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ABSTRACT.

Fast and efficient tritium removal is needed for future DT machines with carbon plasma facing components. A novel method for tritium release has been demonstrated on codeposited layers on tiles retrieved from the Tokamak Fusion Test Reactor (TFTR) and from the Joint European Torus (JET). A scanning continuous wave Nd laser beam was focused to ≈100 W/mm^2 and scanned at high speed over the codeposits,heating them to temperatures ≈2000^{o}C for about 10ms in either air or argon atmospheres. Up to 87% of the codeposited tritium was thermally desorbed from the JET and TFTR samples. Fiber optic coupling between the laser and scanner was implemented. This technique appears to be a promising in situ method for tritium removal in a next step DT device as it does not rely on oxidation,and avoids the associated deconditioning of the plasma facing surfaces and the expense of processing large quantities of tritium oxide.

1. INTRODUCTION

Tritium removal from codeposited layers is a critical issue for next-step devices with carbon plasma facing components [1,2].While tritium removal has been demonstrated via glow discharges and air ventilation in TFTR [3,4]and JET [5],these methods are too slow for a next-step device. Oxidative techniques for removing H-isotopes have been used in TEXTOR [6],however in a next step device these will decondition the plasma facing surfaces,risk collateral damage of in-vessel components and require a large investment in the tritium plant to process the resulting tritium oxide. Heating tritiated codeposits with a rapidly scanning laser beam in vacuum or an inert atmosphere was proposed as a convenient way to thermally desorb tritium without the deleterious effects of oxidation [7]. Recent tabletop experiments with a scanning Nd laser have demonstrated efficient removal of tritium from TFTR tiles [8]. Some aspects of implementation in a next step tokamak are discussed in Ref. [9] and the thermal response of codeposits to high heat flux is further explored in [10,11]. In this paper we extend laser detritiation to laboratory experiments on JET tile samples from the DTE1 campaign.

2. EXPERIMENTAL SETUP

The overall aim of these experiments was to gain experience with laser detritiation of JET codeposits and to find conditions of optimal laser intensity and duration for tritium release with minimal surface change. The experimental setup (Fig.1) was fully reported in [8]. Briefly, a 325W continuous wave Nd laser beam is steered by two orthogonal mirrors and focused inside a chamber containing a tile sample. The laser spot can be scanned over a field of 75×75mm with a velocity of up to 2m/s. The spot trajectory is defined by programming the motion of the scan mirrors via a computer interface.

Typically,a serpentine raster pattern with line spacing 0.5mm is used to cover the tile surface. An area of 5cm^2/s or 2 m^2/h can be scanned at a speed of 1m/s.The laser spot is 1.6mm diameter (FWHM), so a given location on the tile surface experiences first the fringe of the laser spot,then the center,then the fringe in successive passes. At a scan speed of 1m/s the duration of the heat pulse is 1.6ms (FWHM). At maximum laser power on target (257W,128 W/mm^2) the energy incident in one pass at 1m/s is 0.2 MJ/m^2. A pyrometer measures surface temperatures in the range 500–2300^{o}C with 0.3ms

time resolution,and averages over a 0.7mm area on the tile surface. Previous work [8] has showed the presence of ≈0.1mm 'hot spots' due to microstructures in the codeposit. Before and after laser irradiation the tile surface is photographed by a digital microscope to record any changes in the surface. Released tritium was circulated in a closed loop to an ion chamber that measured the tritium concentration. Results from TFTR tiles [8] showed a major fraction of the tritium was desorbed with minimal changes to the tile surface at a laser intensity of 80W/mm^2 and heating duration 10–20ms. The temperature rise of the TFTR codeposits was much higher than that of the manufactured tile material (e.g. 1770^{o}C cf.1080^{o}C) indicating a significantly lower thermal conductivity for the codeposits [10,11].

