Efficacy of photon cleaning of JET divertor tiles

A. Widdowson [a],*, J.P. Coad [a], N. Bekris [b], G. Counsell [a], M.J. Forrest [a],
K.J. Gibson [c], D. Hole [d], J. Likonen [e], W. Parsons [a],
T. Renvall [e], M. Rubel [f], JET-EFDA Contributors [1]

[a] *EURATOM/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxon OX14 3DB, UK*
[b] *Forschungszentrum Karlsruhe, Karlsruhe, Germany*
[c] *University of Manchester, Manchester, UK*
[d] *Department of Engineering and Design, University of Sussex, Brighton, East Sussex, UK*
[e] *Assoc. EURATOM-TEKES, VTT Processes, 02044 VTT, Espoo, Finland*
[f] *Royal Institute of Technology, Assoc. EURATOM-VR, 100 44 Stockholm, Sweden*

Abstract

Photon cleaning by means of a flash-lamp was used for *in-situ* detritiation of the inner wall tiles of the JET divertor in May 2004. Additional trials were also performed *ex-situ* in October 2004 on divertor base tiles. Early work confirmed that for pulse energies between 150 J and 300 J some deposited material was removed. To increase the amount of material removed during photon cleaning, further experiments with higher pulse energies (500 J) were performed and are reported here. Analysis of cross sections confirmed a removal rate of 0.04 μm/pulse, removing ∼80 μm from 200 μm thick deposits over a treatment area of 15×10^{-4} m^2. During the photon cleaning tests at least 12% of the tritium inventory for the tile was removed. It was also shown that deuterium was desorbed from a depth ∼7 μm beyond the depth of material removed. Crown Copyright © 2007 Published by Elsevier B.V. All rights reserved.

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1. Introduction

ITER is currently planning to use carbon (C) tiles at the plasma strike points in the divertor. However modelling and experiment have shown that the presence of carbon will result in the accumulation of carbon-based deposits which trap tritium [1,2]. Since an upper limit for tritium in the ITER vessel exists for safety reasons, tritium trapping is of particular concern and in order to remain within the limit, it will be necessary to remove these accumulations periodically. Tritium (T) can be removed either by desorption as a gas, or removal of *in-situ* deposits. One method of achieving the latter is by photon cleaning, using either a laser [3] or a high power flash-lamp, as reported here.

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* Corresponding author.
  E-mail address: anna.widdowson@jet.uk (A. Widdowson).
[1] See annex of J. Pamela et al., Fusion Energy 2004, Proc. 19th Int. Conf. Lyon, 2004, IAEA, Vienna.

The use of high power light sources for photon cleaning is already established in several non-fusion specialist cleaning roles such as nuclear decommissioning, cleaning the wings of surveillance aircraft and art restoration. Such flash-lamps are capable of delivering several hundred Joules of ultraviolet, visible and infrared radiation in a pulse length of 100 μs. When focused onto an area of several square centimetres, power densities up to several GW/m^2 can be achieved, comparable with lasers.

Trials of a photon cleaning unit were carried out in-vessel using remote handling at JET in May 2004 and further trials were completed *ex-situ* at JET in October 2004. During the *in-situ* trials a range of pulse energies and repetition rates were used. For pulse energies from 150 J to 300 J, changes in the surface appearance of the inner wall tiles were observed after treatment. The change in appearance was due to the removal of material from the tile surface. Additional *ex-situ* results confirmed a significant release of T at these energies. At lower energies (<100 J) hydrogen-isotopes were desorbed from the film, however removal of material from the surface was not achieved.

