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ERO2.0 modelling of divertor marker erosion in ASDEX Upgrade L-mode experiments

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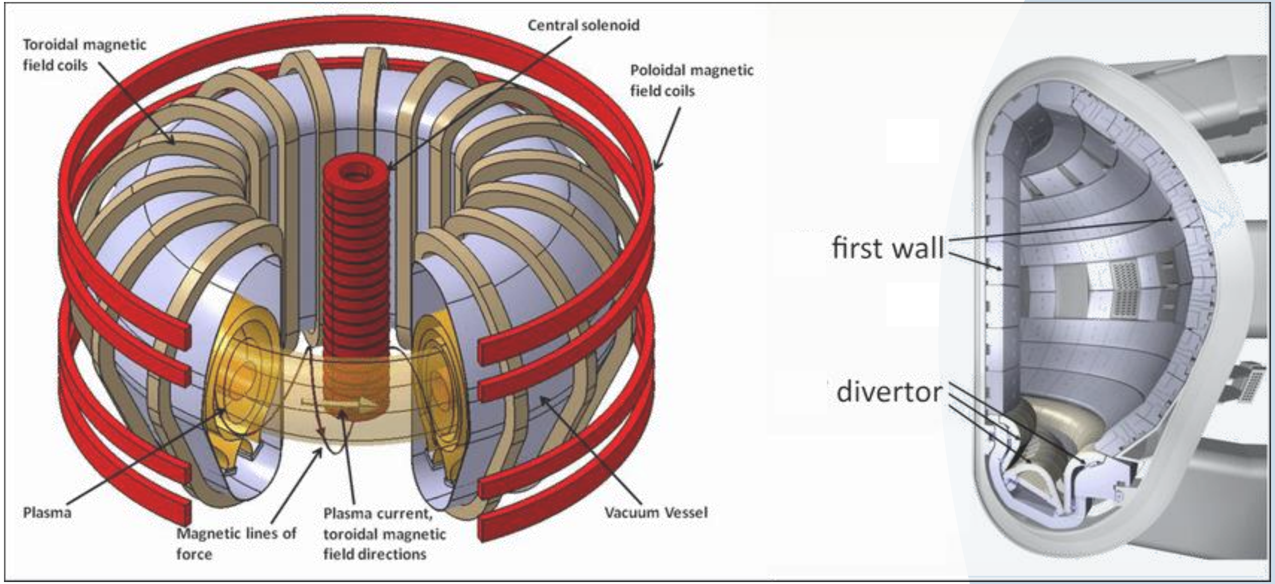
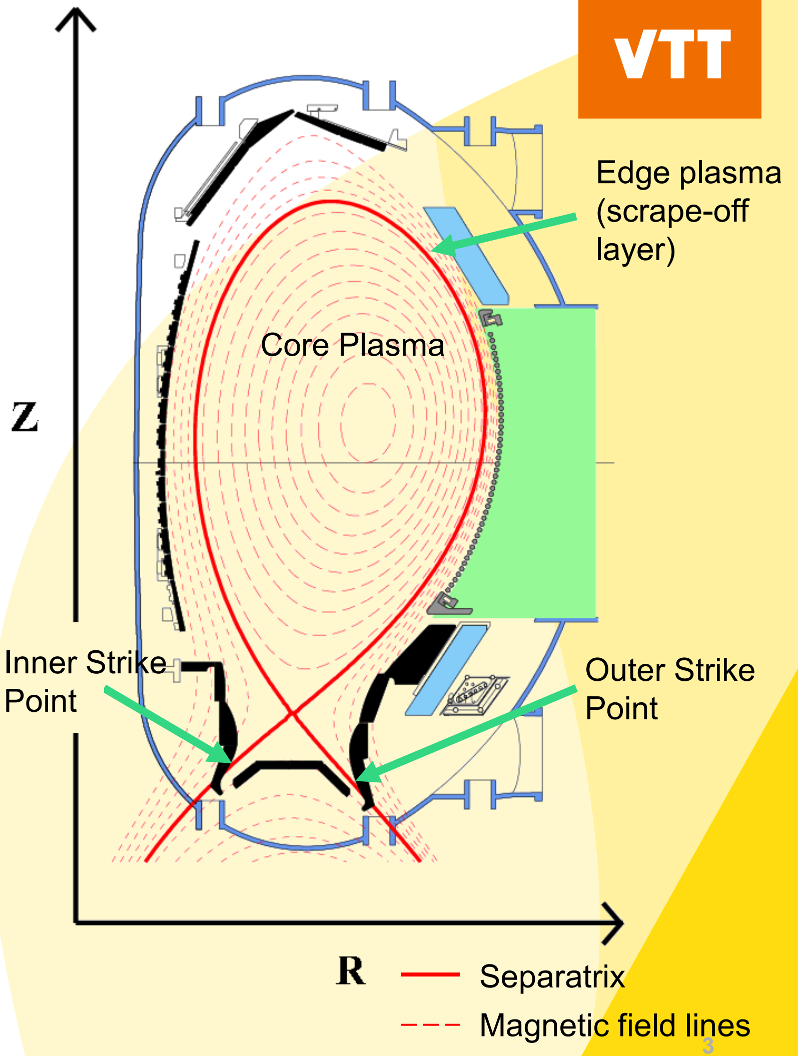
Introduction – basics of tokamak

