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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 in October 2004 in the beryllium handling facility on divertor base tiles. Early work confirmed that for pulse energies between 150J and 300J some deposited material was removed. To increase the amount of material removed during photon cleaning, further experiments with higher pulse energies (500J) were performed and are reported here. Analysis of cross sections confirmed a removal rate of 0.04μm/pulse, removing ~80μm from 200μm thick deposits over a treatment area of $15\times10^{-4}m^2$. 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 ~7μm beyond the depth of material removed.

1. INTRODUCTION

ITER is currently planning to use some carbon (C) target tiles in the divertor. Modelling suggests that carbon-based deposits will accumulate, trapping tritium [1]. An upper limit for tritium in the ITER vessel exists for safety reasons hence, tritium trapping in such deposits is of particular concern. In order to remain within the limit, it will be necessary to remove such accumulations periodically. Tritium (T) can be removed either by desorption as a gas, or removal of in-situ deposits. One method of achieving this is by photon cleaning, using either a laser [2] or a high power flash-lamp, as reported here.

The use of high power light sources for photon cleaning is already established in several non-fusion specialist cleaning roles. Such flash-lamps are capable of delivering several hundred Joules of ultraviolet, visible and infrared radiation in a pulse length of 100μs. When focused onto an area of several square centimetres, power densities up to several GW/m^2 can be achieved, comparable with lasers. However with a flash-lamp a much larger area is treated than a typical laser spot and it is therefore expected to significantly improve cleaning rates over laser-based approaches.

Trials of a photon cleaning unit were carried out in-vessel using remote handling at JET in May 2004 and further trials were completed in the beryllium handling facility (BeHF) at JET in October 2004. During the in-situ trials a range of pulse energies and repetition rates were used. For pulse energies from 150J to 300J, 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 results in the BeHF confirmed a significant release of T at these energies. At lower energies (<100J) 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 the floor tile at the inner corner of the divertor, part of which lies in the shadowed region where carbon-based films of

thickness 100μm or more, with high hydrogen-isotope content, are deposited [3]. This region is of particular relevance for ITER. 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 content [3]. 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 500J at 5Hz with a pulse width of 140μs was used for the detritiation trials. The flash-lamp was mounted in a truncated elliptical cavity protected by a 5mm 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 28mm. The photon cleaning unit and tile were situated in the slit box in the BeHF. The power supply unit and water recirculation unit for cooling the head were outside the BeHF and connected via a feedthrough manifold and 10metre long cables inside the BeHF. Due to the length of cabling and efficiency of the reflecting cavity ~35% of the flash-lamp energy was incident at the surface, with a maximum energy density of 0.06MJ/m^2. During cleaning, the T released from the tile was exhausted through a ventilation pipe from the slit box to the roof stack. Continuous measurements were made of the T content of the exhaust gas, from which 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.1). 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 treated region being reduced to 120mm from 150mm.

Each position was subject to a series of pulses from the flash-lamp. The number of pulses for positions 1 and 2 were 1500 and 2785 respectively. Typical settings were 500J per pulse at a frequency of 4Hz. The release of T per pulse was found to decrease with increasing number of pulses. The effect of this slowdown was likely to be due to the build-up of impurities on the surface or the break-up of the surface creating a thermal barrier. To investigate this, after ~2500 pulses at position 2, a section of the treated surface was stripped using adhesive tape before continuing with a further 285 pulses.

3. RESULTS

Cross sections from the untreated regions of Tile 4 are shown in Fig.2(a) and 3(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 (Fig.2(b), 3(b) and 3(c)). In particular, a darker layer visible ~30μm below the surface of the untreated sample has been removed in the treated samples. The cross sections show that the thicknesses of initial deposits were about 150μm for position 1 and 250μm for position 2. By comparing the difference in thickness between the untreated and treated regions the total amount of material removed was 70μm from position 1 and 90μm from position 2, ~40% of the deposit in the treated areas. From images taken at 1mm intervals across the treated region of position 2 the effective width of the light pulse was measured as 10mm, equating to a treated area

of $12\times10^{-4}m^2$. 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 0.05μm/pulse and 0.03μm/pulse respectively.