2. Experimental details

In this work we report trials of photon cleaning of tile 3BW G4B (Tile 4) from the JET MkII-GB and SRP divertor, using a flash-lamp operated at increased power levels. Tile 4 is at the inner corner of the divertor, see Fig. 1. Part of it lies in the shadowed region where carbon-based films of thickness 100 μm or more, with high hydrogen-isotope content, are deposited. The sloping surface of Tile 4 is accessed by the plasma and has a very thick powdery deposit with a low deuterium (D) and T con-
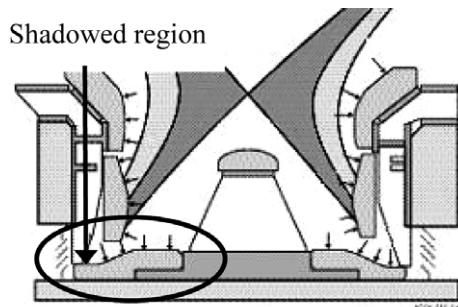
tent [4]. Due to the low concentration of D and T in this region only data from the shadowed area are presented.

A photon cleaning unit consisting of a flash-lamp capable of delivering 500 J at 5 Hz with a pulse width of 140 μs was used for the detritiation trials. The flash-lamp was mounted in a truncated elliptical cavity protected by a 5 mm quartz window. The unit was water cooled, with forced air flow capability. Buffers and rollers on the unit prevented damage to the tile and gave a minimum stand-off from the target of 28 mm. As the tiles for cleaning were possibly contaminated with beryllium (Be), both the tiles and the photon cleaning unit were situated in a ventilated slit box in a facility designed to handle Be contaminated items; referred to as the beryllium handling facility (BeHF). To minimize contamination to the rest of the equipment, the power supply and water cooling units were outside the BeHF and connected to the photon cleaning unit using 10 m long cables inside the BeHF. During cleaning, the T released from the tile was exhausted through a ventilation pipe from the slit box. Continuous measurements were made of the T content of the exhaust gas using an ion chamber. From the flow rate of the exhaust gas through the ion chamber the amount of T released from the tile during cleaning was measured.

Two locations on Tile 4 were treated, position 1 was at the edge of the tile and position 2 was in the centre of the shadowed area (Fig. 2). A mask was placed at one end of the tile to prevent removal of T and thus provide a reference between treated and untreated regions. This resulted in the length of the treated region being reduced to 120 mm from 150 mm.

Each position was subject to a series of pulses from the flash-lamp. The number of pulses for positions 1 and 2 were 1300 and 2785 respectively. Typical settings were 500 J per pulse at a frequency of 4 Hz. The maximum energy density obtained at the tile surface was 0.06 MJ/m^2.

Fig. 1. Diagram of MkIIGB divertor showing the location of Tile 4. The region shadowed from the plasma by Tile 3 (referred to as 'the shadowed region') is indicated by an arrow.
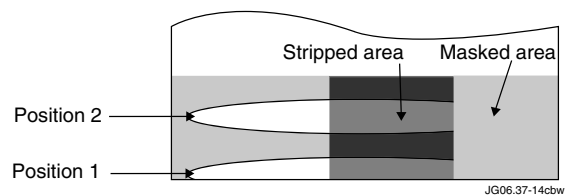

Fig. 2. Schematic diagram showing the area on the shadowed region of Tile 4 treated during the photon cleaning trials.

3. Results

Cross sections from the untreated regions of Tile 4 are shown in Figs. 3(a) and 4(a). In these figures, strata of different layers can be seen, with layers observed in the untreated region correlating with layers in the treated regions (Figs. 3(b), 4(b) and (c)). The correlation of layers in the deposit also makes it easier to confirm that material has been removed. For example, a darker layer visible ~30 μm below the surface of the untreated sample is missing from the treated samples. The cross sections show that the thicknesses of initial deposits were about 150 μm for position 1 and 250 μm for position 2. By comparing the difference in thickness between the untreated and treated regions the total amount of material removed was 70 μm from position 1 and 90 μm from position 2, ~40% of the deposit in the treated areas. From images taken at 1 mm intervals across the treated region at position 2 the effective width of the light pulse was measured as 10 mm, equating to a treated area of $12 \times 10^{-4} \, \text{m}^2$. At position 1 the light source extended over the edge of the tile, thus the area treated was approximately

half that of position 2. From the total number of pulses used to treat positions 1 and 2, removal rates were of the order 0.05 μm/pulse and 0.03 μm/pulse respectively.