- Most widely studied fusion reactor concept
- Plasma-state fuel (D, T) confined in a toroidal chamber with strong magnetic fields
- Temperature in the core plasma ~100 000 000 K



Divertor

- Plasma escaping magnetic confinement is guided along field lines to the **divertor region**
  - Field lines guide plasma to separate **divertor plates**, where it comes into direct contact with the plates
  - Ion flux and temperature are highest at the **strike point**.
  - Particles reaching the divertor are **less likely** to **return** to the main chamber or core plasma
- Although plasma is cooled in divertor prior to PFCs, it may induce sputtering

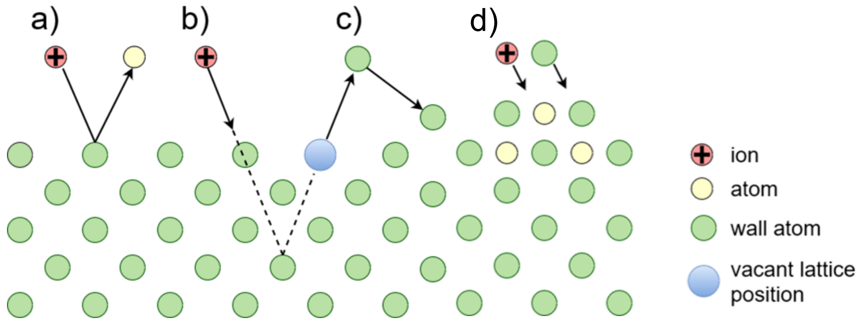


Why understanding wall erosion in tokamaks matters

- Assessing the **lifetime** of plasma-facing components (PFCs)
  - Plasma-induced erosion of wall materials significantly reduces PFCs lifespan in fusion environments
- Estimating the **amount** of wall material such as tungsten (W) **impurities** ending up in the **core plasma**
  - W, as a high-Z impurity, effectively cools the plasma through enhanced radiative losses
- **Migration** and formation of tritium (T) -containing **co-deposited layers** on the PFCs
  - D–T is favorable reaction, but due to high radioactivity and rarity of T, retention on PFCs must be minimized

Sputtering

- Incoming particle initiates collision cascade in solid leading to **ejection of atoms**
- Common **erosion mechanism** in tokamak environment
- Common PWI processes
  - a) reflection, b) sputtering, c) deposition/re-deposition, d) co-deposition



- At the divertor region PFCs particle load lead to:
  - **Gross erosion** (sputtering) of W
  - (Prompt) **re-deposition** → **net erosion** of W differs from gross erosion
  - Potential **PFC damage** (melting, cracking, etc.)

