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GROSS AND NET EROSION BALANCE OF PLASMA-FACING MATERIALS IN FULL-W TOKAMAKS

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Introduction

Successful operation of future fusion reactors requires detailed understanding of the **balance between gross and net erosion** of plasma-facing components (PFCs), predominantly that of **tungsten (W)**

How has this been addressed?

- Marker samples exposed to series of plasma discharges on ASDEX Upgrade (AUG), marker tiles during entire campaigns on WEST
- Varied parameters: (i) **plasma type** (L- and H-mode) **and gas** (D and He), (ii) **marker material** (W vs. Au vs. Mo vs. Re), (iii) **surface roughness**
- Spectroscopic data extracted during plasma operations combined with the results of post-exposure analyses of the marker samples

Main goals of the present work:

- Elucidate how gross and net erosion depend on **local plasma conditions and PFC material properties** in D and He at the divertor
- Compare the results obtained from two full-W devices with each other

Overview of the experiments

AUG

- Exposure of marker samples in the **low-field side (outer) strike point (OSP) region** – erosion determined from changes in the thickness of the marker layers
  a) Mo-coated (~300 nm) graphite samples with small Au marker spots (~30 nm)
     ✓ **Two different spot sizes: 1×1 mm² (gross erosion) and 5×5 mm² (net erosion)**
  b) Mo- or W-coated (30-150 nm) graphite samples with different surface roughness
     ✓ **Roughness varied: R_a~4 nm → >2 μm; nominal value R_a~1 μm**
  c) Graphite samples with W and Mo (~30 nm) markers and uncoated trench (d~0.2 mm)
     ✓ **Prompt re-deposition at the bottom of the trench**
  d) Bulk W tile (R_a~0.2-0.3 μm) with Mo coating and broad (~30 nm) Au markers

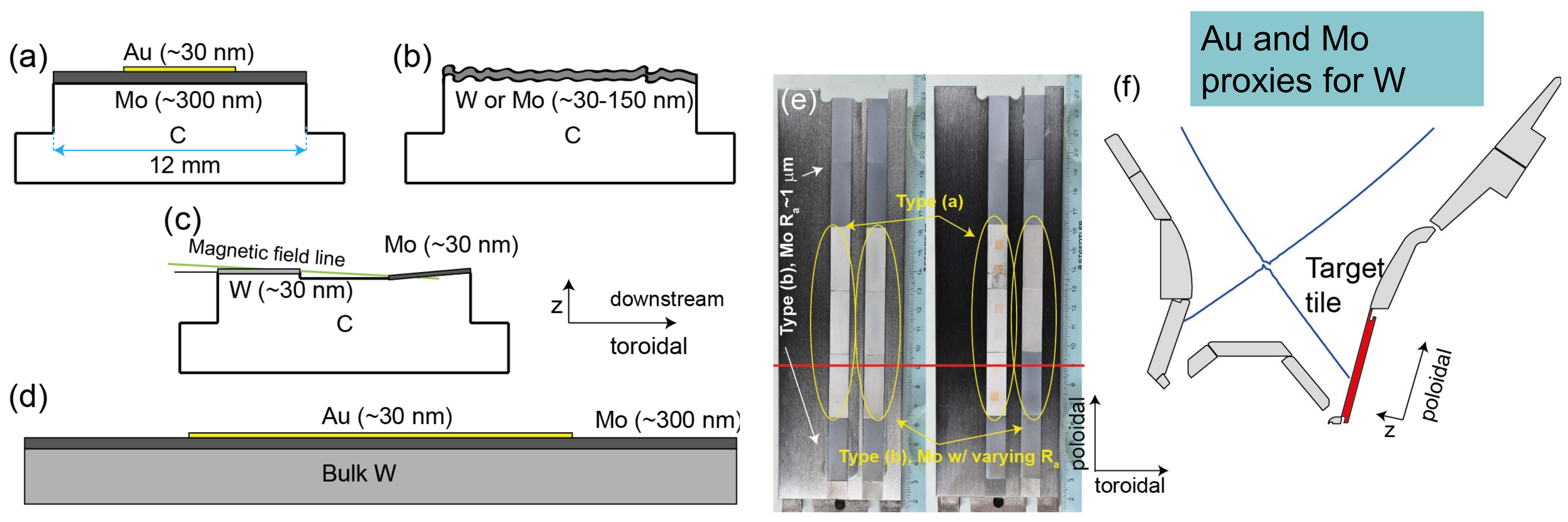
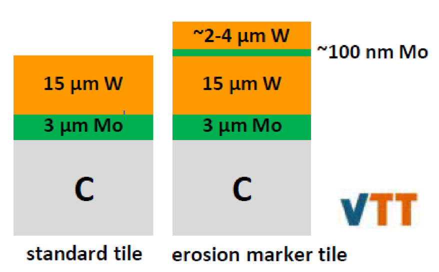


Fig. 1. (a)-(d): Schematic drawings of marker sample types; (e) Example of marker samples mounted on a target tile and the OSP position (red line); (g) Cross section of the AUG divertor, target tile position in red.