The total T removed from the tile was approximately 3 GBq from a total area of $18 \times 10^{-4} \, \text{m}^2$ for positions 1 and 2, where 1 GBq is equivalent to 2.7 μg of T atoms. Assuming that the majority of the T was in the shadowed area and comparing the volume of deposit on the shadowed area with the volume of deposit removed, a total activity of ~24 GBq was calculated for the tile. This value was consistent with the activity measured on an adjacent tile by total combustion and also with off-gas measurements on this tile and an adjacent tile.

During the initial 2500 pulses, the release of T per pulse was found to decrease with increasing pulse number. Two possible explanations for this slow-down were investigated. Firstly, that thermal shock to the surface could create a loosely adhered carbon layer with reduced thermal conductivity which acts as a thermal barrier. Secondly, that metallic impurities accumulate on the surface as C and hydrogen (H) isotopes are removed and that the increased metallic concentration changes the thermal and optical properties of the surface reducing the coupling of energy into the deposit. It was expected that either of these layers could be stripped from the surface using adhesive tape. This would restore the initial thermal and optical properties of the surface and consequently increase the amount of T released when photon cleaning resumed. Thus the central region of the shadowed surface on the tile was stripped, as shown in Fig. 2, and further photon cleaning consisting of 285 pulses was performed across position 2. An increase in the rate of removal from 0.23 GBq/m²/pulse to 0.53 GBq/m²/pulse was observed, approximately half the initial rate of
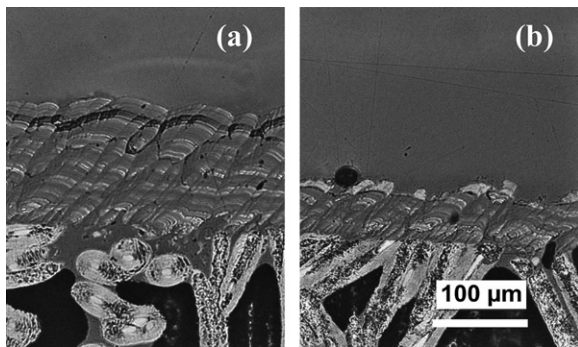

Fig. 3. Cross sections showing deposits on (a) untreated and (b) treated regions at position 1 of Tile 4.
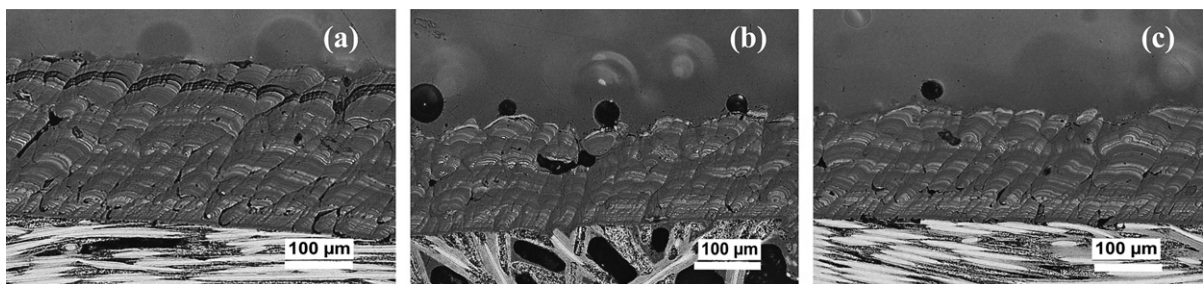

Fig. 4. Cross sections showing deposits for un-stripped and stripped regions from position 2 on Tile 4. (a) Shows untreated region (b) shows the treated only region and (c) shows the treated and stripped region.

removal (1.14 GBq/m^2/pulse). This might be expected as only half of the treated area had been stripped.

