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** See annex of F. Romanelli et al, "Overview of JET Results",*
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## ABSTRACT

Erosion of a tungsten marker coating and deposition on JET divertor tiles used during the experimental campaign 2007-2009 and on Inner Wall Guard Limiter (IWGL) tiles used 2004-2009 were determined. The tungsten coating of the divertor tiles was mostly intact with the largest erosion being about 30%. Local high erosion areas were observed on the load bearing divertor tile 5 and on divertor tile 8. The IWGL tiles showed a complicated distribution of erosion and deposition areas. The total amount of carbon deposited on the all IWGL tiles during the campaign 2004-2009 was estimated to be 65g.


## 1. INTRODUCTION

Erosion of Plasma Facing Materials (PFM) and subsequent re-deposition are critical processes for the operation of fusion devices. Erosion determines the lifetime of Plasma Facing Components (PFCs), re-deposition of eroded material on PFCs and in shadowed areas may lead to an increase of the tritium inventory. During the investigated experimental campaigns JET was operating as a full carbon machine with regular beryllium evaporations.

Erosion of a tungsten marker and deposition of carbon and beryllium were investigated on selected outer divertor tiles exposed 2007-2009 and on Inner Wall Guard Limiter (IWGL) tiles exposed 2004-2009 by means of Rutherford Backscattering Spectroscopy (RBS).

## 2. EXPERIMENTAL

### *2.1. DIVERTOR TILES*

One Load Bearing Tile (LBT), type LBT14-RW, and tiles G7B and G8A from the vertical outer divertor have been analyzed. Their positions are shown on fig. 1. The tiles were installed in the divertor from 2007 to 2009. The tiles consist from CFC and were coated with a W/Re multilayer using Physical Vapor Deposition (PVD). The nominal thicknesses of the coating were 6μm Re + 2μm W + 2μm Re + 4μm W, in total 14μm. W and Re cannot be distinguished in RBS and have almost identical stopping powers and kinematics, so that they were approximated by one single thick W layer. These coatings were not pre-characterized by RBS, but their thicknesses were determined by scanning electron microscopy of cross-sections deposited on witness samples.

### *2.2. LIMITER TILES*

Two IWGL tiles, 3X11L and 3X11R have been analyzed. The tiles were exposed in JET from 2004 to 2009. The tiles were made from CFC. Before installation in JET they were coated by a tungsten and a carbon marker stripe. The thicknesses of the markers have been measured using RBS before their installation in JET. The tungsten marker consisted of a W layer with a thickness of $2\times10^{19}$ atoms/cm$^2$ (about 3μm). The carbon marker consisted of a thin W layer with a thickness of $6\times10^{18}$ atoms/cm$^2$ thick and a C layer with a thickness of $1\times10^{20}$ atoms/cm$^2$ on the top. The W layer marked the initial CFC surface.

### 2.3. RBS ANALYSIS

The tiles were analyzed using RBS in the BOMBARDINO facility at IPP Garching. The analysis was performed using 4.5MeV $H^+$ ions with the detector positioned at 165° in the laboratory measurement system. This energy was chosen to achieve the depth of analysis larger than the thickness of the W-Re layer on the divertor tiles. For limiter tiles the ion energy was the same to avoid additional calibrations of the proton detector. Each measurement was conducted with 5μC of accumulated charge of ion current. The spectra obtained were analyzed using the SIMNRA program [1]. SRIM 2010 stopping powers and non-Rutherford backscattering cross-section data from [2-4] were used for $^{12}C$, $^{13}C$, $^{16}O$, respectively.

## 3. RESULTS AND DISCUSSION

### *3.1. DIVERTOR TILES*

The distribution of erosion and depositions areas on the measured tiles is shown in Fig.1. The W coating remained intact in most areas of the analysed tiles. The remaining thickness of the W-Re multilayer was $1.1\times10^{20}$ atoms/cm$^2$ on average. This number is very close to the nominal initial thickness of the W coating, i.e. the tungsten erosion was low in this area.

The central part of the LBT tile with a width of about 4cm is an area of intense erosion. RBS spectra from this area show characteristics of intense inhomogeneous erosion [5] of up to 30% of the initial coating thickness. The average thickness of the remaining tungsten coating is $8.8\times10^{19}$atoms/cm$^2$ in this area. Due to ambiguities between inhomogeneous erosion and carbide formation in the interpretation of RBS spectra the interpretation of inhomogeneous erosion still requires confirmation by scanning electron microscopy.

