

## Deposition and Fuel inventory in the castellated structure of beryllium limiters after campaigns in JET with the ITER-Like Wall

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### Introduction

Castellated structure of plasma-facing components (PFC) is deemed as the best solution to ensure thermo-mechanical durability and integrity under high power loads. Narrow grooves of castellation and gaps between tiles are areas in which deposition may take place. Therefore, the assessment of fuel inventory is one of main concerns for ITER where all PFC will be castellated. Joint European Torus (JET) is the only tokamak in which large scale tests of castellated structures were carried out already in the carbon-wall machine in nineties of the 20<sup>th</sup> century: [1-4]. A large scale test in the metal surrounding has been carried out since year 2011 at the JET with the ITER-Like Wall (JET-ILW): castellated beryllium limiters and lamellae-type bulk tungsten divertor tiles. This contribution is focused on the morphology of beryllium limiters after two campaigns in JET-ILW: 2011-2012 and 2013-2014, both about 19.5 h of plasma discharges including approx. 13 h of limiter and 6.5 h of X-point operation. The emphasis is on: (i) material mixing on plasma-facing surfaces; (ii) fuel inventory and deposition inside 0.4 mm wide grooves of the castellation, i.e. on surfaces located in the gaps.

### Experimental

To facilitate studies of the castellated structures, the limiter blocks were sectioned into smaller specimens: single castellation pieces, i.e. typically 12x12x12 mm. Cutting was carried out at NILPRP under a strict control of tile temperature (below 60 °C) in order to avoid the release of hydrogen isotopes, because thermal desorption was planned on some samples. In general the cutting was done approximately 0.5 mm above the bottom of the castellated groove, but in a few cases cutting was performed approx. 0.5 mm below the castellation. The latter samples were then split to expose entire surfaces located in the groove.

The analyses described below were performed by means of: (a) X-ray diffraction (XRD) in order to determine the phase composition of limiter surfaces; (b) micro ion beam analysis (IBA) techniques (lateral resolution of 8-10 µm) such as nuclear reaction analysis (µ-NRA) to determine the content of deuterium and particle-induced X-ray emission (µ-PIXE) to quantify the content of metals (Inconel components: Ni, Cr, Fe and W) inside the castellation. From the top of the castellated groove several consecutive regions, 1.8x1.8 mm, were scanned. Results from a given region were averaged to obtain a line scan and this procedure was repeated for all analysed regions. Poloidal and toroidal gaps from all major types of limiters have been studied with IBA: inner wall guard (IWGL), outer poloidal (OPL) and upper dump plates (UDP). For comparison also side surfaces of the bulk tungsten lamellae from the JET-ILW divertor (Tile 5) were analysed.

## Results and discussion

A whole limiter tile after the exposure in JET-ILW is presented in Fig. 1(a) while plots in Fig. 1(b) show diffractograms recorded for a reference Be target and in the deposition and erosion zones of the limiter. The results clearly prove that some Be-W intermetallic compounds ( $\text{Be}_2\text{W}$ ,  $\text{Be}_{12}\text{W}$ ,  $\text{Be}_{22}\text{W}$ ) were formed in the deposition zone. The erosion zone contains only metallic Be; the diffractogram has the same features as the reference sample. The latter result is perceived as a positive one: no compound formation in the erosion zone indicates that no changes in thermo-mechanical properties of Be PFC might be expected.