Cross sections of the un-stripped and stripped regions in Fig. 4(b) and (c) show that within the resolution of the images, equal amounts of material have been removed. This suggests that the formation of loose debris giving rise to a thermal barrier did not occur during cleaning. Results from secondary ion mass spectroscopy (SIMS), however, show the presence of nickel (Ni) at the surface. Fig. 5(a) and (b) shows C, D and Ni depth profiles in the untreated and treated regions, respectively. Due to the presence of surface oxides the untreated sample is prone to charging during SIMS analysis which affects the initial 1–2 μm of the results. This is not a problem for the treated sample as the oxide has been removed by photon cleaning. In view of this charging, the best assessment of Ni content between untreated and treated samples is from the Ni/C ratio, which is >1 at the very surface of the treated sample and remains <1 for the untreated sample. This indicates that Ni is not removed during photon cleaning and that its accumulation could provide the explanation for the slowdown in T removal.
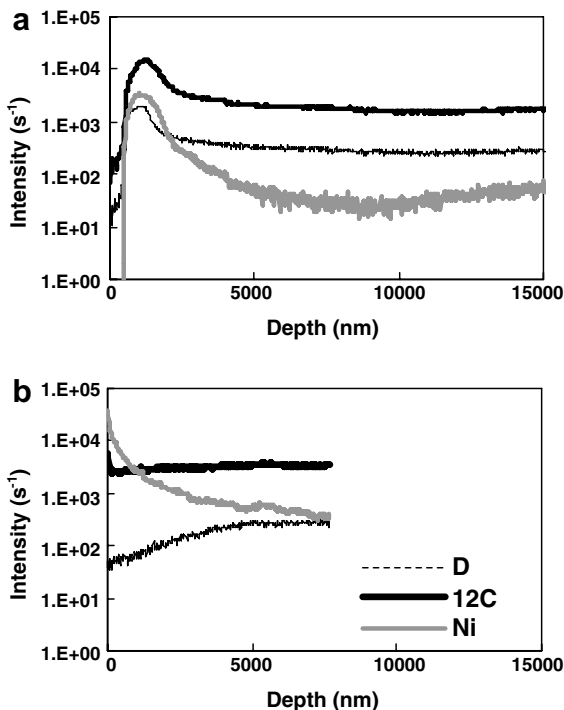

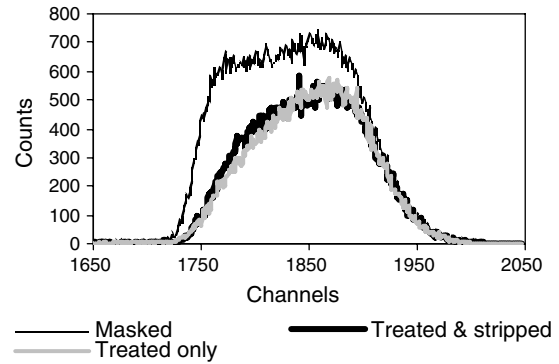Fig. 5. SIMS data for (a) untreated and (b) treated (un-stripped) areas on Tile 4.

Fig. 6. NRA results showing variation in deuterium peak shape from untreated and treated areas on Tile 4.

Fig. 6 shows an expansion of the D peaks obtained by NRA from a treated and an untreated area of the tile. A comparison shows that D is present at the surface for the untreated area whilst for the treated area the D edge is shifted towards higher energy indicating that D has been removed from the surface. For the untreated region a high D concentration is present to a depth of >7 μm (the sampling depth). However for the treated region less *D* is observed, showing that the D has been depleted beyond the sampling depth. Similar results are observed for SIMS analysis; in Fig. 5(a) the ratio of D/C remains constant throughout the profile whilst the ratio for the treated region in Fig. 5(b) increases with depth, i.e., the D level is depleted at the surface and slowly increases up to a depth of ~7.5 μm. At depths >7.5 μm the D/C ratio is expected to remain constant.