- Plasma experiments – **subset of sample types (a)-(d) used** in each of them
  ✓ **L-mode plasmas** with a high T_e (20-30 eV) at the OSP – **in deuterium**
  ✓ **H-mode plasmas** with large or small ELMs and inter-ELM T_e~20-30 eV – **in deuterium**
  ✓ Successive exposure to **L- and H-mode plasmas**, different OSPs used – **in helium**
  Exp 1: H-mode plasmas, 3 OSPs used; Exp 2: L- and H-mode parts, 2 OSPs used

WEST

- Marker samples exposed to **C3 (in D) and C4 (in D and He) campaigns**
  ✓ Part of the tiles removed after C3
- Properties of the marker tiles
  ✓ Mo and W layers → "full-W" components
  ✓ Actual markers (Mo and W) on top



Overview of recent AUG results

- General observations in D, see [1-3] and Fig. 2
  ✓ Erosion **peak around OSP**, Au and Mo eroded at higher rates (factor of 3-15) than W (Fig. 2a)
  ✓ W shows deposition peaks on both sides of the OSP → due to **local re-deposition and E×B drift**
  ✓ Strongest impact on net erosion comes from the **shape of the T_e profile**
  ✓ Gross erosion can also be determined by post exposure analyses ↔ **sub-mm samples** needed

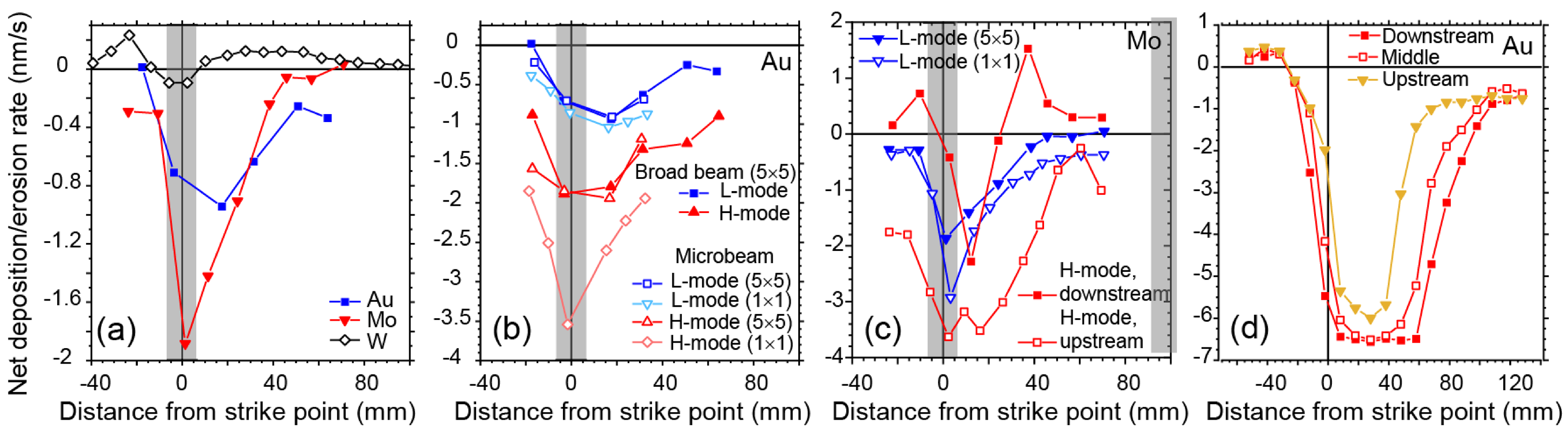


Fig. 2. Net deposition/erosion (pos/neg) of (a) different marker materials in D and in L-mode, (b) Au markers in L- and H-mode, (c) Mo markers in L- and H-mode, (d) Au stripe on the bulk W tile in H-mode.

