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# Overview of material migration and mixing, fuel retention and cleaning of ITER-like castellated structures in TEXTOR

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Abstract

Plasma-facing components (PFCs) in ITER will be castellated by splitting them into small-size blocks to maintain the thermo-mechanical stability. However, there are concerns in particular on retention of codeposited radioactive fuel in the gaps. An R&D program is underway in TEXTOR addressing this acute issue of castellation. Material migration and fuel inventory are investigated using long- and short-term discharge-resolved experiments with castellated structures in TEXTOR. Significant impurity transport to the gaps was detected and results were in part quantitatively reproduced with 3D-GAPS code.

Deposits containing up to 70 at. % of tungsten on the gap areas closest to the plasma were detected in recent experiments. Deposition in the gaps accompanied by metal mixing demand for development of effective cleaning techniques. In experiments with ITER-like castellation, the gaps were cleaned from carbonaceous deposits using oxygen plasmas at 350$^{o}$C. This contribution contains an overview of experimental and modeling results along with recommendations for PFCs in ITER.

*JNM Keywords:* Plasma-material interactions (P0500), Surface effects (S1300), Carbon (C0100), Divertor materials (D0500); Cladding materials (C0500);

*PSI 19 Keywords:* Deuterium inventory, Erosion & Deposition, High-Z material, Tungsten, TEXTOR

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## Introduction

Plasma-facing components (PFCs) in ITER will be exposed to intensive particle and radiation fluxes imposing technological and engineering challenges to the design of PFCs. To alleviate the thermo-mechanical constraints and to ensure the durability of the PFCs it was decided to split the first wall and divertor into a large number of compact cells – by introducing the so-called castellated structures [1, 2]. However, along with the favorable significant reduction of the risk of the PFC failure, the use of castellation has triggered a number of critical issues: primarily, radioactive fuel may accumulate in the gaps of castellated structures [4-6] and the power handling may degrade significantly due to hot spots introduced by the castellation.

While aspects of power handling are the subject of another paper [7], we focus here our review on studies of impurity deposition and fuel accumulation in the gaps of castellated structures based on experiments on TEXTOR and modeling and finally, on gap cleaning using hydrogen and oxygen plasmas.

## II Erosion and deposition in the gaps of castellation structures

### *a. Short-term experiments in TEXTOR*

To investigate the general nature of the impurity and fuel transport into the castellation gaps under well-diagnosed plasma conditions, series of experiments were made in the scrape-off layer (SOL) plasmas of TEXTOR. The castellation was made of TZM alloy (containing 99 at.% of molybdenum) and machined to ITER relevant sizes of 10×10×10 mm. Afterwards, the castellation was mounted on the roof-like limiter and introduced to the SOL plasmas of TEXTOR for exposure to a series of identical repetitive discharges.

During the first experiment, the limiter was exposed to the total fluence of $4.9*10^{19}$ part./cm$^2$ averaged over the area of a castellation with the surface temperature reaching

700$^{o}$C, as measured with a pyrometer on the uppermost part of the castellation. Visual inspection revealed the presence of the deposits both on the plasma-wetted top surface and in the gaps. Therefore, this experiment is referred as a “deposition experiment” [8].

The second experiment was made under the conditions of net erosion: the plasma wetted top surfaces were metallically shiny, whereas deposition patterns were detected in the gaps. The limiter was exposed for a total averaged flux of ~2.0*10$^{20}$ part./cm$^{2}$ [8]. This experiment is referred as “erosion” experiment. A few thermal excursions of the plasma-closest uppermost edge of castellation were detected, with the maximum temperature reaching 1600$^{o}$C. Under these conditions most of accumulated deuterium was likely desorbed from the upper cells of the castellation. Therefore, we mainly rely on the deposition of carbon in our analyses.

Visual inspection of gaps from both limiters revealed plenty of experimental similarities. In the both experiments, the deposits in the gaps were detected on thin stripe-like zones in immediate vicinity of the plasma-closest edges of the gaps as illustrated on Fig.1. The e-folding length of the carbon-containing deposit measured with several ion- and electron-beam surface diagnostics was around 1.0 - 1.8 mm for both experiments.