The total T removed from the tile was approximately 3GBq from a total area of $18\times10^{-4}m^2$ for positions 1 and 2. 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 ~24GBq was calculated, with 12% of the T inventory being removed by photon cleaning. However, this is likely to be an under-estimate of the percentage of T released, since the results reported here show that additional D (and therefore T) was desorbed from the surface beyond the depth of material actually removed. By way of a comparison, the activity of the shadowed region of the neighbouring tile, 3BW G4A, was determined by total combustion of a number of core samples cut from the tile. By calculating the surface area of the cores and extrapolating for the area of the shadowed region, an activity of 12GBq was calculated. In addition, values of 19GBq and 12GBq were obtained from offgas results, for tiles 3BW G4A and 3BW G4B, respectively. Measurements from calorimetry, however, gave activities for both tiles substantially higher than results reported here, 40GBq and 66GBq [4]. Thus the upper estimate of 24GBq for the T inventory of tile 3BW G4B determined from photon cleaning was within the range of previously measured values.

During cleaning, the release of T per pulse was found to decrease with increasing number of pulses. Two possible explanations for this slowdown were investigated. Firstly, that the break-up of the surface created a thermal barrier and secondly, that the build-up of impurities on the sample surface occurred as C and hydrogen (H) isotopes were removed. It was expected that the formation of a thermal barrier or impurities on the surface could be removed by stripping the surface using tape and subsequently increasing the amount of T released when photon cleaning resumed. The area stripped on the tile covered the central region of the shadowed surface, as shown in Fig. 1. After stripping, further photon cleaning was performed across the whole area of position 2 and an increase in the rate of removal from 0.23GBq/m^2/pulse to 0.53GBq/m^2/pulse was observed. The rate had also increased to approximately half the initial rate of removal (1.14GBq/m^2/pulse); which might be expected as less than half of the treated area had been stripped.

Cross sections of the un-stripped and stripped regions in Fig.3(b) and 3(c) show that the deposit on both samples is removed effectively by the light pulse. Within the resolution of the images, no visible difference between the un-stripped and stripped regions is observed. This suggests that a substantial thermal barrier (~10μm) of loose material was not produced during cleaning. Results from secondary ion mass spectroscopy (SIMS), however, show the presence of nickel (Ni) at the surface. Fig.4(a) and 4(b) show C, D and Ni depth profiles in the untreated and treated regions, respectively. Due to the presence of surface oxides on the untreated region the sample is prone to charging during SIMS analysis which affects the initial 1-2μm 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 efficiently during the photon cleaning process and consequently builds up on the surface. Such a build-up of Ni could result in the reduced T removal rate observed and subsequent removal of a Ni-rich layer by stripping could result in the recovery of the T removal rate.

Figure 5 shows an expansion of the D peaks obtained by Nuclear Reaction Analysis (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 >7μm (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.4(a) the ratio of D/C remains constant throughout the profile whilst the ratio for the treated region in Fig.4(b) increases with depth, i.e., the D level is depleted at the surface and slowly increases up to a depth of ~7.5μm. At > 7.5μm the D/C ratio is expected to remain constant.

DISCUSSION

The results show that deposits are removed from the tile surface at a rate of ~0.04μm/pulse for an area of $\sim 12\times10^{-4} m^2$, increasing to $\sim 15\times10^{-4} m^2$ if the mask were removed. Based on these removal rates, and assuming a continuous operation of the flashlamp at 500J per pulse and frequency of 5Hz, a 10μm deposit would be removed at the rate of $0.06 m^2$/hr. 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. The slowdown in T removal is likely to be due to build up of Ni, and other metallic species, in the treated areas (Fig.4). A Ni-rich layer could have a significant effect on the coupling of the pulse energy into the surface, thus decreasing the efficiency of material removal and T desorption. 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 ~0.04μm/pulse only a small amount of deposit would be required to have a significant effect on T removal. Thus extended cleaning may result in low removal rates.