For tokamak applications it is advantageous to fiber optically couple the beam from an external laser to an in-vessel scanner. Fiber optic coupling of the laser to the scanner also smoothes any spatial inhomogeneities in the focal spot. In situ laser detritiation is proposed for the poloidal limiter tiles inside the JET vessel during the 2004 shutdown when the vessel would contain air and both air and argon atmospheres were used in the laboratory experiments. For some of the laboratory experiments the laser beam was coupled to the scanner via an armor jacketed 5m long, 600μm fused silica fiber with antireflection coatings on the fiber ends. The maximum power delivered to the tile sample was 257W. The complete spatial profile of the focal spot was measured at full laser power by scanning the beam over a 35 l pinhole on gold plated copper disk placed at the same position as the tile samples.The transmitted light was measured with a PIN diode. The full width at half maximum was 1.6mm. Previous estimates of both the fiber coupled case and direct coupled case were made by measuring the mark made by a stationary spot on a tile and were 1.8mm for the fiber optic case and 2mm for the direct coupled case (slightly defocused).A comparison of the thermal response of TFTR cube KB13-13E-Z2 irradiated at 93W/mm^2 ,scan speed 1m/s with the new fiber optic coupling,to TFTR cube KC17-1C-Z3 irradiated at an estimated 80W/mm^2, scan speed 1m/s with direct coupling between the laser and scanner, showed a temperature rise of 2017^{o}C with the fiber optic cf.1682^{o}C and tritium release of 1.5 mCi/cm^2 cf.2.3mCi/cm^2. These differences are within the variation experienced from different samples.In both these cases the codeposit appeared to be undisturbed with a small darkening in color.

3. LASER SCANNING EXPERIMENTS

A total of seven samples from JET were irradiated by the laser.These were 2cm diameter cylinders cut from carbon fiber composite divertor tiles and a graphite poloidal limiter tile. The samples were from the plasma facing side of the inner divertor vertical tile (IN3-cylinder 16), the bottom edge of this tile at the entrance to the louvers (IN3-15,(this area had a very high tritium concentration));the inner base divertor tile 4 (1BN4 –8, 1BN4 –9,1BN4 –10); the outboard base divertor tile (1BN7–15) and poloidal limiter 4B (PL4B7top-6). The plasma facing surface was typically divided into four zones that were irradiated separately at different laser power and scan speeds.The samples showed a wide variety of erosion and deposition conditions,even on the same sample and in some areas the deposited layer had flaked off. Tritium depth profiles [12] and surface analyses [13] for JET tiles have been reported previously.In comparison,the TFTR samples reported in [8]were from three tiles on the inner limiter,the codeposits were more homogeneous and without flaking.

3.1.TEMPERATURE RESPONSE OF JET SAMPLES

The most conspicuous feature of response of the JET samples was the much higher temperature increase for codeposits compared to the bare tile material,as was the case for the TFTR samples.The peak temperature for the codeposited area on PL4B7top-6 was 1790^{o}C compared to a much lower peak temperature of 1195^{o}C on an adjacent 'bare' spot where the codeposit had flaked off (both scans 80W/mm^2 at 1m/s).Generally tritium was released from both TFTR and JET samples at temperatures above 1500^{o}C A precise temperature threshold was diffcult to identify since the temperature depended strongly on the surface topography,which varied across a single sample.Often the peak temperature of JET samples exceeded 2300^{o}C the upper limit of the pyrometer.

The temperature time history varied significantly with the surface morphology. Fig.2 compares the response of two samples cut from the same inner base divertor tile and both exposed to similar laser power (80 and 74W/mm^2) and scan speed of 1m/s.1BN4-8-4L is from an erosion area in the strike point region and shows a 5ms duration temperature excursion to 1434. Sample 1BN4-9-z2.1 is 107 mm away but shadowed from plasma flux by tile 3. The pyrometer viewed the deposit on the surface of 1BN4 –9. The temperature rose to over 2300^{o}C (the limit for the pyrometer) and the duration of the temperature excursion was extended to ≈30ms.The deposit appears to be less thermally conductive and/or not in good thermal contact with the substrate (for more details see Ref.[11]). The dramatically different peak temperatures for the same heat flux illustrate the difficulty of deducing heat flux from measurements of surface temperature rise during ELMs in tokamaks [14].

