

## Carbon deposition and fuel accumulation in a castellated limiter exposed under erosion-dominated conditions in the SOL of TEXTOR

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### Introduction

Castellated structures were proposed as coverage of the divertor area and the first wall of ITER to ensure the thermo-mechanical durability of a machine [1]. However, the fuel can be accumulated in the gaps of castellation. Investigations of fuel inventory in the castellated structures are underway on several tokamaks [2-4]. Metallic limiters with ITER-similar castellation were exposed in the SOL of TEXTOR. For the first limiter exposed under deposition-dominated conditions, carbon deposits were found both on top, plasma facing surfaces and in the gaps. The fuel accumulation in the gaps was essential and a conservative estimate demonstrated that at least 30% of fuel is retained in the gaps [4]. Recently, another castellated limiter was exposed in the erosion-dominated area of the SOL of TEXTOR. Below is the description of the new experiment.

### Exposure in TEXTOR

The limiter used in the experiment had the same design as described in [4]. Castellated structure consisted of 6×8 cells (8 rows with 6 cells each) with gaps of 0.5 mm between them. The dimensions of cells were 10×10×10 mm. Castellation was made from TZM alloy consisted of 99 at % Mo 0.5 at % Zr, 0.1 at % Ti. The first row of castellation was made from graphite.

The castellated limiter was exposed under erosion dominated conditions in the SOL of TEXTOR. Total exposure duration was 219 plasma seconds, 39 NBI-heated shots were carried out. During the exposure the temperature of the bulk of the limiter was within 220-300 °C as measured by thermocouples. Surface temperature was monitored with optical pyrometers and was rising from 300°C up to 430°C during the discharge. Excursions of the surface temperature of the leading edge of castellation up to 1850°C were observed for 1-1.5

seconds due to plasma shifts. Electron temperature and density were measured by helium beam diagnostic. The flux density averaged over the area of castellation was  $1 \times 10^{18}$  ion/(cm<sup>2</sup>×sec). Total fluence received by the castellated structure was  $\sim 2 \times 10^{20}$  ion/cm<sup>2</sup> which is approximately 4 times more than fluence accumulated during the experiment described in [4].

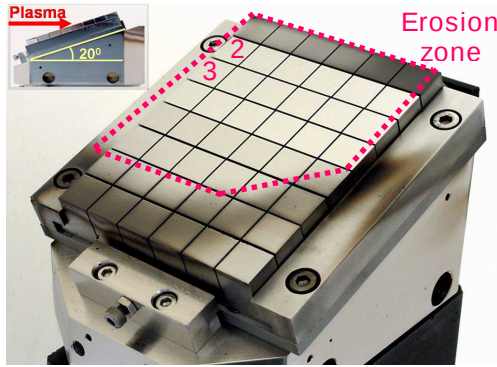


Fig.1. Castellated limiter after exposure in the SOL of TEXTOR

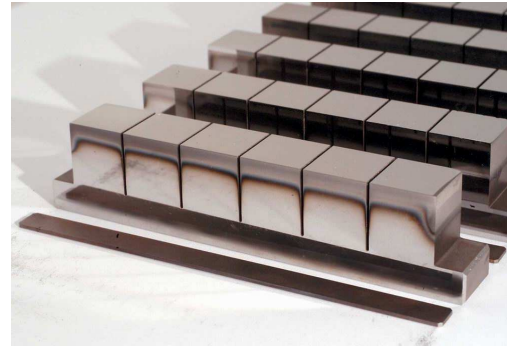


Fig.2. Castellated limiter after exposure in TEXTOR. Deposits in the gaps.

### Investigations of castellated structure after exposure

After exposure a region of net erosion was found on the castellation, as it is shown in Fig. 1. Plasma facing surfaces on the top of the structure were metallically shiny. After the disassembly of the limiter, the deposits were found in the gaps in between the cells of castellation as it can be seen on Fig. 2. Two different deposition patterns were noticed during the inspection of gaps as illustrated on Fig.3. As one can see, for the given geometry of the experiment there were two clearly different sides of gaps: plasma facing sides (side A on the scheme in Fig.3.) and sides, shadowed from plasma (side B on the scheme). During visual inspection, the narrow shiny areas were found on plasma facing sides in the parts of the gaps directly exposed to plasma. On the plasma shadowed sides of gaps, these areas were absent.

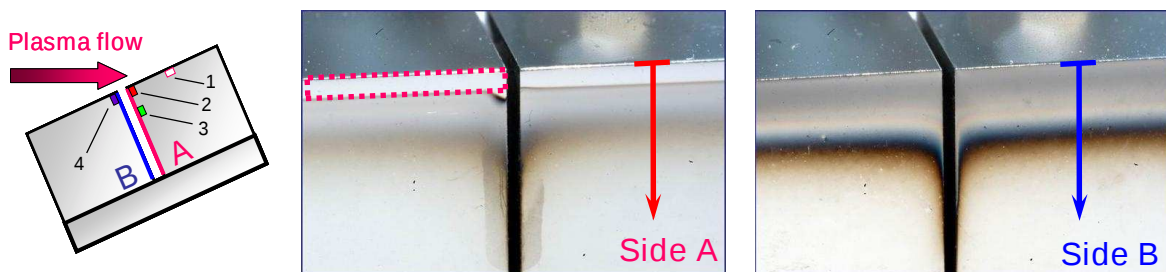


Fig.3. Two sides of gaps: A – plasma open side; B – plasma shadowed side. Red marked area is the shiny area of the gap A directly exposed to plasma. The arrows represent EPMA line scans. Numbered color boxes – locations of SIMS measurements.