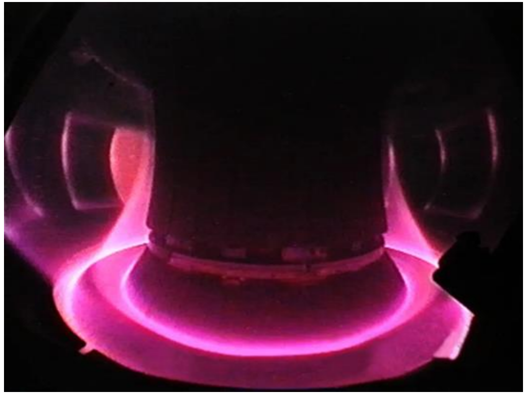
How to experimentally study wall erosion in tokamak environment [1]

- **Exposing** well-defined **samples** to controlled plasma discharges
  - Considerations for sample design:
    - Proxy material that is **separable** from surrounding materials
    - Similar **mass** and **ionization** energy as wall material
    - Sample **geometry** determines whether the study targets net or gross erosion
- Defining changes in **material thickness** through **post-mortem measurement**
  - Change in material thickness defines net erosion/deposition
  - Measurements should be material specific (RBS)
- **Simulations** help to understand physics behind the **experimental observations**

[1] R. Bastasz, et al., J. Nucl. Mater. **310–314** (1995) 220–222

ASDEX Upgrade (AUG)

- Medium-size **tokamak** located at Max-Planck-Institut für Plasmaphysik (Garching, Germany)
- Operational since 2007
- First wall equipped with **W-coated** graphite or **bulk-W** tiles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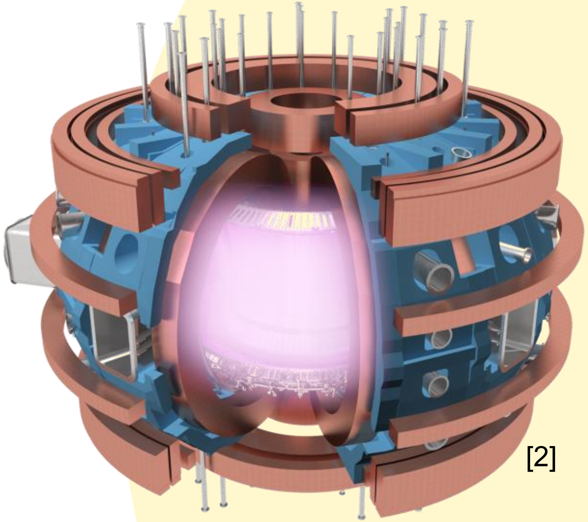
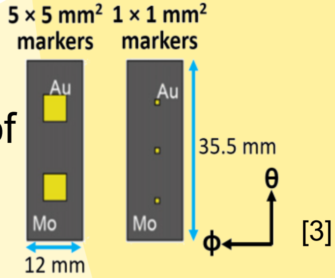
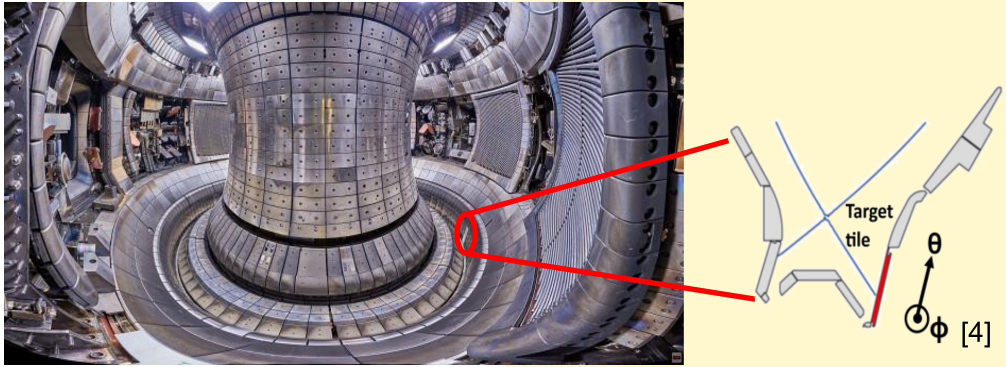

[2]

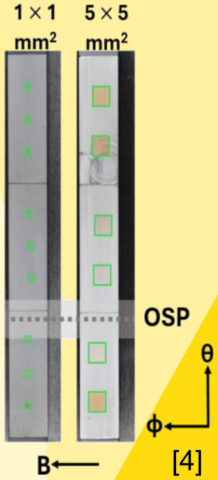
[2] IPP Online picture archive - https://www.ipp.mpg.de/1471827/asdex_upgrade