However, there were also significant differences in experimental results. The most significant is the difference in the amount of impurities deposited on the plasma-wetted top surfaces and in the gaps. For the deposition experiment the impurities were found primariliy on the top surfaces: $C_{top}/C_{gaps.}$~ 3, where $C_{top}$ and $C_{gaps}$ are integrated carbon amounts on top surfaces of castellation cells and in the gaps respectively. Carbon amount was derived based on the results of multiple line scans made both on the top surfaces and in the gaps, integrated over top or gap areas correspondingly. For the erosion experiment the amount of impurities on the plasma-wetted top surfaces was essentially zero, while in the gaps the deposits with a thickness of up to 500 nm were detected. This implies, that despite for the erosion-dominated conditions at the top surface, the screening and attenuation of eroding particle fluxes was sufficiently effective to turn these conditions to deposition-dominant inside the gaps.

*b. Long-term exposure*

To investigate the impurity transport into the gaps on a long-term basis and to correlate these results with results of short-term exposure, two blades of the ALT II (Advanced limiter Test II) [9] were coated *ex-situ* with a silicon layer with a thickness of 300-400 nm. This layer served as a marker, helping to evaluate erosion and deposition occurring on the blades. A catcher plate was installed at the bottom of the gap formed by the two instrumented ALT II blades. The blades were installed into TEXTOR and exposed for an entire campaign comprising ~ 9500 plasma seconds, including 7 boronizations and accounting for a total fluence of $2.9*10^{21}$ part./$cm^2$ averaged over the plasma-wetted top surface. Several surface analyses were applied to study the impurity deposition patterns in the gaps. Deposits with a thickness of up to 30 µm were detected at the parts of gaps nearest to plasma in a complete similarity to the results of short-term exposures, suggesting the common nature of the physical processes governing the impurity transport into the gaps. At the same time, thick deposits of up to 1 µm were found at the bottom or exposed gaps. While there are several hypotheses to explain the observed deposition patterns, more investigations are needed to understand the physical processes leading to the detected enhanced deposition at the bottom. Deeper insight to the processes governing the impurity transport and deposition in the gaps is provided by the dedicated modeling and is described in more details later in this paper.

*c. Mitigation of deposition by the shaping of the castellation*

Both results of dedicated short-term experiments and the long-term exposure demonstrate, that the deposition in the gaps remains significant independently on whether erosion- or deposition-dominated conditions are at the plasma-wetted surface of castellation. These results highlight the necessity for development of the deposition mitigation techniques.

Optimization of the geometry of castellation cells seems to be a natural way of mitigating the impurity transport into the gaps, by eliminating the areas of gaps directly facing the plasma and contributing to the enhanced impurity transport into the gaps. Such areas are referred to as plasma-open areas.  To evaluate the effect of cell geometry on the mitigation of the impurity deposition in the gaps, a double roof limiter was exposed in TEXTOR. Tungsten castellation cells of conventional rectangular form were used along with cells of a new roof-like geometry to shadow the plasma-open areas of the gaps from the plasma as it is illustrated on Fig. 2. The castellation of both geometries was exposed in a same experiment in the same plasma conditions allowing for a direct comparison between two exposed castellation geometries [10].

Investigations after the exposure have shown that a shaping of the castellated cells may indeed lead to the reduction of the impurity deposition and fuel accumulation. However, the decrease of carbon deposition was not very significant hardly exceeding 30% compared to the rectangular castellated cells. Similar to results from the long-term experiment, deposits reaching 200 nm were detected at the bottom of the castellation. The measured deposition at the bottom corresponds to about 14% of the total impurity accumulation in the gap. Better understanding of physical processes leading to the impurity deposition in the gaps is required to gain control over deposition. Significant intermixing of the sputtered tungsten into deposits at the upper part of the plasma-open areas of gaps was detected. The atomic fraction of tungsten reached 70 at.%. Such a massive metal intermixing will make for a significant challenge to removal of impurities from the gaps.

*d. Modeling of deposition in gaps*

Physical processes occurring inside the gap were modeled in a flexible 3D geometry with the new Monte-Carlo code 3D-GAPS. A detailed description of the code is provided in [11]. The following physics models were implemented into the code and used for evaluation of the deposition patterns:

- Particle reflection: cosine, isotropic or specular angular distribution
- Reflection coefficient: pre-defined or fitted from TRIM [12]
- Elastic neutral collisions with molecules of residual gas
- Plasma penetration into the gap: coupling with particle-in-cell (PIC) simulations
- Homogeneous surface mixing model for surface concentrations
- Simple model for chemical erosion

The simulated data was compared with experimentally measured profiles of carbon deposition. Edge plasma parameters from either the He-beam diagnostic or fast scanning Langmuir probe were used. Experimental data was later matched with the PIC code SPICE2 [13, 14] and translated inside the gap.

