

Research on laser-removal of a deuterium deposit from a graphite sample

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Abstract. The paper presents experimental results of investigation of a removal of deuterium deposits from a graphite target by means of pulsed laser beams. The sample was a part of the TEXTOR limiter with a deuterium-deposited layer. That target was located in the vacuum chamber, pumped out to 5×10^{-5} Torr, and it was irradiated with a Nd:YAG laser, which generated 3.5-ns pulses of energy of 0.5 J at $\lambda_1 = 1063$ nm, or 0.1 J at $\lambda_3 = 355$ nm.

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1. Introduction

It is well known that graphite tiles or carbon fibre composites (CFC) are often used in various tokamak facilities [1-3]. During plasma discharges performed with the pure deuterium-gas filling, some portion of deuterium is deposited and occluded upon surfaces of the inner armour of the tokamak chamber. This deuterium is partially removed during successive tokamak discharge, but some portion remains in the exsposed parts for a long time. In fact, in addition to deuterium, there are deposited also some heavy impurities (e.g. Si, B, Ni, Cr, Fe and W species), which originate from eroded surfaces of the tokamak armour [4].

In order to induce a decomposition and removal of the deposited layers, some efforts were undertaken to use repetitive laser pulses [5-7]. Some preliminary studies with the use of a Nd:YAG laser, which were undertaken at the IPPLM, gave positive results [8], but information about efficiency of the deuterium removal was rather scarce. On the other hand, the massive accumulation of fusion fuel (i.e. deuterium and tritium) in carbon-containing inner parts of the tokamak chamber might have a serious impact on the safety and economy of the tokamak operation, particularly in future ITER experiments [9]. Therefore, the main aim of the reported research was to investigate the efficiency of a laser-removal of deuterium from a graphite sample, which was earlier exposed to deuterium discharges in a tokamak.

2. Experimental setup

The investigated target constituted a deuterium-deposited graphite sample (Toyo Tanso, IG-430U) cut out from a TEXTOR toroidal limiter, which was earlier exposed to a series of discharges performed with the pure deuterium filling. That target was placed in the centre of the quasi-spherical vacuum



chamber equipped with a pumping system and several operational or diagnostic ports. The vacuum chamber was initially pumped out to the final pressure of 5×10^{-5} Torr.

One of the side ports, oriented at an angle of about 60° to the target surface, was equipped with an optical window used to let in pulsed laser beams from a Nd:YAG laser, which could generate 3.5-ns pulses of energy of 0.5 J at $\lambda_1 = 1063$ nm, or 0.1 J at $\lambda_3 = 355$ nm. The diagnostic port oriented perpendicular to the target surface was connected with an electrostatic ion energy analyzer equipped with the deflection system consisted of two coaxial metallic cylinders. Ions, which reach the detector (photomultiplier), were separated on the path of flight due to their energy and mass spread. Another diagnostic port, oriented at an angle of about 60° to the target surface in the opposite direction than the laser beam axis, was used for measurements with an ion collector coupled with a fast oscilloscope. The detector constituted a Faraday cup which was applied for measurements of ion current in a stream of charged particles. These two ion diagnostic tools were similar to that used during the previous preliminary studies [8], but in the reported study the use was also made of a Mechelle[®]900 spectrometer in order to apply the optical emission spectroscopy (OES) technique. The scheme of an experimental setup is presented in Fig 1.

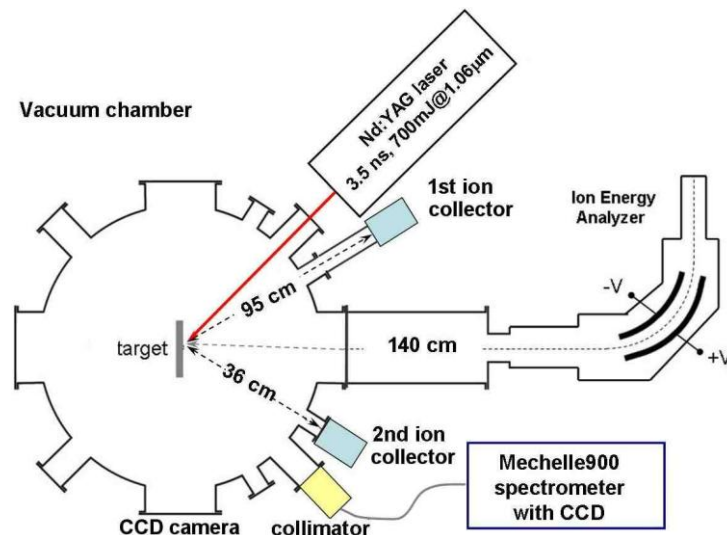


Figure 1. Experimental setup used for studies of C-targets irradiated by laser pulses.