The experiment

- **Mo**-coated graphite samples with **Au** marker surfaces of two sizes (**5 × 5 mm²** and **1 × 1 mm²**) were placed **at outer strike point** (OSP) area of AUG divertor
  - 5 × 5 mm²: re-deposition expected on marker surface → **net erosion**
  - 1 × 1 mm²: re-deposition expected outside marker surface → **gross erosion**
- Samples were subjected to 8 identical plasma discharges
  - Total exposure time: **~32 s**
  - Strike point conditions: $n_{e,OSP}$**~0.5×10^{19} m^{-3}**, $T_{e,OSP}$**~20 eV**
- Main findings:
  - Erosion **peak** near **OSP**
  - Maximum **net erosion** rate **1.0-1.1 nm/s**







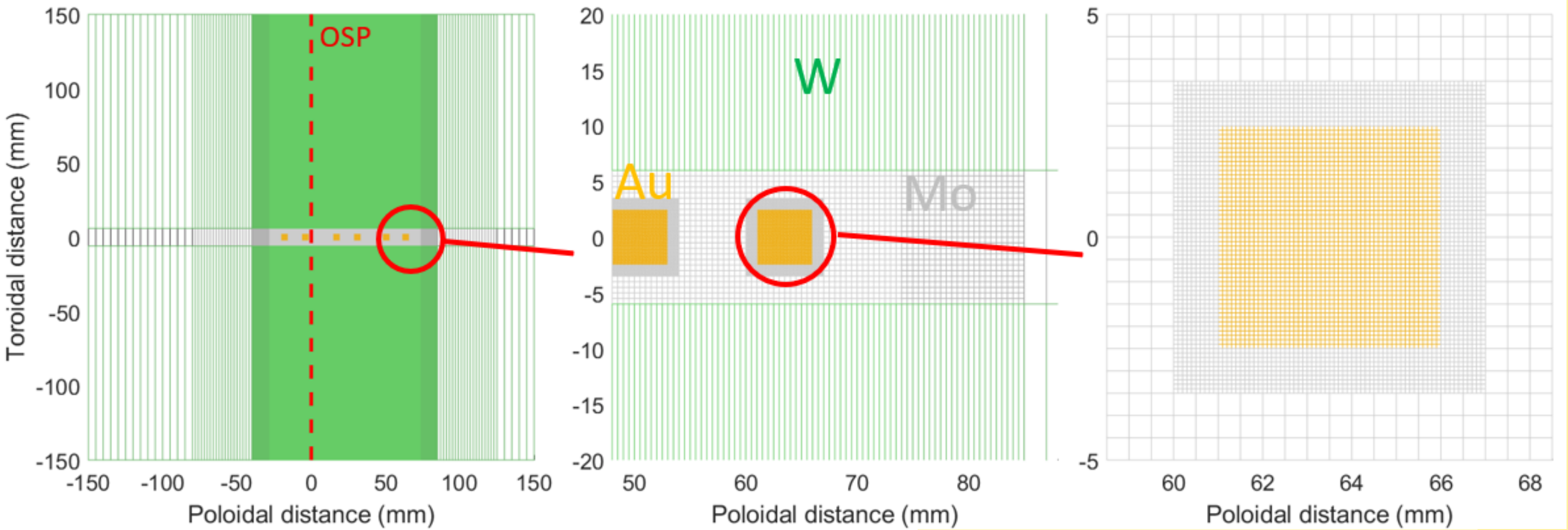
[3] A. Hakola et al., Nucl. Fus. **61** (2021) 116006
[4] A. Hakola et al., Nucl. Mater. Energy **25** (2020) 100863

Simulation tools

- **ERO2.0** - 3D Monte Carlo trace impurity code for modelling plasma-wall interactions (PWI) [5]
  - Upgrade to earlier ERO code
- **SDTrimSP** – Binary Collision Approximation (BCA) code to simulate atomic collisions in solid targets [6]
  - Sputtering and reflection yield data used in ERO2.0
- **OSM** – ”Onion Skin Model” to produce background plasma solutions in the scrape-off layer (SOL) plasma [7]