It was found that elastic collisions of particles with molecules of the residual gas inside the gap play a negligible role in the impurity distribution in the gap for experimental conditions in TEXTOR. On a contrary, a simple model of chemical erosion has proven to change the distribution of carbon in the gap. Tracing of particle reflection from the side walls of a gap coupled with taking into account angular distributions of reflected particles have led to the best agreement with measured deposition patterns illustrated in Fig. 3. In modeling, a constant chemical re-erosion yield $Y_{chem}$=2.0% has provided the best fit with an experimental data. Such a value of $Y_{chem}$ agrees well with experimental data obtained in the SOL of TEXTOR. In future, the model will be upgraded to allow for a changing chemical erosion coefficient along the depth of the gap. Nevertheless, the deposition at the bottom of the gap still could not be reproduced by 3D-GAPS leaving a room for the further optimization of physical model used for the simulations. Details of modeling may be found in [15].

*e. Cleaning of the deposits inside the gaps*

Since it is expected that deposition in the gaps of ITER will happen despite the mitigation techniques, the development of effective gap cleaning techniques is of paramount importance. To address this issue, several plasma-discharge techniques were tested in laboratory conditions [16] in the TOMAS toroidal device at FZJ [17]. Castellated cells of ITER-like geometry - 10×10×10 mm - were pre-coated with an amorphous deuterocarbon film (D/C~0.3). The properties of this film were measured in the MirrorLab [18]. The castellated samples were then inserted into the glow- or electron-cyclotron resonance reactive plasma and exposed in TOMAS. Reactive hydrogen and oxygen plasmas were applied to evaluate their relative cleaning effectiveness. The castellation was kept at 200$^{o}$C and 350$^{o}$C during the cleaning. The effect of the width of gap was investigated, for this purpose the 1 mm wide and 2.5 mm wide gaps were studied. The main results are provided in Fig. 4. The most effective deposit removal was achieved during the treatment in oxygen plasmas. The effectiveness of such a cleaning in the gaps was weakly dependent on the temperature of the sample. The results clearly demonstrate that the largest deposit removal was attained at the plasma-closest areas of the gaps and at the gap bottom, i.e. at the locations where the most of the deposition and fuel accumulation is usually detected, accounting for up to 90% of the total inventory in the gaps.

**Summary and outlook**

A coherent research program is underway at the TEXTOR tokamak to address physics issues related to castellated structures for the ITER first wall and divertor. Impurity deposition and fuel accumulation in the gaps of castellated structures and possible ways to mitigate such deposition, castellation melting and melt layer motion, cleaning of the castellated structures are among the critical issues of the performance of a castellation in ITER. The research program comprises the discharge-resolved short-term experiments, long-term exposures of castellated structures in TEXTOR, the dedicated modeling and laboratory experiments.

The results of short-term experiments largely agree with those of long-term exposures, demonstrating the common nature of physical processes governing the deposition in the gaps in these experiments. To gain a better understanding of these processes, a dedicated modeling effort is underway. The Monte-Carlo 3D-GAPS code is used for modeling with the plasma background at the vicinity of castellation is taken from experiments and traced further inside the gaps using the SPICE2 code. Quantitative agreement of modeled and experimental patterns of carbon deposition on the plasma-closest, carbon-rich areas of gaps was attained. Particle reflection inside the gap coupled with chemical erosion of re-deposited carbon layers are believed to be playing a decisive role in the impurity deposition in the gaps. At the same time, the significant deposition at the bottom of gaps observed both in the short-term and long-term experiments at TEXTOR could not be reproduced by the modeling indicating that an important physics may be still missing.

According to the results of experiments in TEXTOR, the deposition in the gaps of the castellated structures occurs independently of whether erosion- or deposition-dominated conditions prevail at the plasma-wetted surface of a castellation. This makes gaps the potentially giant reservoir for impurity and fuel accumulation in ITER.

The formation of mixed metal-containing layers in the gaps of castellated structures exposed under erosion-dominated conditions in TEXTOR represents the situation which is likely to occur in ITER. Mixed deposits will provide severe difficulties for gap cleaning. A significant effort is now focused on studies of cleaning of castellated structures using reactive plasma discharges. Current studies show, that the highest efficiency of deposit removal is attained using the electron-cyclotron discharge in oxygen on the plasma-closest uppermost areas of the gaps and at the bottom of the castellation structures – in the same areas where the most of deposition usually occurs in tokamak experiments. Whether it is possible to remove the metal-containing mixed layers remains to be investigated. The results of experiments in TEXTOR imply that both deposition mitigation and cleaning techniques should be developed for ITER castellation to alleviate the issue of tritium inventory.