3.2.TRITIUM RELEASE

The high surface temperatures readily released tritium from the deposited layers.The area of heavy deposition on the bottom edge of tile 3 (IN3-15)released 71 mCi/cm 2 (2.4 GBq/cm^2). In contrast,the erosion area on the vertical plasma facing side of the same tile (IN3- 16) released only 0.25 mCi/cm^2 (9MBq/cm^2). For deposition areas,repeating a laser scan yielded an additional 10–15% more tritium.While not a large amount,this is a significant fraction of the tritium remaining and so repeating a scan is worthwhile to maximize the detritiation efficiency. Tritium remaining in the deposited layer after the laser scan,was released by baking the sample in an air atmosphere. To do this the laser spot was defocused and remained stationary on the sample surface,which was heated to ≈500^{o}C. The residual tritium was released within 5 –10 min. Previous work including [15]has shown that baking to 500 air releases nearly all codeposited tritium. Fig.3 shows all the results for JET and TFTR samples scanned under a variety of conditions.The detritiation efficiency (ratio of tritium released by the laser scan to the total released in the scan and bake)was high in the deposition regions where most of the tritium is located and reached 87% for PL4B7top-6.

The atmosphere inside the chamber is circulated continuously. It is clearly important to check for reabsorption, for example by isotope exchange with water on the interior chamber surface or reabsorption back into the graphite, that could hinder pumping tritium out of a next step device. Fig.4 shows the tritium concentration after a laser scan in an argon and air atmosphere.After an initial

transient there is very little reabsorption. The atmosphere inside JET during the shutdown is air, which is exchanged every hour. On this time scale nearly all of the tritium remained in gaseous form and could be pumped out. A second issue is the potential for tritium to be driven deeper into the tile by the laser heating. This would be unlikely on a millisecond time scale and we note previous work showed that heating a JET tile to 460 for 1 h did not cause tritium to diffuse deeper into the tile [16].

The effect on the surface of the intense heat of the laser was small at the fast scan speeds used (1 ms, 0.2 MJ/m^2 incident energy) as was the case for TFTR samples. The surface changes from a brownish hue to dark gray but the codeposit was still intact even though the surface temperature briefly exceeded 2300^{o}C (Fig.5).Thick friable codeposits such as at the base edge of inner divertor tile 3 change appearance somewhat on laser scanning.Sample IN3-16 is of interest as a material –the surface has comparable Be and C concentrations [13]. Here the surface layer after laser exposure became a pattern of 100μm beads. This sample showed low tritium release (0.25mCi/cm^2, 9MBq/cm^2) and,unlike the other samples,the tritium concentration in the chamber rose slowly and continuously during the bake.Mixed material issues add significant uncertainty to predictions of the behavior of tokamak materials and more investigations using tokamak-generated materials are needed.

SUMMARY

Laser detritiation was able to release up to 87% of the tritium trapped in codeposits on JET tiles,similar to the results from TFTR samples. Fiber optic coupling between the laser and scanner was implemented and three samples were scanned in an air atmosphere to mimic the situation during the JET shutdown. The temperature rise and fraction of tritium released was reduced in erosion areas,but the tritium inventory in such areas is small. The detritiation efficiency was highest in deposition regions with high tritium concentrations. The sample-to-sample variability of the JET samples makes it difficult to make precise comparisons with the TFTR samples. For JET samples the temperature excursions on regions of heavy deposition often exceeded 2300^{o}C and showed a protracted ‘ragged’ character possibly indicating burn up of dust from a more friable codeposit and/or chemical reactions with oxides present in the tiles [11]. The experience to date has shown that this technique is very promising for the removal of tritium from next step devices and an engineering scale demonstration during the JET 2004 shutdown has been proposed.