As shown in Figure 1, in order to record optical emission spectra the use was made of another diagnostic port. It was equipped with a quartz window and an optical collimator, which was coupled with the Mechelle[®]900 spectrometer through a quartz-fibre cable. The spectrometer recorded optical spectra in the wavelength range of 300–900 nm by means of a PCO-SensiCam camera coupled with a computer and an appropriate spectroscopic software [10–11].

3. Experimental results

The reported experiments were started by taking time-integrated pictures of a plasma plume produced from the target irradiated by a single laser pulse. Conditions of the laser focusing were changed by applying lenses of $f = 10$ –70 cm focal length, placed at a distance $l_f = 10$ –75 cm from the target. Corresponding time-integrated pictures were compared. Examples of such pictures are shown in Fig. 2. The applied $f = 10$ cm lens with a protecting glass can be seen in Fig. 2a.

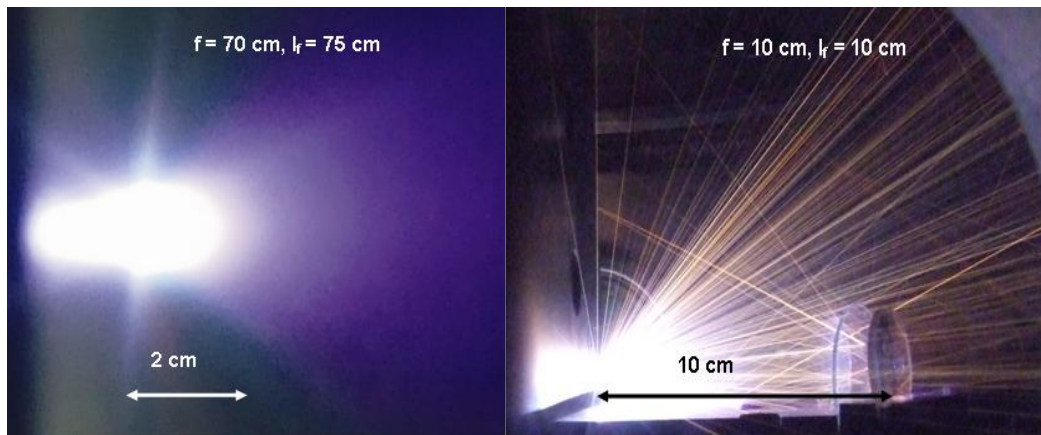


Figure 2. Time-integrated pictures of plasma produced by a single laser pulse focussed upon a deuterium-saturated carbon-target: a) at $f = 70$ cm, $l_f = 75$ cm; b) at $f = 10$ cm, $l_f = 10$ cm.

From the time-integrated picture presented in Fig. 2a one can easily see that the plasma plume, produced during irradiation of the investigated target by a pulsed laser beam at $f = 70$ cm and $l_f = 75$ cm, was quasi-symmetrical to the axis perpendicular to the target surface. When the lens of a $f = 10$ cm was situated near the target, at a distance $l_f = 10$ cm from its centre, the time-integrated picture shown in Fig. 2b demonstrated distinct traces of ion species (mainly carbon ions) emitted from the eroded target.

The optical emission spectrum, as emitted from the laser-produced plasma plume, was recorded by means of a Mechelle[®] 900 spectrometer for different numbers of laser pulses. A comparison of a chosen part of such a spectrum, which was time-integrated over each 5 successive shots (generated with a frequency 1 Hz) during a series of 50 laser pulses, is presented in Fig. 3.

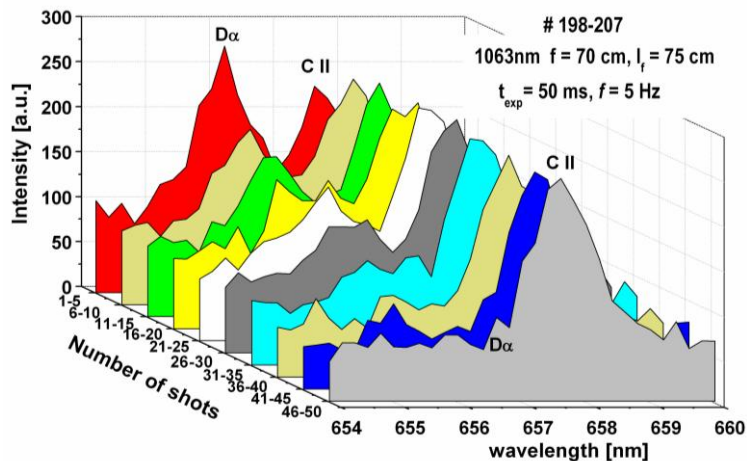


Figure 4. The chosen part of the optical emission spectrum (ranging from 654 nm to 660 nm), which was recorded for each successive 5 shots during a series of 50 laser pulses (1063 nm, 0.5 J) focussed at $l_f = 75$ cm, with lenses of $f = 70$ cm, upon the deuterium-saturated graphite target (C + D₂).