4. Discussion

The results show that deposits are removed from the tile surface at a rate of ~0.04 μm/pulse for an area of ~12×10^{-4} m^2, increasing to ~15×10^{-4} m^2 if the mask were removed. Based on these removal rates, and assuming a continuous operation of the flash-lamp at 500 J per pulse and frequency of 5 Hz, a 10 μm deposit would be removed at the rate of 0.06 m^2/h, this is lower than expected and in addition does not take account of the slowdown in T removal per pulse observed as the deposit is removed. Results from SIMS suggest that the slowdown in T removal is likely to be due to the accumulation of Ni, and other metallic species on the surface of the treated areas. The power density applied by the flash-lamp is unlikely to be sufficient for the removal of metallic impurities and at the current

removal rate of ~0.04 μm/pulse only a small amount of deposit would be required to have a significant effect on T removal rates. This implies that prolonged cleaning may result in the reduction of removal rates.

During the photon cleaning trials the deposited layer proved hard to remove; not only were the removal rates low compared to tests with polymeric films in the laboratory, but the stripping process did not remove significant material from the layer. Taking note of this, the thermal properties of the deposit, which have not been measured, were assumed to resemble those of plasma-deposited diamond-like carbon (DLC) films. These films are similarly hard to remove and have a H/C ratio close to that of the deposited layers in the shadowed region of Tile 4. The thermal properties (temperature dependant heat conductivity and heat capacity) and mass density of the DLC films were used to calculate the temperature profile into the deposit using a simple finite difference solution to the heat diffusion equation in 1D. A 1D solution was considered acceptable for this study as thermal gradients perpendicular to the surface were much larger than those parallel to the surface in any direction due to the Gaussian foot-print of the flash-lamp heat flux. For the maximum power density of 375 MW/m^2, surface temperatures in the range 1600 K to 2400 K were calculated. The 'bulk' temperature exceeds 700 K, high enough for the desorption of D and T, to a depth of ~8 μm – as observed in the NRA and SIMS results. However, the process for the removal of the deposit at these temperatures, where vaporisation is unlikely to play a significant role, is less clear and was not confirmed during these trials. Possible mechanisms include thermal shock, i.e., rapid expansion of the surface causing a shock wave, thermally enhanced chemical reaction of oxygen and hydrogen with the carbon deposit to form carbon dioxide and methane, and photo-chemical dissociation due to the UV component of the flash-lamp output [5]. Evidence of extensive thermal shock was not visible in the cross sections (Figs. 3(b) and 4(b)), which suggests that chemical reactions in air or UV driven dissociation were the more probable removal mechanisms during these trials.

Although the removal of D and T does occur by desorption, complete removal of the deposit from the tile surface is the desired way of reducing the T inventory. As only partial removal of the deposit occurs here, even higher temperatures at the tile surface would be required to increase the removal rate. This could be achieved with minor modifications to the current photon cleaning system so that lower energy pulses in rapid succession could be delivered to the tile surface. One advantage of using lower pulse energies would be to increase the lifetime of the flash-lamp by at least two orders of magnitude.

5. Conclusions

During the photon cleaning experiments it was shown that deposits were removed without leaving debris on the tile surface. Although removal rates were lower than anticipated, modification to the system would allow increased heating of the sample surface and consequently increase removal rates. It is suggested that the decrease in T removal rate with increasing pulse number could be due to the accumulation of Ni and other metallic species on the treated surface. Analysis of the concentration of metallic species at the treated surface compared to the untreated surface by particle induced X-ray emission and Rutherford backscattering would confirm this. However, with the increased surface heating proposed above, the complete removal of metallic species may also be possible which would allow the photon cleaning process to be performed without the need for mechanical intervention.

References

[1] G. Federici, C.H. Skinner, et al., Nucl. Fusion 41 (2001) 1967.
[2] J.P. Coad, M. Rubel, et al., Fusion Sci. Technol. 48 (2005) 551.
[3] C.H. Skinner, C.A. Gentile, et al., J. Nucl. Mater. 313–316 (2003) 496.
[4] J.P. Coad, P.L. Andrew, et al., J. Nucl. Mater. 313–316 (2003) 419.
[5] G.F. Counsell et al., EFDA Task TW1-TVP/CODEP, Final Report, November 2003, 63.