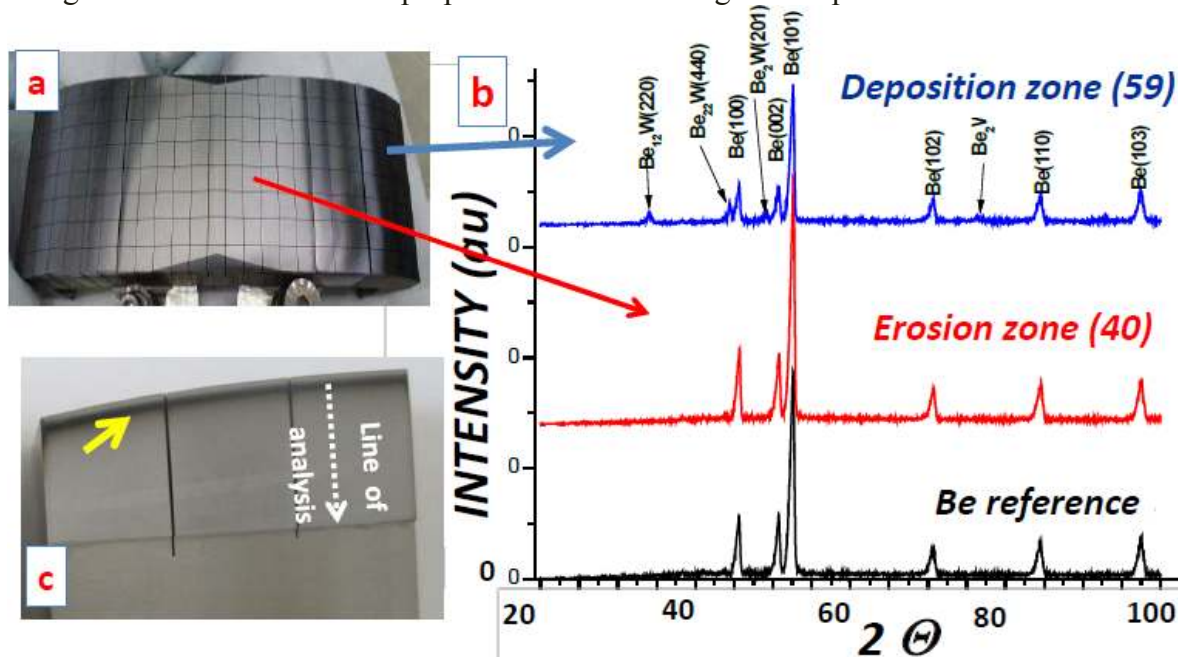


Fig.1. (a) Castellated beryllium limiter tile from JET-ILW; (b) X-ray diffractograms. (c) side of a sectioned tile.

In Fig. 1(c) one perceives a narrow deposition belt, marked with a yellow arrow, in the top part of the tile, i.e. at the very entrance to the castellated groove. Micro-IBA was performed for more than 70 specimens from top to the bottom of the gap. Plots in Fig. 2 show representative deposition profiles of deuterium and metals (features magnified by a factor of 1000) in a toroidal gap of the IWGL (first ILW campaign 2011-2012). The deposition width of deuterium is approximately 1 mm and this is characteristic for all recorded profiles. The profile has a characteristic fine structure: (i) low D content at the very entrance to the gap, (ii) increase of the concentration with maximum reached at about 0.5 mm and then sharp decrease. Plots in Fig. 3 show a comparison of deposition in two perpendicular gaps, toroidal and poloidal, on the same specimen from the OPL. Differences are insignificant both in the shape of profiles and the deuterium content. Also the content of nickel from Inconel eroded from the wall is very small: well below  $1 \times 10^{15} \text{ cm}^{-2}$ , while the level of tungsten does not exceed  $2 \times 10^{13} \text{ cm}^{-2}$ .

Most measured profiles are qualitatively and quantitatively very similar to those presented in Fig. 2 and 3. There are a few different cases: (i) flat profiles with a very small D content, below  $1 \times 10^{17} \text{ cm}^{-2}$ ; (ii) very narrow profiles, less than 0.5 mm, peaked at  $1 \times 10^{19} \text{ cm}^{-2}$ . The latter is presented in Fig. 4, which shows a deposition from the top to the very bottom of the castellated groove. The measurement was performed in order to verify the hypothesis on the deposition at the bottom which serves as the ultimately trap for neutrals which either entered the gap at right angle or reached the bottom as consequence of multiple reflections. Indeed, a small and narrow peak is detected at the bottom, but the deuterium content is very low. It is,

therefore, not decisive for the overall inventory. It should also be stressed that the amount of carbon is very low thus confirming small amount of carbon impurities in JET-ILW.