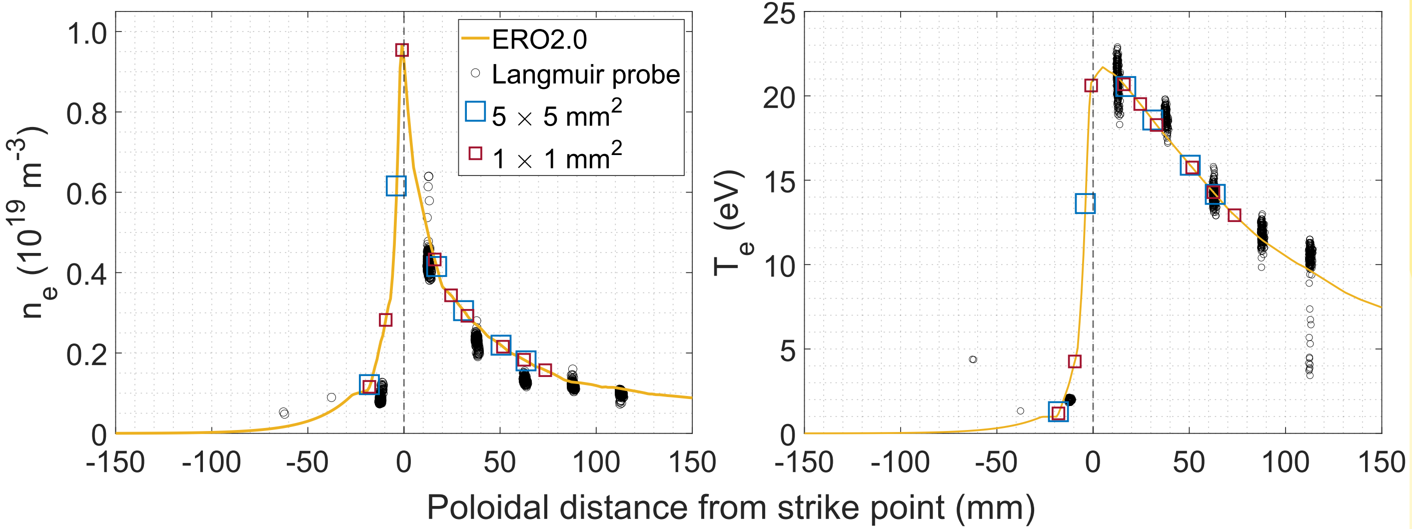
[5] J. Romazanov et al., Phys. Scr. **T170** (2017) 014018
[6] A.Mutzke et al., SDTrimSP Version 6.00, IPP Report 2019-02
[7] P. Stangeby, et al., Nucl. Fusion **35** (1995) 1391.

Simulation geometry



- Simulation volume **300 × 300 × 50 mm²**
- Poloidal-toroidal surface along outer target plate constructed from **rectangles** with decreased sizes in areas of interest

Background plasma and parameters of simulation



- Applied background plasma created with OSM follows the Langmuir-probe (LP) measurements of electron density and temperature at the outer divertor target [3]
- Spatially homogenous constant impurity concentrations of $\mathbf{c_B = c_C = c_N = 0.5\%}$ and $\mathbf{c_W = 0.005\%}$, with average charge states $\mathbf{Z_B = 3, Z_C = 4, Z_N = 5, Z_W = 13}$ [4]