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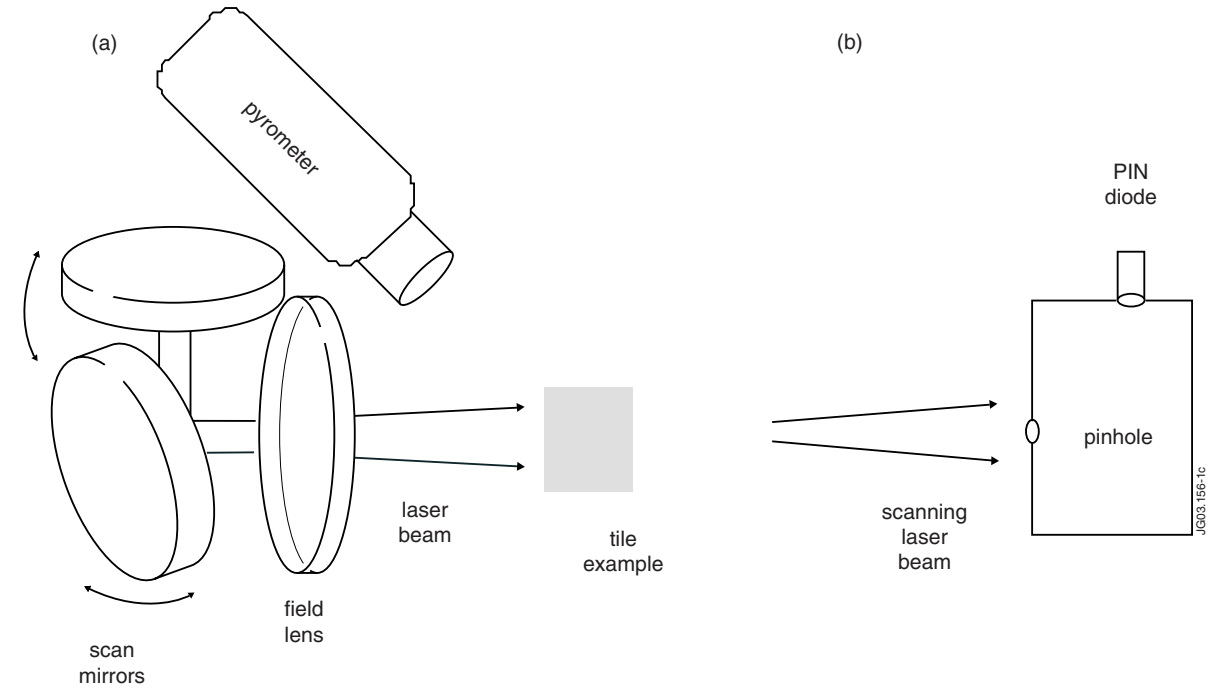

Figure 1: Experimental Setup.

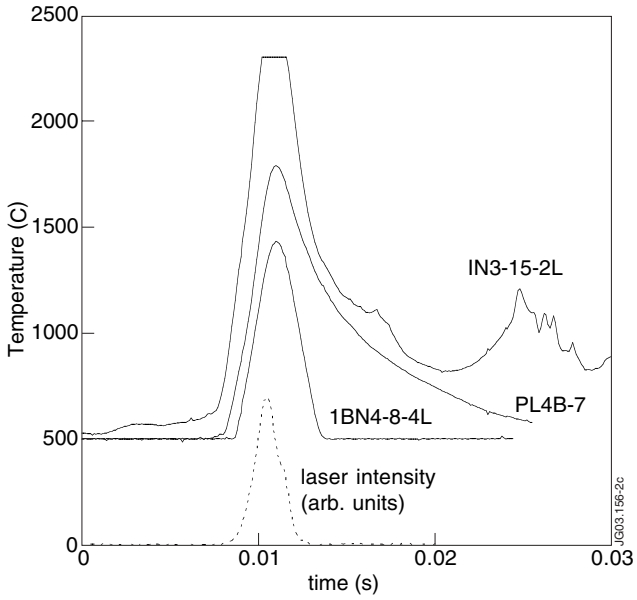

Figure 2: Temperature response of deoosition region 1BN4-9-z2.1 (upper curve) and erosion area IBN4-8-4L (lower curve) to two successive passes of the laser spot. The laser time history (measured separately) is shown dotted. The pyrometer operates in the region 500 – 2300°C.