The outer area of the LBT tile is an area of small deposition. Both carbon and oxygen were detected on the surface of the tiles on top of the W coating with amounts of up to $2.6\times10^{19}$ atoms/cm$^2$ of C and $2\times10^{18}$ atoms/cm$^2$ of O. This area is 6cm wide and continues to the end of the tile.

In the lowermost area of tile G7B, $^{13}C$ depositions have been detected up to $1.5\times10^{18}$ atoms/cm$^2$. $^{13}C$ originates from the injection of a $^{13}CH_4$ tracer at the end of the campaign. The area where $^{13}C$ depositions are detected is 6 cm wide. The area of $^{13}C$ deposition is also an area of W erosion with average amount of W in it being $1\times10^{20}$ atoms/cm$^2$. The distribution of $^{13}C$ on the surface of the tile does not fully correspond to the distribution of $^{12}C$.

The middle area of tile G7B is an area of W erosion. The intensity of erosion increases in the downward direction. The thickness of the remaining W layer goes down from $1.2\times10^{20}$ atoms/cm$^2$ to $1\times10^{20}$ atoms/cm$^2$. This area is 4cm wide.

Only the top surface of G8A tile shows signs of intense, inhomogeneous erosion, similar to the central area of LBT. The erosion intensity increases to the separation line between two G8N surfaces with the thickness of the remaining W layer $1.1\times10^{20}$ decreasing from atoms/cm$^2$ at the farthest point from the separation line to $7.6\times10^{19}$ atoms/cm$^2$ at the separation line. Other surfaces of the tile show low levels of erosion that disappear in the downward direction.

### *3.2. IWGL TILES.*

The IWGL tiles showed a complicated distribution of erosion and deposition areas, a schematic map of the distribution of these areas is shown in Fig.2. On both tiles the carbon marker stripe has totally disappeared in all areas close to the plasma. Most probably this is not due to erosion, but due to delamination of the stripe.

The outermost areas of the limiter tiles, which are farthest away from the plasma, are the least affected. They show only very small modifications by the plasma operation (Fig.3). On the 3X11L tile this area is 3cm wide; on 3X11R this area is 4cm wide.

The areas close to the plasma are areas of intense erosion. The tungsten marker stripes were almost totally eroded with only very small amounts of tungsten remaining (remaining W was below $9.7\times10^{17}$ atoms/cm$^2$ for 3X11L tile and $4\times10^{18}$ atoms/cm$^2$ for 3X11R). On the 3X11L tile this area is 5cm wide; on 3X11R tile this area is 3 cm wide and continues till the end of the tile. The observed large erosion is in qualitative agreement with profiler measurements of the tiles [7], which indicated also a large carbon erosion in these areas.

On the 3X11L tile, there is an additional area of deposition about 3 cm wide in the central part of the tile, where the IWGL tiles have a small recessed area. The maximum amount of C detected on the surface of the W marker stripe is $2\times10^{19}$ atoms/cm$^2$ in this area. Similar central deposition areas have been previously observed in [6] and were qualitatively explained by the recess in the central part of thetiles.

Between the areas of intense erosion close to the plasma and the areas with little modifications far from the plasma areas with intense deposition are observed. Carbon deposits up to $2.3\times10^{20}$atoms/cm$^2$ on tile 3X11L tile and $9.6\times10^{19}$ atoms/cm$^2$ on tile 3X11R were detected using RBS. Using optical microscopy of tile cross-sections films of up to 48μm have been observed, see Fig.4. RBS and optical microscopy show very similar thickness profiles of the deposits Combining RBS data in atoms/cm$^2$ and optical microscopy data in μm is a direct measure of the density of the deposited film, which is 0.67-0.83g/cm$^3$. The concentration of beryllium in the deposited films was below the detection limit of RBS. On the 3X11L tile this area is 3cm wide; on 3X11R tile this area is 5cm wide.

The amount of carbon deposited on the surface of the analyzed limiter tiles can be extrapolated to the whole surface area of the IWGLs. assuming the same amount of deposition on all tiles. During the experimental campaign 2004-2009 in total 65g carbon were deposited on the deposition dominated areas of the IWGL limiters. This is in good agreement with profiler measurements of IWGL tiles after the 2007-2009 campaign, which gave a carbon deposition of 35g in the deposition dominated areas [7]. Despite the observed carbon deposition in the deposition dominated areas it should be noted that the IWGL tiles are a net carbon erosion area, because the erosion in the erosion-dominated areas exceeds the deposition in the deposition-dominated areas [7].