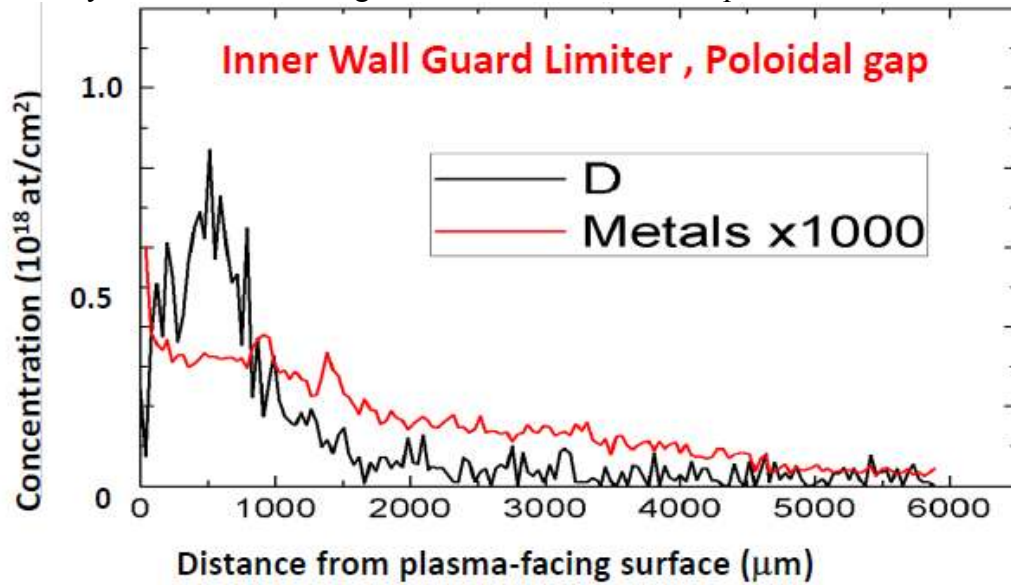


Fig.2. Deposition profiles of deuterium and metals inside the castellated groove of a Be limiter.

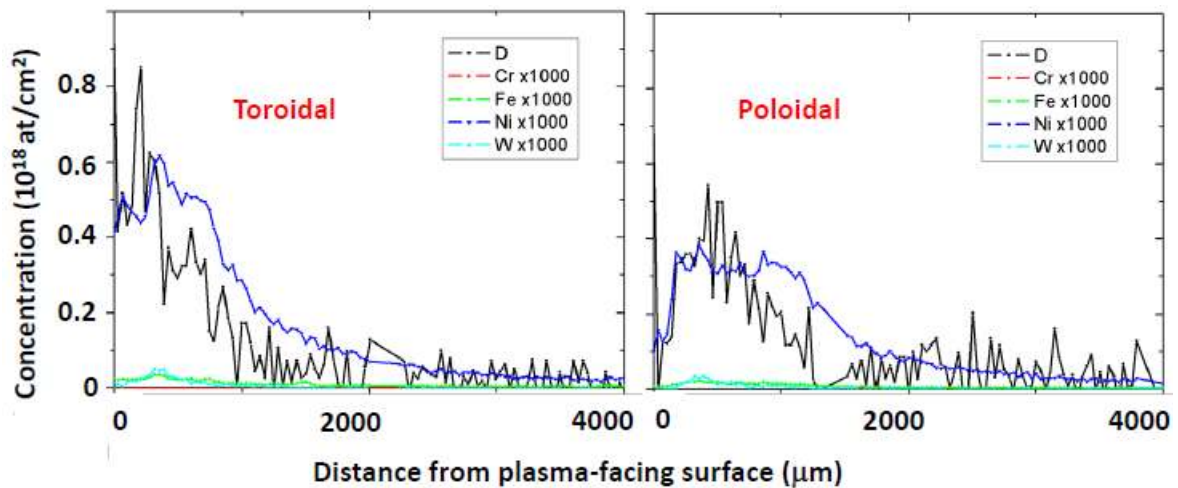


Fig.3. Deposition profiles of deuterium and metals in two perpendicular gaps of the outer poloidal limiter.

