Effective laser–induced removal of co–deposited layers from plasma–facing components in a tokamak

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An experimental set–up and spectroscopy diagnostic method for laser–induced fuel removal and decomposition of co–deposited layers on plasma–facing components from tokamaks are described. For irradiation of a graphite limiter tile from the TEXTOR tokamak Nd:YAG 3.5-ns pulse laser with a repetition rate of 10 Hz and single pulse energy of up to 0,8 J at 1,06 μm has been used. The spectroscopy system allowed recording of spectra in the visible wavelength range including CII and Dα spectral lines . The evolution of CII and Dα spectral lines was observed pulse–by–pulse during the co–deposit removal. The efficient ablation of the 45 μm thick co–deposit occured after approximately 50 laser pulses.

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1 Introduction

Carbon based materials, in particular CFC, due to good thermo–mechanical properties are planed to be used for the lower vertical target, i.e. for the strike point zone in ITER [1]. The main drawback of such a solution is that the presence of this element can lead to the fuel accumulation by co–deposition [2–5]. Massive fuel accumulation at the level which was observed in remote areas shadowed from the direct plasma impact at JET [6–8] would have a serious impact on the safety and economy of the ITER operation. Based on experience gathered following the full deuterium–tritium campaigns in carbon–wall devices, e.g. TFTR [9] and JET [10], a development of reliable and efficient methods of fuel removal is indispensable.

Until now several methods have been tested which are based on tokamak discharges in D_2 fuelled plasma, H and He glow discharge [10], plasma torches and photonic (laser or flashlamp) cleaning. Only the laser–assisted treatment lead to the removal of the whole co–deposit [11–15]. However, it is also important to develop diagnostic method for real–time observation of the removal process. Based on experimental evidence presented in [16] it has been decided to introduce the spectroscopy diagnostics into the experimental set–up. The main focus of this paper is on description of the new spectroscopic diagnostics of the system for co–depostit removal and on discussion of obtained results.

2 Experimental set–up

The apparatus is composed of a large vacuum chamber, a target holder attached to a linear manipulator, a laser and a diagnostic equipment: ion collectors and an optical spectrometer. Detailed description of the experimental set–up can be found in [15]. The irradiation was performed using a repetitive Nd:YAG laser generating 3 ns pulses of energy of up to 0.8 J with adjustable repetition rate up to 10 Hz at the wavelength of 1 060 nm. The laser beam is characterised by the "top hat" spatial beam profile, and beam divergence of less than 0.5 mrad (for more details see information about NL303HT laser model at www.eksma.com). Single pulse irradiations or series of shots could be performed. The beam–to–target angle was $35 \div 40^\circ$. The power density of the laser beam on the target surface has been set using a focusing lens thus enabling the change of the beam spot diameter. The lens could be mounted either inside or outside the vacuum chamber. The irradiation has been done with two variants of medium focussing which was proved to be near optimal in the previous experiments [1]. The diameters of beams at the target were $\sim$3,5 and 4,5 mm. The emission spectra of the plasma plume were collected using a 0.33 m focal length spectrograph and a fast gate, micro–channel plate (MCP) image intensifier optically coupled to an Andor CCD camera. The spectra were taken in the first order of diffraction where the reciprocal dispersion of the spectrograph was $\sim$13 Å/mm. The width of the entrance slit was 150 µm. The plasma plume was imaged on the entrance slit using a 180 cm focal length camera lens. The spectra were registered about 3 mm from the target. The image intensifier was gated for 2 microseconds by a high voltage pulse generator triggered by the laser signal. The same signal triggered the controller and data acquisition system.

The experiments have been carried out with an ALT (ALT–II, Advanced Limiter Test II) limiter tile retrieved from the TEXTOR tokamak after the long–term plasma operation, over 4 plasma hours. ALT–II is the main limiter composed of eight blades with 28 tiles each, the total area is 3.4 m^2. The view of the TEXTOR vacuum vessel and the arrangement of components can be found in [5]. The deposit thickness in the deposition zone of the plate is $40 \div 50$ micrometers and the deuterium–to–carbon ratio in the film is around 0.1 [17]. Comparative laser irradiation studies have been performed for a virgin graphite plate (Ringsdorff EK98) as a reference target.

