiated from inside (e.g., input laser window) or under heat-transfer from the surface (pulsed heating/cooling of mirror surface). For contaminating *films*, the pulsed thermal expansions of the films can lead to both inertial forces and mechanical tension. In addition, laser irradiation of deposited films can result in extra pressure of gasified deposited material (explosion mechanism) and/or thermo-desorption of a gas adsorbed in the cleaned surface or in deposited films. The explosion mechanisms can intensify cleaning process but can also damage a cleaned surface [13] and lead to re-deposition of evaporated materials. A typical curve "laser cleaning efficiency – laser power density" is presented in Fig.1 for the cleaning of a corrosion layer on a steel plate. Successful laser cleaning requires combination of both high efficiency (e.g., nanosecond-range laser pulse) and prevention of optical surface damage; the latter means rather long laser pulses and moderate power density.

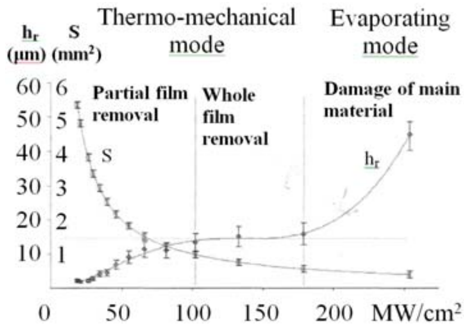

FIG.1. Experimental data for laser cleaning efficiency for removing of the corrosion layer from a steel plate. Profiles of the removed layer depth h_r and the laser footprint area (equivalent to a laser power density, under the fixed energy parameters of laser pulse) demonstrate a gradual transition from thermo-mechanical to evaporating mode [14].

To reach the conflicting objectives we need accurate data on *optical* properties of cleaned deposits, which determine a portion of absorbed laser power, and *thermo-mechanical* properties of cleaned deposits, which determine an optimal value of cleaning laser power density. In addition, deposits on large-scale optical mirrors may be of different types and possess different optical and thermo-mechanical characteristics. Furthermore, it is difficult to use the technique for cleaning of large-scale collecting mirrors due to challenging transport of cleaning radiation to the multiple mirror system of the TS diagnostic in ITER divertor and a necessity for laser radiation-resistant collecting optics. An example of the application is a launcher directing laser radiation into the divertor plasma of outer leg. The technique is suitable for cleaning non-transparent deposits, when absorbed laser power is quite predictable, but does not apply for laser-radiation transparent deposits. Unfortunately, hydrocarbon deposits can be quite often transparent in a wide spectral range. In the case of mirror cleaning the transparent deposits can cause an unpredictable laser light absorption due to interference phenomena. Most deposits well absorb UV (<300 nm) or infrared (>10 μm) laser radiation. However, these types of laser radiation are extremely difficult to manage, because of the limited set of materials that can be used for delivery of the radiation.

2.2. Advanced Protective Techniques

Plasma Cleaning Discharge: All known plasma-etching techniques for thin film coatings, widely applied in a semiconductor and optical industry, usually utilize the knowledge of composition and morphology of etched substance. Consequently, their eligibility for tokamak purposes is not straightforward. Particularly, substances containing chlorine and fluorine, commonly employed for etching, are inapplicable in the tokamak. Conventional techniques based on gasification of thin film coating by oxidation (heating or discharge in oxygen) [15], also are not suitable due to possible in-vacuum facility damage. The plasma cleaning techniques without activators, unfavorably affecting tokamak plasma discharge or in-vacuum elements, are the main priority of current research. All plasma cleaning techniques are based on two main cleaning mechanisms: chemical erosion and physical sputtering. The chemical erosion turns on, if chemically active particles interacting with contaminated surfaces generate volatile molecules (like H_2, CH_4, C_2H_2, HCN) or participate in surface reactions leading to desorption of secondary radicals with low sticking coefficient (like CH_3, C_2H_5). An increase in substrate temperature facilitates removal of hydrogenated carbon films and carbon-based materials via the chemical erosion. For targets with low temperature, the activation energy can be provided by the low-energy ion bombardment. This physical sputtering process is the well-known and widely applicable cathode sputtering by accelerated ions. The use of the physical sputtering cleaning techniques demands optical materials, which are more resistant to sputtering than the deposits to be removed. The main advantage of physical sputtering is that the cleaning efficiency practically does not depend on the film generation conditions and only slightly depends on their chemical composition. Our experiments [16] demonstrate that SS samples retrieved after long-term exposure to the working and wall-conditioning discharges without shutter protection from the tokamaks T-10 and Globus-M, were resistant to chemical erosion in pure hydrogen even after a significant temperature increase, but were effectively cleaned out by ions ~150 eV actually irrespective of deposit characteristics. Another promising mechanism is the chemical treatment and/or sputtering just during deposition process. The newly formed deposits are composed of individual islands or loosely coupled molecule conglomerates and often less resistant than mature films. Our experiments [8] demonstrate complete inhibition of CH deposits under the discharge in H_2/CH_4 mixture with addition of 5% N_2. A pressure of the resulting gas mixture was 7-20 Pa, ion impinging energy was ~30 eV, CH_4 flow was equal to N_2 flow. The cause of the deposition inhibition was that carbon pre-utilized for a-CH film formation, transformed into HCN molecules. The attained cleaning rate exceeded 25 nm/min, such as deposition rate without inhibitor (N_2) equaled to 25 nm/min (compare to the etching rate ~3nm/min for the previously generated or mature a-CH deposits demonstrated at the discharge in H_2/N_2 mixture). The cleaning rate of 25 nm/min is significantly higher than required for protection of first mirrors of divertor TS, and only twice as high as measured deposition rate (~10 nm/min) on first walls of operating tokamaks (ASDEX, DIIID, T-10). In the experiment we used chemical sputtering [17], a process, whereby ion bombardment causes or facilitates a chemical reaction involving particles that are weakly bound to the surface. Another prospective technique is a discharge in the gas flow, where the contamination rate decreasing results from the decreasing of partial impurity density and the impurity life time [18].