During the photon cleaning trials the deposited layer proved hard to remove; not only were the removal rates low, but the stripping process did not strip significant material from the layer. Taking this into account, the thermal properties of hard carbon film (e.g. diamondlike carbon which has a similar H/C ratio as these deposits) were used to calculate the temperature profile using a 1D finite element model. For the maximum power density of $375 MW/m^2$, surface temperatures in the range 1600K to 2400K were calculated. The process for the removal of the deposit at these temperatures is not confirmed here, but could include thermal shock or chemical reaction. Possible mechanisms for material removal are discussed elsewhere [5]. The temperature of the surface remains above 700K, high enough for the desorption of D and T, to a depth of ~8μm. This supports the findings from NRA and SIMS showing desorption of D to depths >7μm. 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.

CONCLUSIONS

During these photon cleaning experiments it was shown that deposits were effectively 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 increased removal rates. It is suggested that the decrease in T removal rate with increasing pulse number could be due to the build-up of Ni, and other metallic species, on the tile surface. Further analysis of the tiles is required to confirm this.

ACKNOWLEDGEMENTS

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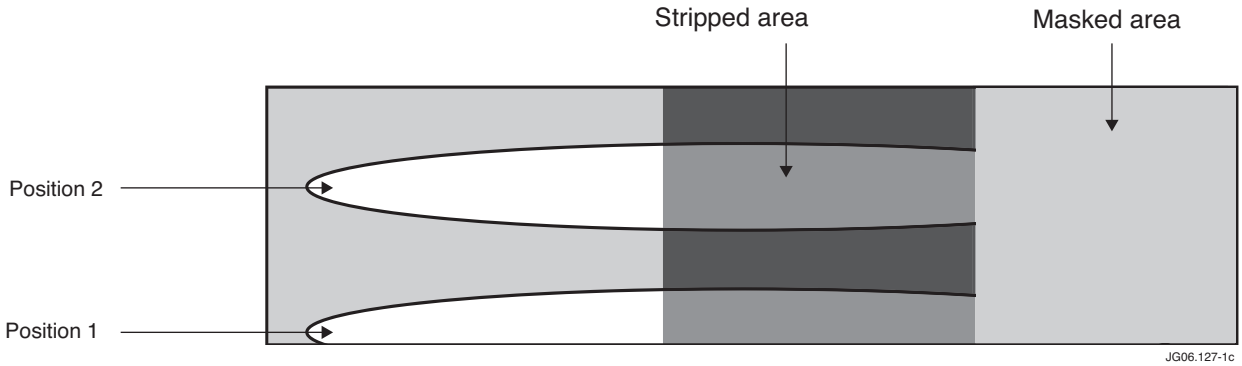

Figure 1. Schematic showing the regions treated on Tile 4 during photon cleaning.

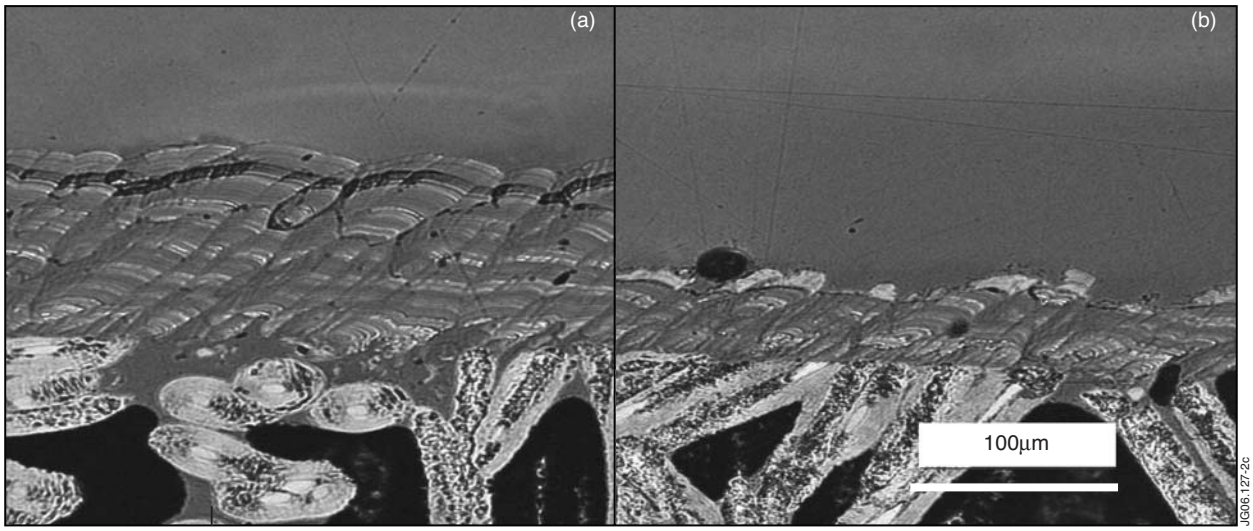

Figure 2. Cross sections showing deposits on (a) untreated and (b) treated regions at position 1 of Tile 4.