3 Results and discussion

Plasma spectroscopy

The emission spectra consist mainly of bremsstrahlung and CII and CIII lines. The lines of neutral carbon are not observed. Due to the relatively high electron density, $N_\mathrm{e} \geq 10^{23}\ \mathrm{m}^{-3}$, it can be assumed that the laser induced plasma is in local thermal equilibrium (LTE). The criterion of LTE has the form [18]

$$N_\mathrm{e} \geq N_\mathrm{e}^\mathrm{cr} = 1.6 \times 10^{18}\, T_\mathrm{e}^{1/2} (\mathit{\Delta} E)^3 \,, \tag{1}$$

where N_e^cr is the critical electron density (in m^{-3}) necessary to fulfill LTE conditions, T_e is the electron temperature (in K), and $\mathit{\Delta} E$ is the largest energy gap of atomic (ionic) energy level system (in eV). Since such energy gap for CI – CIII system is about 13 eV the electron density necessary to fulfill the above criterion is $\sim 6{\times}10^{23}\ \mathrm{m}^{-3}$ at a temperature of 3.0×10^4 K, which is typical for the plasma plume some mm from the target. In practice the criterion can be lowered one order of magnitude because of the absorption of resonance lines.

The above criterion is a sufficient condition provided that the transport of particles and transient phenomena do not influence the Saha balance [18]. The estimations show that the diffusion of the particles from the plasma plume do not destroy LTE conditions.

The electron density was determined from the Stark broadening of the CIII line as well as from the broadening of Dα line. The Stark broadening parameters were taken from [19] and [20]. At the distance of 3 mm from the target the value of $8.5{\times}10^{23}\ \mathrm{m}^{-3}$ was found from the CIII line. The electron density obtained from Dα line is considerably smaller and amounts to $2{\times}10^{23}\ \mathrm{m}^{-3}$. This difference is very likely caused by the fact that the results are obtained from the time and space–averaged line profiles while the electron density changes both in time and space.

The electron temperature was determined from the intensity ratio of the CIII 5695.92 Å line and 5662.47 Å CII ionic line. The ratio of the intensities of lines from the subsequent ionization stages multiplied by the electron density is a function of temperature [21]:

$$\frac{I'}{I} N_\mathrm{e} = 4.83 \times 10^{21}\ \frac{g' A' \lambda}{g A \lambda'} T_\mathrm{e}^{3/2} \exp\left(- \frac{E' + E_\mathrm{ion} - E - \mathit{\Delta} E_\mathrm{ion}}{k T_\mathrm{e}} \right) , \tag{2}$$

here I is the line intensity, λ the wavelength, g the statistical weight of the upper level, A the transition probability, E the energy of the upper level, E_ion the ionization energy, and $\mathit{\Delta} E_\mathrm{ion}$ the lowering of the ionization potential. Primed quantities denote the higher ionization stage. N_e is in m^{-3} and T in kelvins. The transition probabilities were taken from [22].

Assuming the electron density of $8.5{\times}10^{23}\ \mathrm{m}^{-3}$ the temperature 3.8×10^4 K was found. The obtained values of the electron density and temperature are consistent with previously obtained data in similar conditions [23, 24] although our value of the electron temperature is higher.