From the spectra shown in Fig. 3 one could easily see that the intensity of spectral lines corresponding to C II ions did not change noticeably during the whole series of the applied laser pulses, while the intensity of spectral lines from deuterium (the D_α line in that case) decreased considerably. Hence, one could deduce that the erosion of the graphite substrate was comparable for each laser shot, while the successive laser shots caused a removal of deuterium from the irradiated target.

These statements were confirmed by an analysis of the recorded spectra, and in particular by the measured intensity of the D_α line ($I_{D\alpha}$) versus the number of laser shots and the histogram showing changes of the $I_{D\alpha}/I_{CII}$ as a function of the laser shots, as presented in Fig. 4.

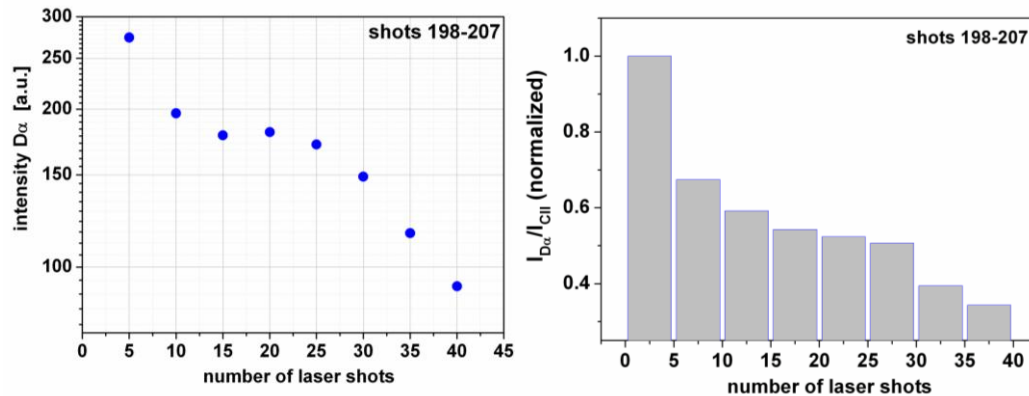


Figure 4. Decrease in the D_α intensity and in the $I_{D\alpha}/I_{CII}$ ratio, as observed with an increase in the number of the laser pulses.

It should be noted that spectroscopic measurements analogous to those presented in Figs. 3 and 4 were also carried out for other focusing conditions (i.e., $l = 10$ cm and $l_f = 10$ cm), and the obtained results were very similar when the laser was operated at the 1st harmonic $\lambda_1 = 1063$ nm, at energy 0.5 J.

In contrary, when the laser wavelength and energy was changed, i.e. when the 3rd harmonic $\lambda_3 = 355$ nm was used and its energy was decreased to 0.1 J, there were recorded carbon lines of lower intensity and no deuterium lines. Hence, one could deduce that 0.1 J pulses were insufficient to induce a removal of the deposited deuterium.

During the detailed analysis of the OES measurements particular attention was paid to changes in profiles of the D_α and C II lines in order to determine parameters of the investigated ion species. Some results are presented in Fig. 5.