## CONCLUSIONS

Erosion of tungsten marker layers and deposition were investigated on JET outer divertor tiles exposed during the discharge period 2007-2009 and on Inner Wall gGuard Limiter tiles (IWGLs) exposed during the period 2004-2009.

On most areas of the divertor tiles only a small erosion of the tungsten coating was observed. Exceptions are several areas of intense erosion: On the central area of the load-bearing tile 5 (LBT tile) intense and probably inhomogeneous erosion has been observed.

Here about 30% of the initial coating thickness were eroded. Another intense erosion area is the horizontal part of the G8A tile.

Some small deposition was observed in several areas. The outermost area of the LBT tile shows carbon deposition up to $2.6\times10^{19}$ atoms/cm$^2$. $^{13}$C deposits have been detected in the lower 6cm wide area of G7B tile with up to $1.5\times10^{18}$ atoms/cm$^2$.

A complicated distribution of net erosion and deposition areas is observed on the IWGL tiles. A central area of small deposition is observed in the recessed part of tile 3X11L, followed by a strong net erosion area where even the tungsten marker stripe was fully eroded. In the following net deposition area deposits with thicknesses up to 48μm are observed. The total amount of carbon deposited in the deposition-dominated areas of the IWGLs in the experimental campaign of 2004-2009 has been estimated to be 65g. These findings are in good agreement with results from tile profilometry presented in [7].

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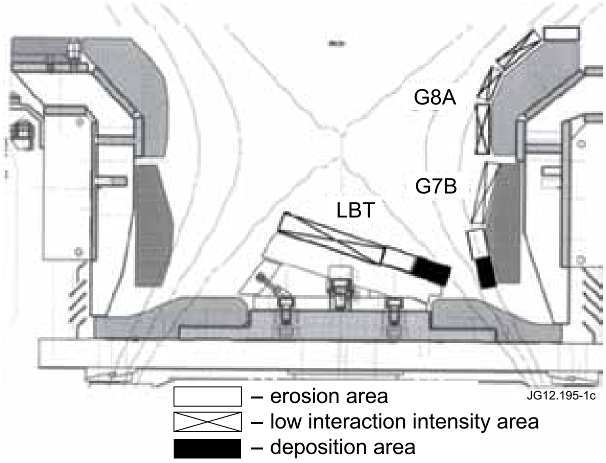


*Figure 1: Positions of measured divertor tiles and a qualitative map of the distribution of erosion and deposition areas.*

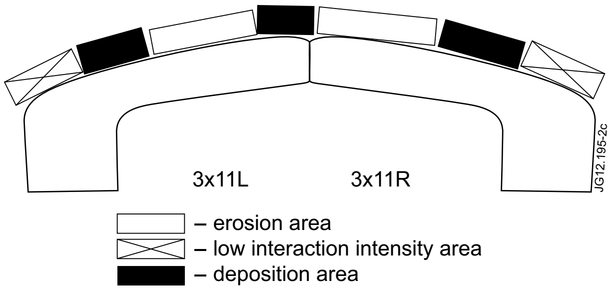


*Figure 2: Qualitative mMap of erosion and deposition areas on the pair of inner wall guard limiter tiles.*

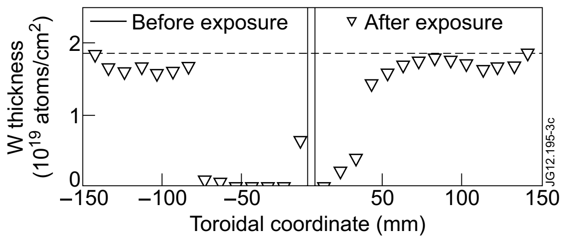


*Figure 3: Initial W marker stripe thicknesses (dashed line) and remaining thicknesses after exposure (hollow triangles) vs. the distance to the tile borders for the left and right inner limiter tiles. Solid lines indicate borders between left and right tiles.*

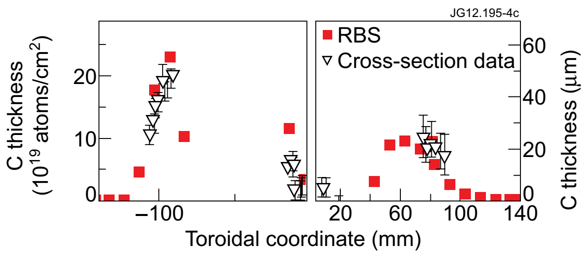


*Figure 4: Thicknesses of carbon deposits on the W stripe marker after exposure vs. the distance to the tile borders for the left and right inner limiter tiles. Solid lines indicate borders between left and right tiles. Cross-section data were obtained by optical microscopy.*