The future investigations will focus on gaining the better understanding of physical processes responsible for the impurity deposition in the gaps, mitigation of deposition by more sophisticated gap shaping, code improvement and further cleaning tests on ITER-relevant mixed Be-like deposits.

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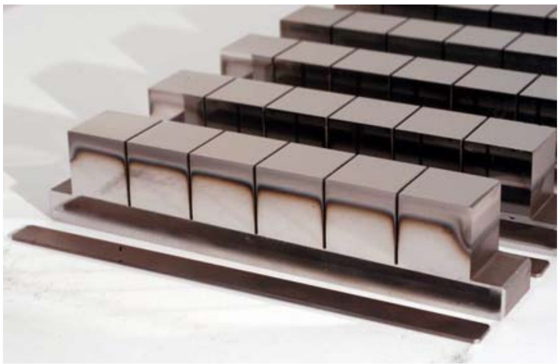
**Figure captions:**

**Figure 1.** Carbon deposition in the gaps of the castellated limiter exposed in TEXTOR

**Figure 2.** Scheme of exposure and a view of a castellated limiter with two castellation geometries: conventional - rectangular and shaped – to mitigate the deposition.

**Figure 3.** Comparison of the modeled carbon deposition pattern (continuous line) with experimental results (squares). The gap geometry is shown with blue, the numbers correspond to distance along the gap (in mm). The direction of plasma flow is shown with a red arrow. Grey area correspond to the bottom of a gap.

**Figure 4.** Comparison of carbon deposit removal efficiency averaged over area of gaps. The data shown for glow discharge (1-4) and for ECR discharge (5-6) in oxygen and hydrogen, for various temperatures of the castellation during the cleaning and for various widths of studied gaps: 1 mm and 2.5 mm.



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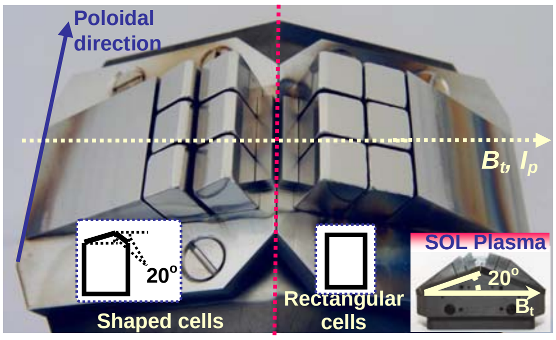


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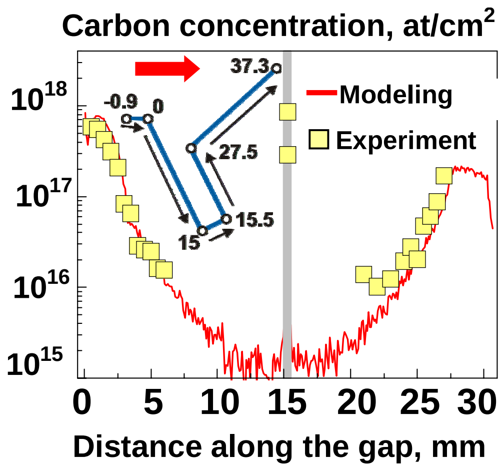
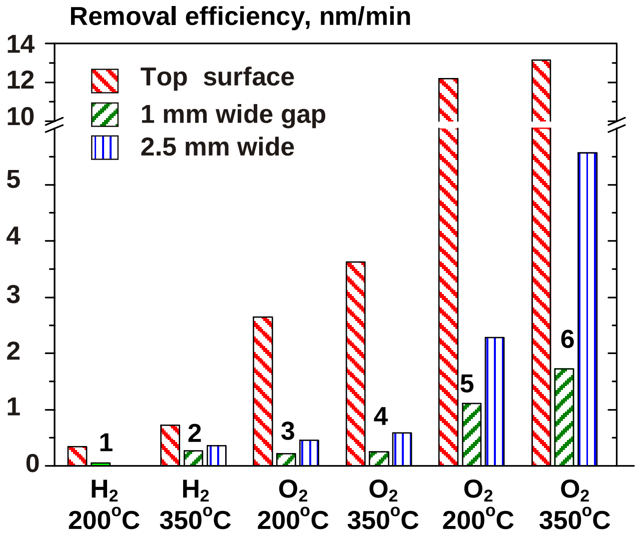



**Figure 3 (new).** Comparison of the modeled carbon deposition pattern (continuous line) with experimental results (squares). The gap geometry is shown with blue, the numbers correspond to distance along the gap (in mm). The direction of plasma flow is shown with a red arrow. Grey area correspond to the bottom of a gap.

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