Blow-out Techniques: Decreasing of hydrocarbon impurity density inside diagnostics ducts can be achieved by a directed gas flow or by selective impurity pumping. Let’s consider the model, in which small quantity of hydrocarbon molecules diffuse from divertor plasma to an optical surface through a long diagnostic duct with absorbing walls and a gas counter-flow used for reduction of the diffusive flow. In the model, hydrocarbon partial density decreases towards the optical surface (mirror or window). The rough estimate of the impurity propagation through the channel can be performed via one-dimensional transport equation taking into account the loss of CH-radicals on the walls:

$$u\frac{\partial n}{\partial x} = D\frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau} \qquad (1)$$

where x – measurement along channel axis, u – counter-flow rate, D – diffusion coefficient for impurities in the main gas, n – impurity density, τ – impurity life time, determined by the contaminating impurity loss on duct walls due to sticking to the walls and/or surface chemical reactions transmitting the radicals to a volatile matter (like methane).

The equation (1) solution:

$$n(x) = n(0)\cdot e^{-x\left[\frac{1}{2L_u}+\sqrt{\frac{1}{4L_u^2}+\frac{1}{2L_\tau^2}}\right]} \qquad (2)$$

where $L_u=D/u$, $L_\tau=(D\cdot\tau)^{1/2}$ – typical space intervals.

According to the solution, impurity penetration depth is determined by both impurity loss on the duct walls (the decreasing of L_τ) and the rate u of gas counter- flow (the decreasing of L_u). In real conditions, a specific geometry of gas feed system and gas-wall interactions will create spatially inhomogeneous gas flow rates, so the impurity spread in a channel will depend on the channel shape and the gas flow pattern. The preliminary modeling exercise is carried out for the channel of 30 x 30 mm cross-section and 300 mm length. It is the model of a duct directed from under the divertor cassette and used to launch a laser probing beam to the plasma. The model shows that counter-flow of deuterium through a 5mm tube in the center of the channel bottom decreases methyl (CH_3) partial density by 4 orders along the whole channel length under a gas flow of ~0.18 Pa·m^3/s (i.e., ~0.001 of the total gas puffing flow in ITER). The problem was solved via Fluent 6.3 software using a finite elements method (FEM) assuming background neutral pressure 10 Pa. The same gas flow of ~0.2 Pa·m^3/s is appropriate for compensation of gravitation force of ball-shaped carbon dust particles of less than 10µm. Thereby the counter gas flow in the laser launcher duct is suitable for both blow-out of small dust particles and for the reduction of permanent diffusion hydrocarbon flux [19]. Unfortunately, the technique gives predictable results for steady state conditions only. Fast plasma phenomena, such as ELMs and NTMs can markedly change pressure in the divertor and induce convective flows of deposits.

Mirror Materials: Another passive protection technique is the proper way for optical component material selection. It may be materials characterized by either less deposition rate of hydrocarbon films [20] or high reflectivity mirrors [21]. Deposition-induced spectral distortion of reflectivity can be minimized using high reflective mirror materials [21] (see Fig.2). The hydrocarbon and amorphous carbon films are practically transparent in visible and IR range. Such films could change a mirror reflectivity non-uniformly depending on wavelength due to interference effects [22]. In addition, we can use the protective layer of certain thickness as an antireflection coating in some restricted spectral regions, for CH films of less than ~200 nm thick. For example, Fig.2 b&c demonstrates blue shift of the reflection in a silver mirror protected by 210 nm sapphire layer.