[1] A. Hakola et al., Phys. Scr. **T167** (2016)
[2] A. Hakola et al., Nucl. Mater. Energy **12** (2017)
[3] A. Hakola et al., Nucl. Mater. Energy **25** (2020)
[4] A. Lahtinen et al., Proc. EPS 2017

- Comparison between L- and H-mode
  ✓ Gross erosion **amplified by ×10-100**, net erosion by a **factor of ×2-4** (Fig. 2b) in H-mode
  ✓ Migration can also be enhanced: occurrence of **areas with net deposition** (Fig. 2c)
  ✓ H-mode can **lead to strong damage** of the markers (Fig. 2d)

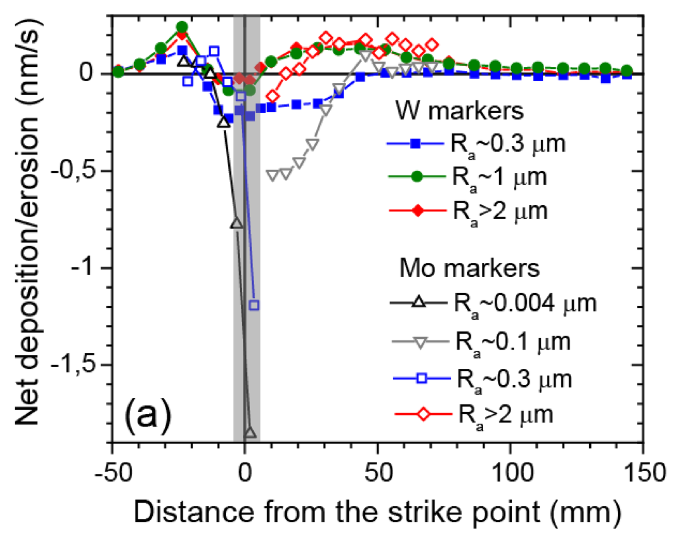
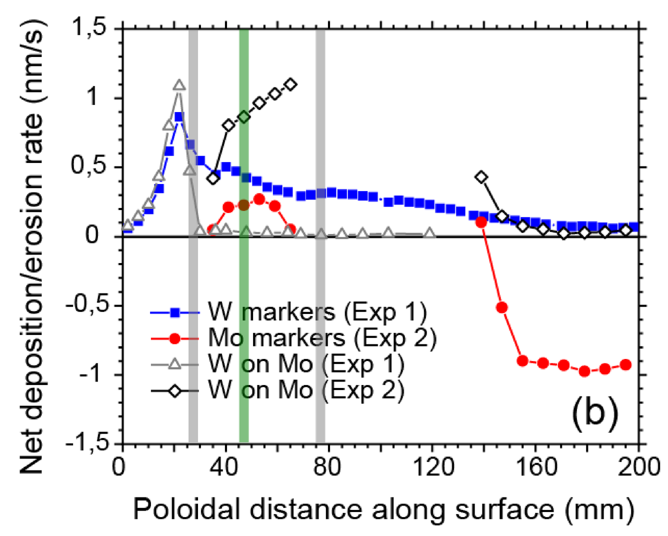


Fig. 3. (a) Net deposition/erosion of W and Mo markers with different surface roughness in L-mode

- Effect of surface roughness, see [4]
  ✓ Increasing **roughness reduces net erosion** (Fig. 3a), roughest samples even show net deposition areas
  ✓ Erosion also depends on the **type and structure of the coating** (comparison Mo markers: Fig. 2c and Fig. 3a)

- Erosion in D and He, see [5-7]
  ✓ Strong erosion sources in He but also stronger flow of material into divertor → **net deposition if impurities** predominantly present (Exp 1)
  ✓ Minimizing the presence of impurities (Exp 2) leads to the occurrence of **net erosion – but less than in D**!?



[5] S. Brezinsek *et al.*, Nucl. Mater. Energy **12** (2017)
[6] A. Hakola *et al.*, Nucl. Fusion **57** (2017)
[7] S. Brezinsek *et al.*, Proc. PSI 2020

Fig. 3. (b) Net deposition/erosion of W and Mo markers and deposition of W on Mo in He plasmas. OSP positions marked in green (Exp 1) and gray (both Exp 1 and Exp 2) bars.

Overview of recent WEST results

- Spectroscopically determined divertor gross erosion in line with AUG data, see [8]
- Impurities (O, C for WEST) have a strong role in determining the erosion patterns
- Campaign-averaged net erosion/deposition picture similar to AUG results, see [9]: erosion at the strike points, thick co-deposited layers next to them, especially at the inner side
- **Net erosion rate at the OSP >0.1 nm/s** → similar to AUG (**NB!** only L-mode on WEST)

[8] G. van Rooij *et al.*, Phys. Scr. **T171** (2020)
[9] M. Balden *et al.*, Proc. PFMC 2021

Conclusions

1. **Small enough marker samples** can be used for determining gross and net erosion
2. In H-mode, gross erosion ×10-100 but **net erosion ×2-4 higher than in L-mode**
3. Rougher surfaces → **suppressed net erosion and enhanced formation of co-deposits**
4. In He plasmas, erosion amplified by higher mass/charge of plasma particles but impurities can overcompensate this → **apparent net deposition**

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.