[3] A. Hakola et al., Nucl. Fus. **61** (2021) 116006
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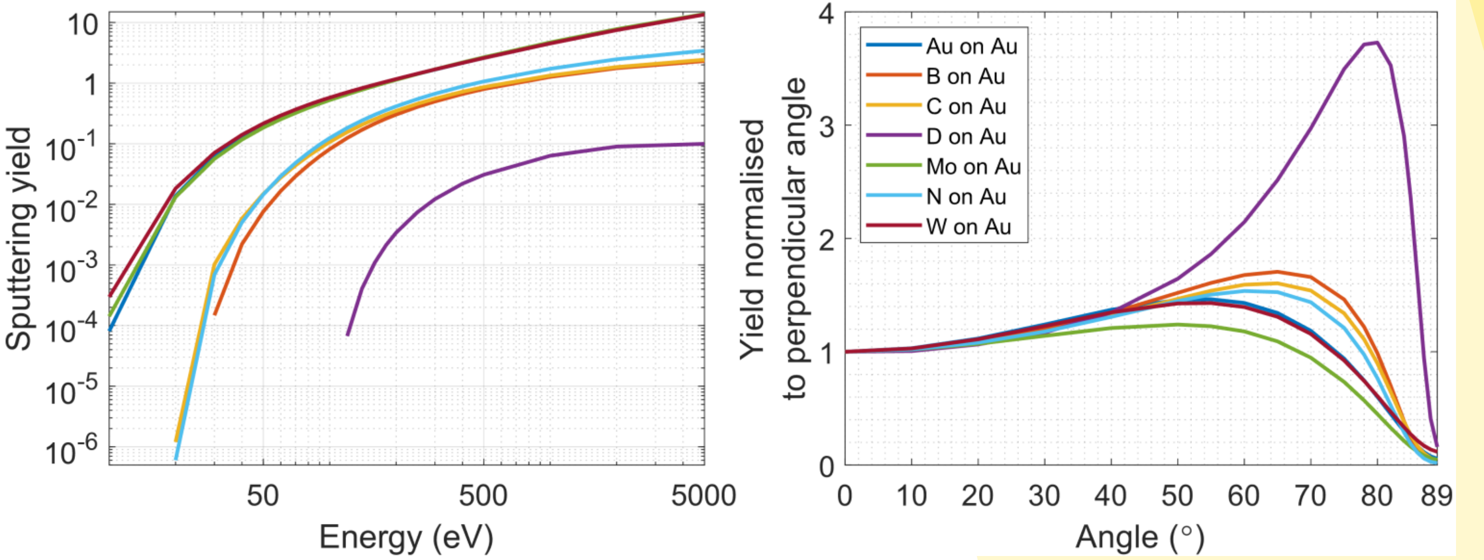
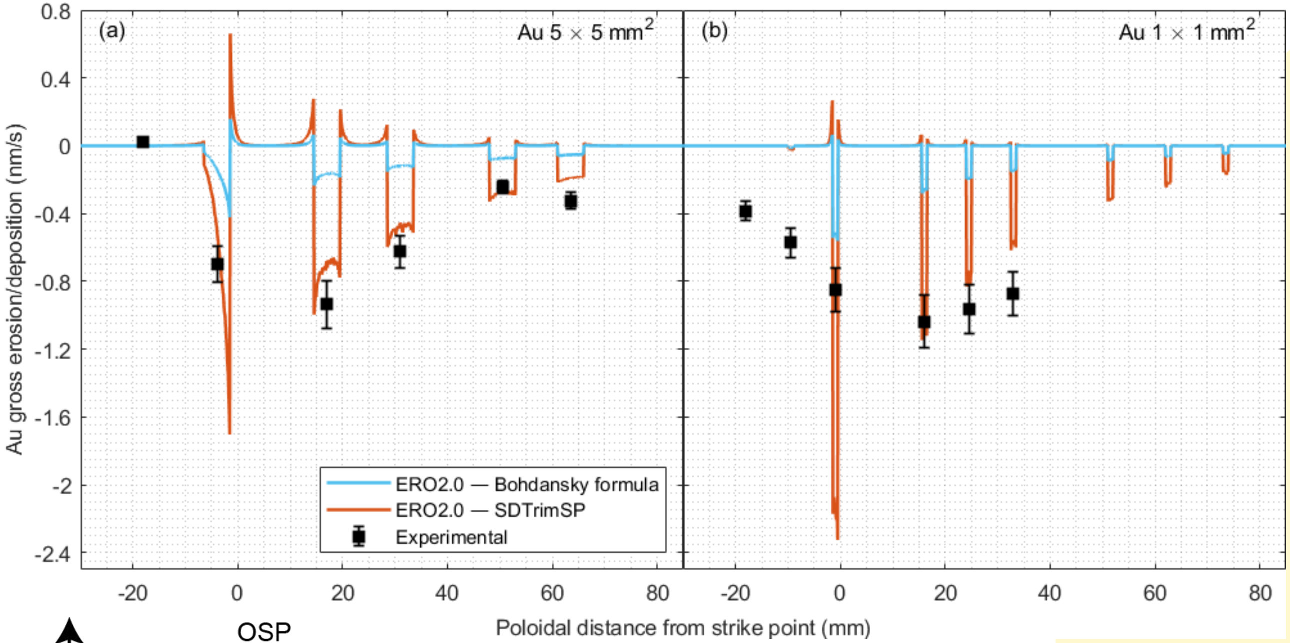
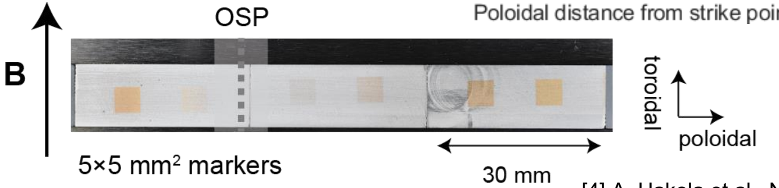
Sputtering data