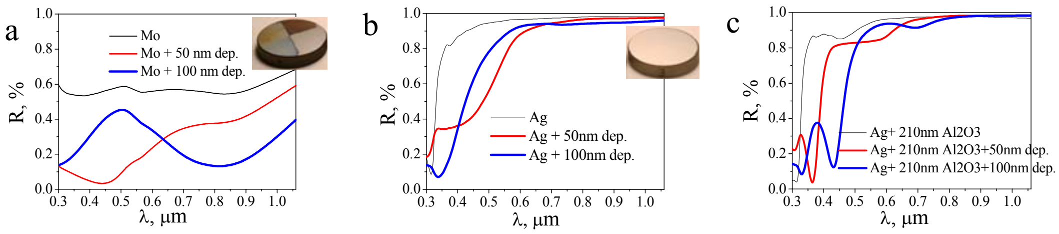

FIG.2. Reflection Spectra of Deposited Metal Mirrors (a) Mo , (b) Ag and (c) Ag protected by 210nm of Al_2O_3 free of coating and with 50nm and 100nm thick deposits. All calculations were made for amorphous carbon deposited films and unpolarized emission reflected at 45°of incidence [21].

Protective dielectric layers of low rate sputtering and chemical modification, like Al_2O_3 or Ta_2O_5, will reduce the risk of failure for high-reflectivity metal mirror materials (e.g., Al, Ag, Au, Cu), thus increasing time for cleaning or replacement. The coating may result in significant reduction or even complete elimination of the erosion of plasma facing components. Reflectivity of carbon contaminated mirrors can easily recover in the erosion-dominated conditions, because sputtering threshold for the provisioned protective dielectric layer is larger than for a carbon film. In addition, the regular shaped interference pattern (a number of interference fringes per spectrum channel) specific to thick protective coating >10 λ is preferable for handling severe deposition. In this case, dielectric coating can be used as a supporting structure [21].

Further efforts are necessary and being performed to develop tailor-made protected mirrors with high reflection coefficient, expected to tolerate neutron irradiation, sputtering and heating up to 250 °C. However, it does not mean that high reflectivity mirrors need no cleaning. Ideally, the deposits should be thin enough to prevent internal stress intrinsic for thick deposit layers. Significant internal stress may cause serious degradation of the films bringing about surface blistering, cracking and flaking. In addition, the composition of contaminating film appearing on the surface of the mirror may be rather complicated depending on mirror location inside the vacuum vessel. The conservative assumption has been made assuming optical properties of contaminating films to be similar to amorphous carbon coatings. Also interplay of Be and C, which can have very severe consequences, has not been analysed at the moment, because the data on the issue are still insufficient.

3. Cleaning Technique Development for In-Machine Components of TS in Divertor

All considered techniques have both advantages and disadvantages. In our opinion, most optical elements near the ITER plasma require a set of deposition prevention and/or cleaning techniques complementing each other. Contamination of optical elements in the divertor is a special issue, such as divertor tile material redistributed by disruptions which can seriously deteriorate reflection/transmission properties of optical elements in the divertor. Unfortunately, additional pumping in the divetor port is not practical [23] and the only way to pump out volatile contaminants is to design special duct walls absorbing impurities or converting contaminating radicals to volatile molecules (like methane) through radical-surface reactions. For a time period of tokamak cleaning discharge both laser launcher and the first collecting mirrors (see Fig.3) should be protected by shutters. Their design along with special arrangements for launcher replacement is now under development. The laser cleaning will operate automatically, removing coarse nontransparent contaminating pieces from laser launcher. For removing lesser particles (<10 μm) and avoiding deposition of volatile contaminations, specially designed laser launcher duct with additional gas puffing is now under development.

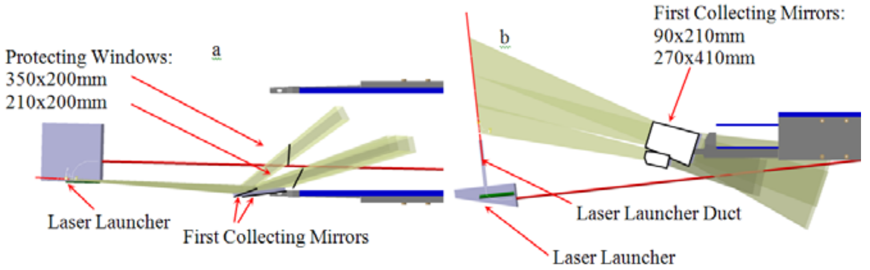

FIG.3. Layout drawing of the first optics TS in the divertor port (a) upper view, (b) side view.