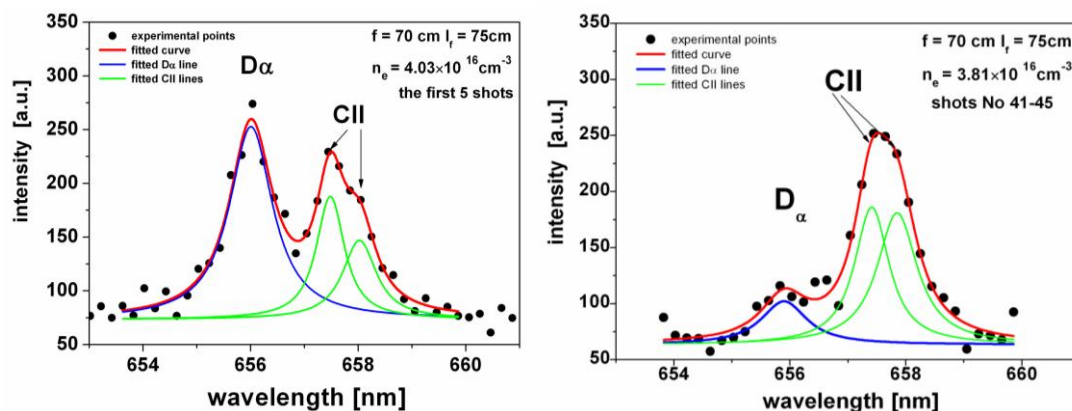


Figure 5. Fitting of profiles of the D_α and C II spectral lines for the spectrum recorded for the first 5 laser pulses (left) and for that observed after 41-45 shots (right).

On the basis of the profiles presented in Fig. 5 it was estimated that the deuterium population after 40 laser pulses decreased very strongly. In contrary, after such a treatment the population of C II ions did not change considerably. This conclusion was consistent with the previous statements. The electron concentration (N_e), which was determined from the Stark broadening of the D_α line profile recorded for the first 5 laser pulses, amounted to about $4 \times 10^{16} \text{ cm}^{-3}$, while this parameter estimated

from the D_α profile recorded during shots nos. 41-45 was equal to about $3.8 \times 10^{16} \text{ cm}^{-3}$. It should be noted that in the last case intensity of the analyzed line was considerably lower. After changes of the focusing conditions (i.e., changes of a distance between the lens and the target, at the constant focal length f) the N_e changed from about $4 \times 10^{16} \text{ cm}^{-3}$ (see above) to about $7 \times 10^{16} \text{ cm}^{-3}$.

In order to investigate the emission of ions from the laser-irradiated target the use was made of the ion collector described above. Some examples of ion signals, which were recorded with that collector, are presented in Fig. 6.

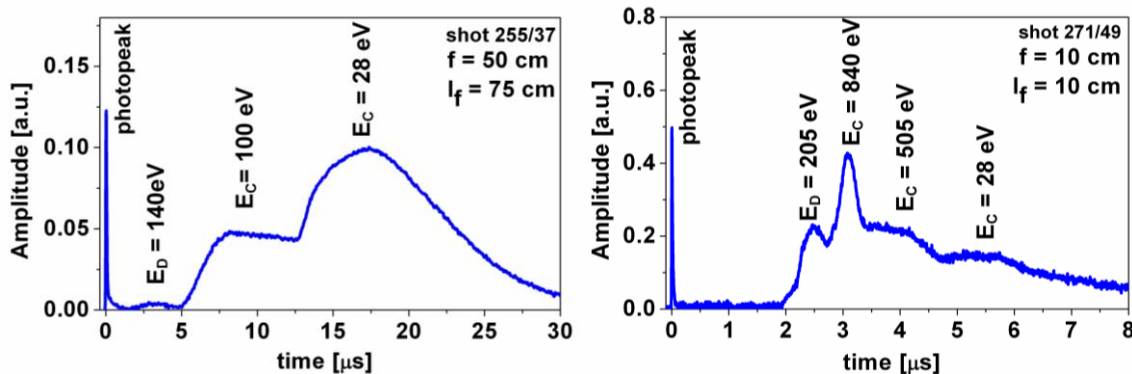


Figure 6. Time-resolved ion signals recorded with the ion collector situated at a distance of 36 cm from the target irradiated by 5 laser pulses ($\lambda_1 = 1063 \text{ nm}$, 0.5 J) at different focusing conditions: with the lens of $f = 50 \text{ cm}$ placed at a distance $l_f = 75 \text{ cm}$ (left), and with the lens of $f = 10 \text{ cm}$ placed at a distance $l_f = 10 \text{ cm}$ (right)

Basing on the well know time-of-flight (TOF) technique it was possible to estimate ion energies corresponding to the recorded ion peaks. The results of simple computations showed that (depending on the laser focussing conditions) energies of deuterons ranged from about 50 eV to about 200 eV, while energies of carbon ions (considering mainly C II) ranged from about 30 eV even to about 850 eV.