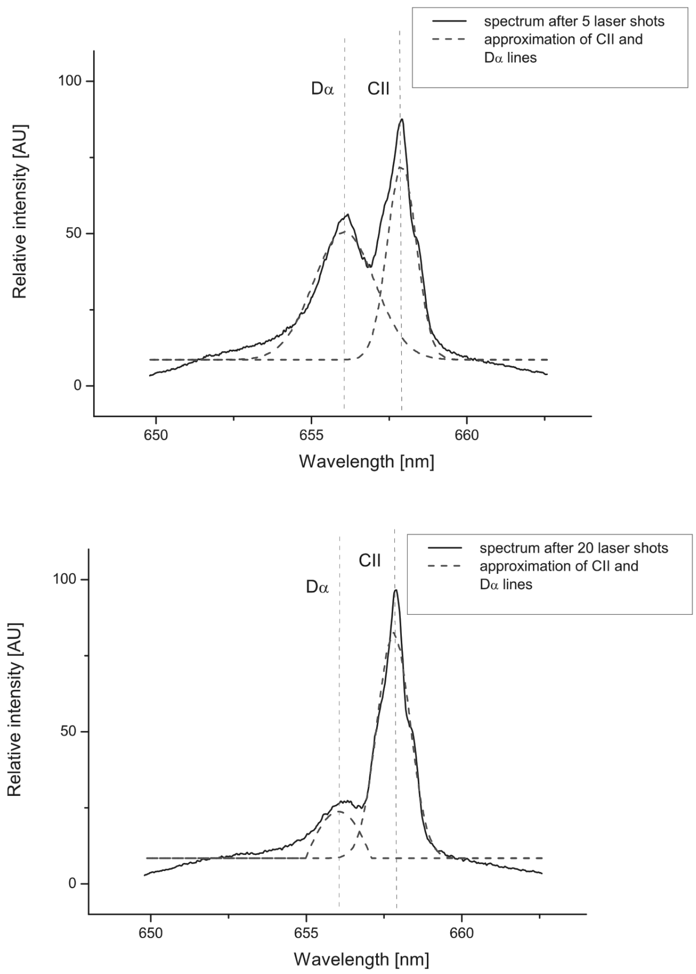

Fig. 1. Spectra collected after 5 a) and 20 b) subsequent shot in the series.

The pressure of the plasma plume was estimated from the equation of the ideal gas. The value of 0.88 MPa was found at the distance of $\sim$3 mm from the target.

Fuel removal

During single and series of laser pulses the deuterium removal was assessed by comparing the intensities of carbon and deuterium lines. The signals recorded from the irradiated sample and deconvolution of spectra are shown in Fig. 1. It is clearly observed that the intensity of deuterium line drops significantly (an order of magnitude) during the subsequent shots thus indicating the efficient removal of fuel. The Fig. 2 shows the decrease of the relative deuterium content in the laser–induced plasma recorded near the target during subsequent shots. The decrease is stronger for the sharper focussing which is fully consistent with previous results [15]. The number of shots needed to remove fuel from the 45 μm thick co–deposit was approximately 40 and 50 for 4.5 mm and 3.5 mm focussing, respectively. As it can be inferred from Fig. 2 the amount of deuterium remaining in the sample after a series of shots amount to about 3 % of the original value. The research has proven that optical spectroscopy is a reliable method for on–line observation of the efficiency of co–deposit removal by laser beams.

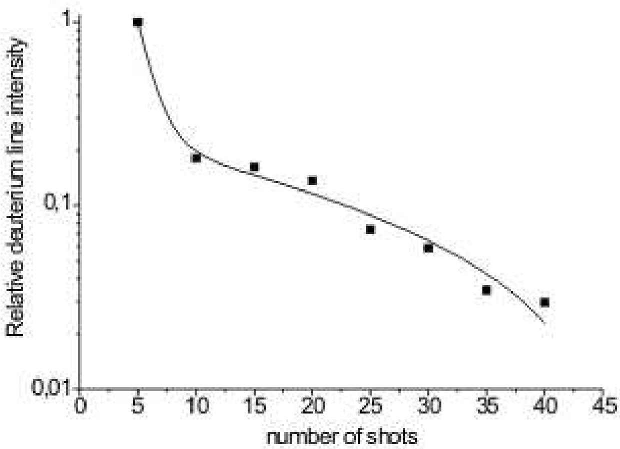

Fig. 2. Calculation of relative deuterium line intensity in reference to the carbon lines.

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