All collection optics placed after the first mirrors will be protected by thin (~1 mm) protecting windows, used also to seal from the outside a vessel with the collecting optics. The windows are to be created in the area of moderate neutron flux (expected total flux ~10^{17} n/cm^2), has no load (vacuum on both sides) and should be used for deposit protection of all the following optics (except of first mirrors). For preserving the optical properties of the first collecting mirrors the same techniques as for the launcher protection (except of laser cleaning) in combination with plasma cleaning and selection of special mirror materials will be used. Application of an effective additional cleaning technique such as plasma cleaning is justified, since in large-aperture ducts the performance of a blow-out technique is lacking.

4. Conclusion

In recent years, the research and development programs on preventive and cleaning techniques of in-vacuum mirror protection from plasma contamination have been essentially intensified, and significant progress was achieved pursuing the first mirror protection issue for ITER. New techniques for deposit mitigation have demonstrated promising results, and new methods for the in-situ mirror cleaning in ITER are under development. The essential issue, which needs to be addressed in the near future, is an extensive development of introduced techniques under experimental conditions (exposure time and contamination fluxes) similar to those expected in ITER. Then, the most urgent needs include model estimates of the pollution fluxes for each diagnostic mirror and test operations of special protective appliances for each diagnostic assembly.

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[1] GORODETSKY, A.E., et al., "Methyl radical chemical reactions on a tungsten surface", Plasma Dev. and Op., 1, **16** (2008) 25-35.
[2] WALKER, C., "Comparative characteristics of drives", G55GR 5497-11-20R0.1.
[3] WILSON, D., et al., "Engineering Design of the Divertor LIDAR Thomson Scattering System", JET-P(92)72, 17th Symp. Fusion Tech. (SOFT-17), Rome, Italy, (1992).
[4] CHAVAN, R., et al., "A Frictionless Steering Mechanism for the Front Steering ECCD ITER Upper Port Launcher", 3rd IAEA Tech. Meet., J. Phys. Conf. Ser. 25 (2005).
[5] JACOB, W., ROTH, J., "Tutorial: Chemical Sputtering of Carbon: Review of Literature Data and Actual Results", IPP Workshop on "Chemical Sputtering of Carbon", (2004).
[6] LITNOVSKY, A., et al., "First tests of diagnostic mirrors in a tokamak divertor: an overview of experiments in DIII-D", Fusion Engineering and Design, **83** (2008) 79.
[7] VUKOLOV, K.Yu., et al., Proc. 33rd EPS Conf., Roma, Italy, P1.116, (2006).
[8] GORODETSKY, A.E., et al., "Transport and deposition of carbon and nitrogen containing radicals and ions produced by glow discharge in hydrogen/methane/nitrogen mixtures", Protec. Met., 6, **44** (2008) 542-547.
[9] VUKOLOV, K.Yu., et al., to be published.
[10] CHMEL, A.E., "Fatigue laser-induced damage in transparent materials," Mater. Sci. Eng. B, **49** (1997) 175–190.
[11] LU, Y.F., REN, Z.M., "Laser microprocessing and the applications in microelectronics industry", Proc. SPIE. **4157** (2000) 191-199.
[12] VEIKO, V.P., SHAKHNO, E.A., "Physical mechanisms of laser cleaning", Laser cleaning, Ed. by Luk'yanchuk, B.S. Singapore: World Scientific (2002) 311-340.
[13] OLTRA, R., et al., "Modeling and diagnostic of pulsed laser-solid interaction", Applications to laser cleaning, Proc. SPIE. **3885** (2000) 499-508.
[14] VEIKO V.P., et al., "Laser Cleaning of Surfaces of Metals: Physical Process and Application", Iz.VUZ. Seriia Priborostroenie (St. Petersburg), 4, **51** (2008) 30-36.
[15] GUBBINI, E., et al., "'On-line' cleaning of optical components in a multi-TW-Ti:Sa laser system", Vacuum **76** (2004) 45-49.
[16] KOCHERGIN, M.M., et al., "Research on mirror cleaning in inductively and capacitively driven radio-frequency discharges", Plasma Dev. and Op., 2, **14**, (2006), 1–6.
[17] COBURN, J.W., WINTERS, H.F., "Surface science aspects of etching reactions", Surface Science Reports **14** (1992) 161-269.
[18] GORODETSKY, A.E., et al., to be published.
[19] BULOVICH, S.V., et al., to be published.
[20] VOITSENYA, V.S., et al., "The environment effect on operation of in-vessel mirrors for plasma diagnostics in fusion devices", Proc. 12th Int. Cong. Plasma Phys., France, (2004).
[21] MUKHIN, E.E., et al., "Prospects of use of diagnostic mirrors with transparent protection layer in burning plasma experiments", Varenna, AIP Proc., **988** (2007) 365 –369.
[22] VUKOLOV, K.Yu., et al., "Exposure of stainless steel mirrors in T-10 tokamak", Plasma Dev. and Op., 3, **12**, (2004) 193 – 202.
[23] WALKER C., private communication.