Figure 7. Macro-photography of a part of the investigated deuterized-graphite target, which shows micro-craters formed after the irradiation at different focusing length ($f = 50 \text{ cm}$ and 70 cm) and different distances of the lenses from the target ($l_f = 70 \text{ cm}$, 75 cm and 80 cm). All craters were produced by the 1063-nm laser pulses. The crater no. 1 was produced at $f = 70 \text{ cm}$ and $l_f = 75 \text{ cm}$; the crater no. 2 was produced by at $f = 70 \text{ cm}$ and $l_f = 80 \text{ cm}$; the crater no. 3 - at $f = 70 \text{ cm}$ and $l_f = 85 \text{ cm}$; the craters nos. 4 and 5 - at $f = 70 \text{ cm}$ and $l_f = 70 \text{ cm}$; the crater no. 6 - at $f = 50 \text{ cm}$ and $l_f = 70 \text{ cm}$; the crater no. 7 - at $f = 50 \text{ cm}$ and $l_f = 80 \text{ cm}$; and craters nos. 8 and 9 were produced at $f = 50 \text{ cm}$ and $l_f = 75 \text{ cm}$.

The laser-erosion of the investigated target was also investigated by macro-photography of the irradiated surface. An example is shown in Fig. 7.

Pictures of the micro-craters produced during the reported experiment are indicated by successive numbers in Figure 7. Measurements performed with an optical microscope showed that these micro-craters were of 1200-3000 μm in diameter and 30-150 μm in depth.

4. Conclusions

The main results of the reported study can be summarized as follows: On the basis of the recorded optical spectra it was found that the removal of deuterium from the surface layer of the target depends strongly on the laser wavelength and energy. Considerable differences in the intensities of the investigated spectral lines (mainly D_α and C II) were observed after the applied series of the laser pulses of $\lambda_1 = 1063$ nm and energy 0.5 J. This observation showed a high efficiency of the deuterium removal. In contrary, the use of laser pulses of $\lambda_3 = 355$ nm 0.1 J led to very weak erosion of the substrate material (carbon), but no removal of deuterium was achieved. More accurate analysis of spectroscopic data confirmed the above statements.

Measurements performed with an ion collector did also confirm the emission of deuterons and carbon ions. Signals obtained from the ion energy analyzer (at the highest applied power flux density) showed that the plasma included carbon ions with an electric charge ranging up to 4+. The signals from the ion collector allowed to estimate that in that case the peak energy of the carbon ions amounted to about 1 keV.

In conclusion it might be stated that to ensure an efficient removal of deuterium deposits one should apply laser pulses of $\lambda_1 = 1063$ nm and energy above 0.5 J focused upon a spot of 1-3 mm in diameter, ensuring power density of $0.7 \cdot 10^9$ W/cm². In the future it is planned to perform experiments with the 3rd harmonic of Nd:YAG laser to reach a higher power density and to observe eventual differences in the deuterium removal process.

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References

- [1] Skinner, C. H., Gentile, C. A., Ascione, G. Carpe, A., Causey, R. A., Hayachi, T., Hogan, J., Langish, S., Nishi, M., Shu, W. M., Wampler, W. R. and Young, K. M., *J. Nucl. Mater.* **290-293**, 486 (2001).
- [2] Andrew, P., et al., Stork, D. (Ed.) Technical Aspects of Deuterium Tritium Operation at JET (special issue), *Fusion Eng. Des.* **47**, 211 (1999).
- [3] Fortuna, E., Rubel, M. J., Philipps, V., Kurzydowski, K. J., Martens, Ph., Miskiewicz, M., Pisarek, M., Van Oost, G. and Zieliński, W., *J. Nucl. Mater.* **367-370**, 1507 (2007).
- [4] Rubel, M. et al., *J. Nucl. Mater.* **307-311**, 111 (2002).
- [5] Shu, W.M., Kawakubo, Masaki, K., Y. and Nishi, M. F., *J. Nucl. Mater.* **313-316**, 584 (2003).
- [6] Skinner, C. H., Bekris, N., Coad, J. P., Gentile, C. A., Hassenein, A., Reisdwig, R. and Willms, S., *Phys. Scripta* **T103**, 34 (2003).
- [7] Ivanova, D., Rubel, M., Philipps, V., Schweer, B., Freisinger, M., Gierse, N., Penkalla, H., Petersson, P., Dittmar, T., *J. Nucl. Mater.* **415**, S801 (2011).
- [8] Gasior, P., Badziak, J., Czarnecka, A., Parys, P., Wolowski, J., Rosinski, M., Rubel, M. and Philipps' V., *Phys. Scripta* **T123**, 99 (2006).
- [9] Loarer, T., Corre, Y., Delpech, L., Devynck, P., Douai, D., Ekedahl, A., Guilhem, D., Gunn, J. P., Klepper, C. C., Marandet, Y. and Vartanian, S., *Nucl. Fusion* **53**, 033003 (2013).
- [10] Kurucz-database: <http://www.pmp.uni-hannover.de/cgi-bin/ssi/test/kurucz/sekur.html>
- [11] NIST database: <http://physics.nist.gov>