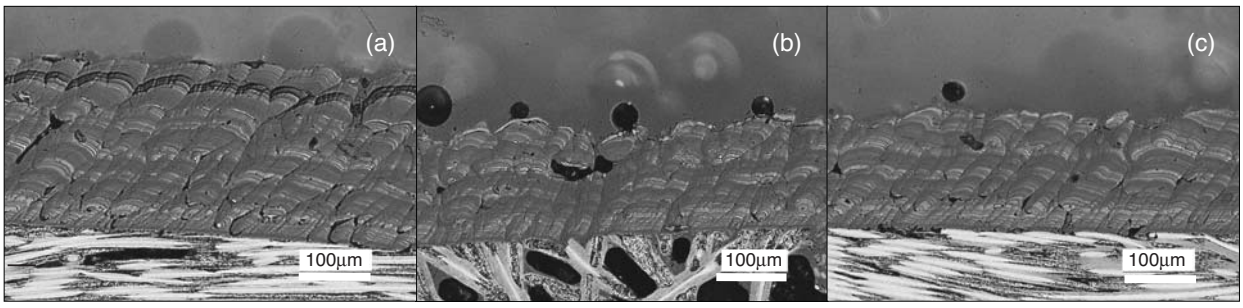

Figure 3. Cross sections showing deposits for un-stripped and stripped regions from position 2 on Tile 4. (a) Shows untreated region (b) shows the treated only region and (c) shows the treated and stripped region.

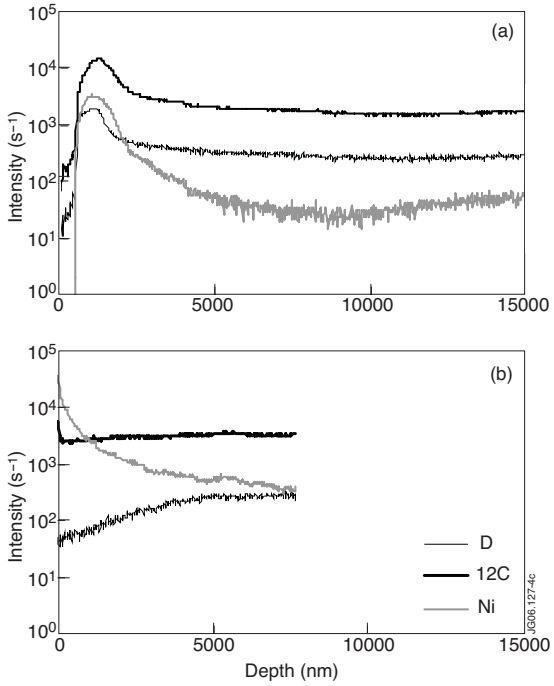

Figure 4. SIMS data for (a) untreated and (b) treated (un-stripped) areas on Tile 4.

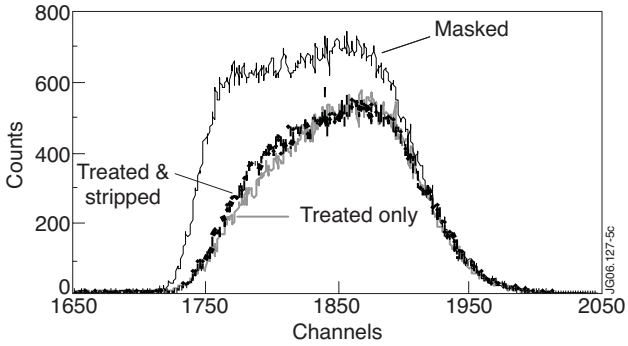

Figure 5. NRA results showing variation in deuterium peak shape from untreated and treated areas on Tile 4.