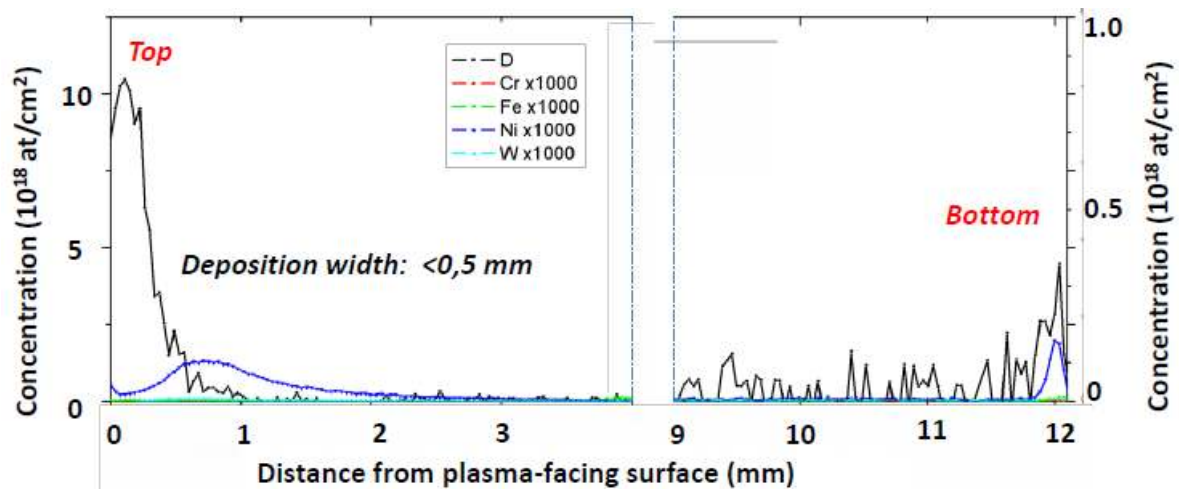


Fig.4. Deposition profiles of deuterium and metals along the entire depth of the castellated groove.

## Summary and concluding remarks

Results on the fuel retention on surfaces in the gaps (castellated Be limiters and W lamellae) are summarised by several points.

- Very shallow deuterium deposition is measured in the castellation: 0.5 – 1.5 mm. No differences are identified between results from the two JET-ILW campaigns.
- Small quantities of D are found in the castellation both in erosion and deposition zones.
- No difference is observed between poloidal and toroidal gaps. This result could be expected after long operation periods, i.e. full experimental campaigns.
- No dust accumulation is detected inside the castellation.
- Very small retention is measured on surfaces in gaps between W lamellae in the divertor.

These comprehensive studies of deposition in the castellated grooves of the beryllium limiters from JET-ILW indicate that the total deuterium can be estimated in the range from  $0.7 \times 10^{22}$  to  $14.2 \times 10^{22}$ ; a detailed report is presented in [5]. The upper value is on the same level as the retention determined by Heinola [6] on plasma-facing surfaces. The most important is that the overall retention is significantly lower than that measured after campaigns in JET-C.

All measurements consistently show small retention and steep deposition profiles on surfaces inside the castellation. These results actually could be expected. The statement is based on earlier data for metallic castellated structures used in the presence of carbon walls: (i) beryllium divertor and limiters JET-C [3,4] and (ii) short-term probes or test limiters exposed in TEXTOR [7] and in other machines [8]. Short-term experiments could be modelled, but modelling of results after entire experimental campaigns is difficult because of a variety of operation scenarios. However, modelling with the ERO-code has successfully reproduced steep profiles in narrow gaps (0.5 mm). Calculations also show very significant increase of deposition (and inventory) with the increase of the gap width, e.g. by a factor exceeding 10 when the width of castellation is increased from 0.5 mm to 2 mm. In conclusion, experimental and modelled results give a clear indication for ITER regarding the need for very careful design of tiles with particular emphasis on shaping and narrow castellation grooves.

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