To characterize the elemental content of deposit, Secondary Ion Mass Spectrometry (SIMS) measurements were made on several locations both on plasma facing top surfaces and in the gaps. Deposits are found to consist of C, D, H, O and B. SIMS measurements were calibrated using stylus profiling of SIMS crater and SIMS sputter speed was calculated. This allowed the estimation of the deposit thickness. No deposits were found on top surfaces on the area of net erosion. No deposits were found either on plasma exposed shiny parts of plasma open gaps. In fact, this supports an idea, that these narrow areas are the areas of net erosion. The same time, deposits with a thickness up to 100 nm were detected below the shiny area i.e. deeper in the gaps on the plasma open sides. For comparison, on the plasma shadowed side of the gap the deposit thickness was  $\sim 0.5 \mu\text{m}$  measured on the plasma closest location. An example of SIMS measurements made in rows 2 and 3 along with deposit thickness estimation is given in Fig. 4.

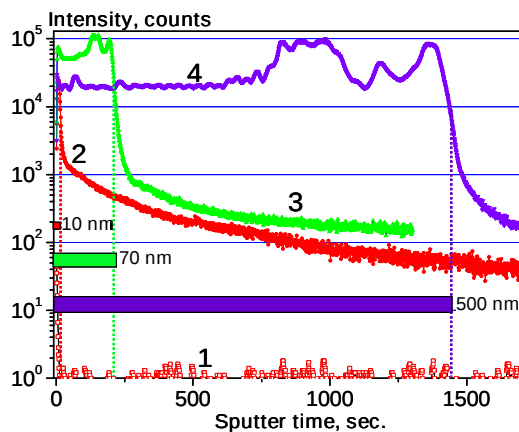


Fig.4. SIMS measurements on top surfaces and in the gaps of castellation. Locations of measurements are shown in Fig.3. Carbon signal is plotted.

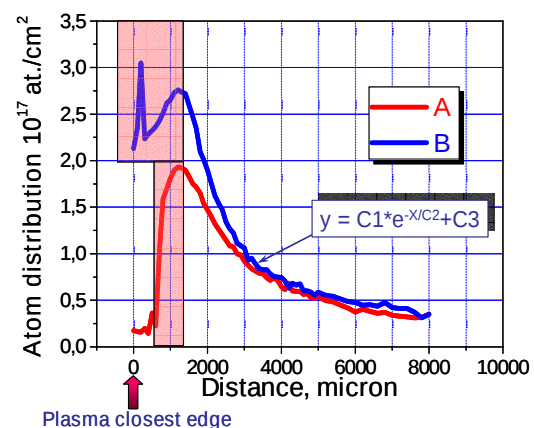


Fig.5. EPMA measurements of deposit thickness in the depth of gaps. The directions of line scans are plotted in Fig.3. Carbon signal is shown.

In order to investigate the distribution of the deposit thickness along the depth of the gaps, Electron Probe Micro Analysis (EPMA) measurements were carried out. EPMA line scans were made along the depth of the gaps as shown in Fig. 3. The carbon  $K_{\alpha}$  line was scanned. As it can be inferred from the EPMA scans presented in Fig.5, deposit thickness decreases exponentially with a depth of a gap with e-folding length of about 1.7-2 mm.

EPMA and SIMS measurements revealed the presence of molybdenum from the castellation, intermixed into the deposited layers. In order to estimate the amount of molybdenum in the deposit, modeling was performed, in which the intensity of X-ray radiation from the sample detected by EPMA measurements, was simulated for a known

deposit thickness by varying the molybdenum content in the deposit. The results of modeling show the best fit for experimental data under assumption that the deposit contains at least 65 at. % of molybdenum.

Nuclear Reaction Analysis (NRA) investigations were carried out to estimate the total deuterium (fuel) content. Measurements were done both on top surfaces and in the gaps. The amount of D fuel in the gaps was measured to be  $(5\div 10)\times 10^{16}$  D/cm<sup>2</sup>, whereas on the top surfaces the D amount is at or below measurable limit:  $\sim 1\times 10^{15}$  D/cm. Based on the results of NRA measurements and total fluence estimations, an assessment of fuel inventory in the castellation was made, showing that the amount of D fuel in the gaps corresponds roughly to about 0.02÷0.04 % of the total fluence impinging on castellation.

### Summary

Castellated limiter with ITER-like geometry was exposed under the erosion-dominated conditions in the SOL of TEXTOR. After the exposure, deposits were found in the gaps, with a negligible amount of deposited material that was detected on top surfaces open to the plasma. The thickest deposits are located on plasma shadowed sides of the gaps with maximum thickness up to 0.5 µm on the plasma closest locations as it was measured with SIMS diagnostic. The deposit thickness decrease exponentially with the depth of gaps with e-folding length of 1.7-2 mm as inferred from EPMA measurements. Material intermixing was found to occur in the deposited layers. Deposits are mixed Mo:C:D:O:B:H layers. Gaps contain at least  $(5\div 10)\times 10^{16}$  of D fuel atoms per cm<sup>2</sup>. This corresponds roughly to 0.02÷0.04 % of total averaged D fluence impinging on the castellation.

### References

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