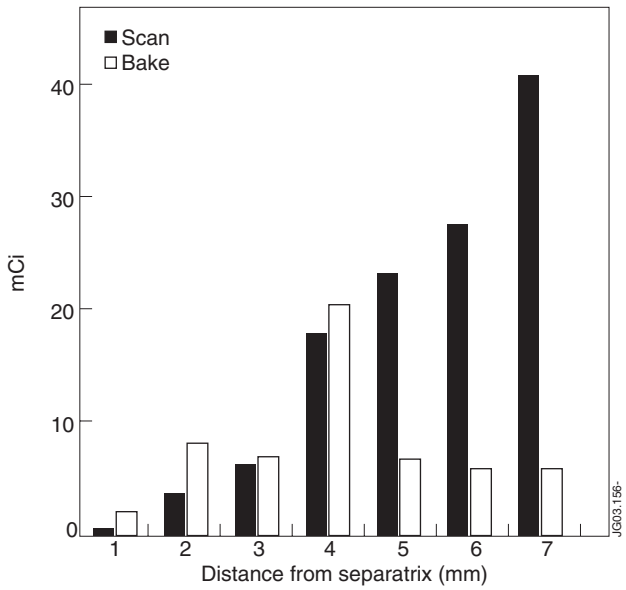

Figure 3: Tritium released by laser scanning and the subsequent bake in air for samples from JET and TFTR.A variety of scan conditions were used,some not yet optimal. Nonetheless the results illustrate that the detritiation efficiency is high at the locations with the highest concentrations of tritium. The column labels from 1 –7 correspond to:
JET:IN3-16, JET:1BN4-8, JET:1BN7-15, TFTR:KC22-6E, JET:1BN4-9, TFTR:KC22-6C, JET:PL4B-7 (top).

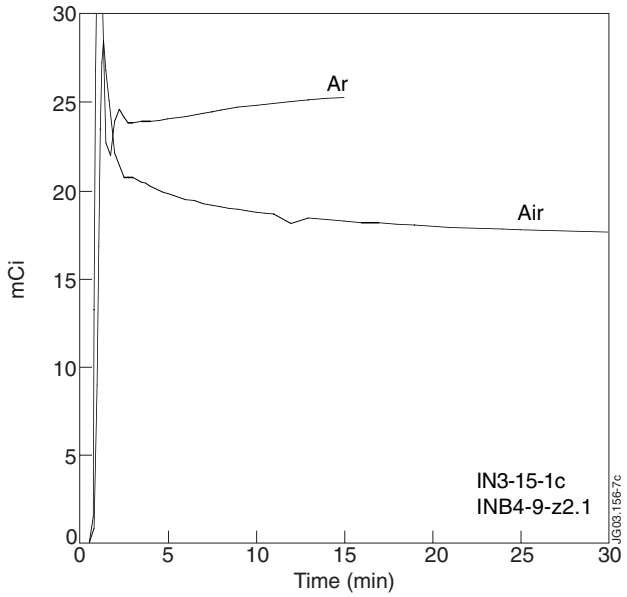

Figure 4: Tritium concentration vs.time after laser scan in argon atmosphere (IN3-15-1c)and air (INB4-9-z2.1).

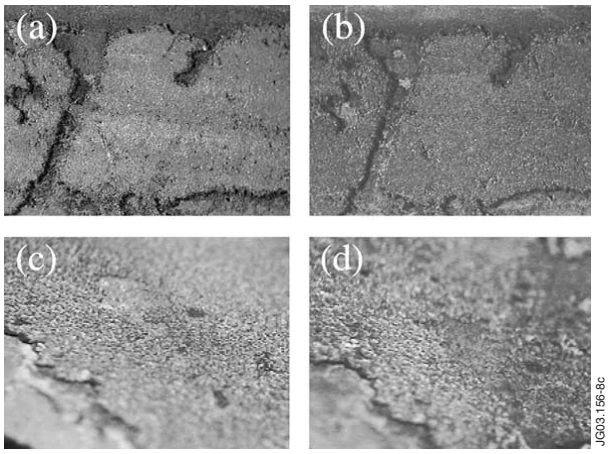

Figure 5: Images of the tile surface of sample 1BN4-9 before (a) and after (b) two laser scans at 1m/s,128W/mm^2 in air, peak temperature >2300^{o}C and PL4B7top-6 before (c) and after, (d) three laser scans at 1m/s,80 W/mm 2 in argon, peak temperature 2082^{o}C. Images (a) and (b)were taken at normal incidence, (c) and (d) at 45^{o}C. Each image covers 9.6mm in the horizontal direction.