- Angle dependent erosion and reflection data for Au computed using **SDTrimSP**
- Angle dependent results are compared to previously used sputtering yields provided by the **Bohdansky formula** with no angle dependency [4]



Net erosion of Au markers reproduced reasonably well in ERO2.0 simulations with new SDTrimSP sputtering data

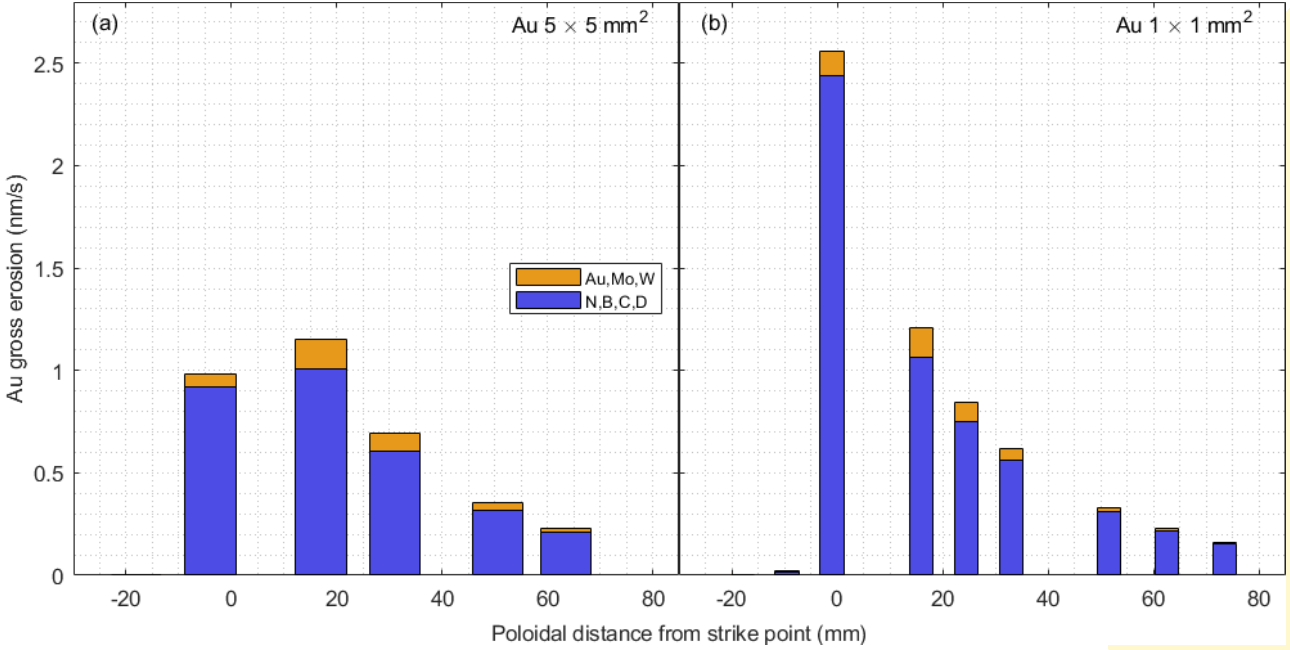




- **Significantly improved match** to measured **net erosion of Au** with new **SDTrimSP** data with respect to estimates given by the Bohdansky formula
- **Deviations** around OSP and PFR arise from (i) uncertainties in **location** of **OSP** and **absence of LP data** in its immeadiate surroundings, (ii) **shape** of n_e and T_e **profiles** in the PFR and (iii) **experimental uncertainties**

[4] A. Hakola et al., Nucl. Mater. Energy **25** (2020) 100863

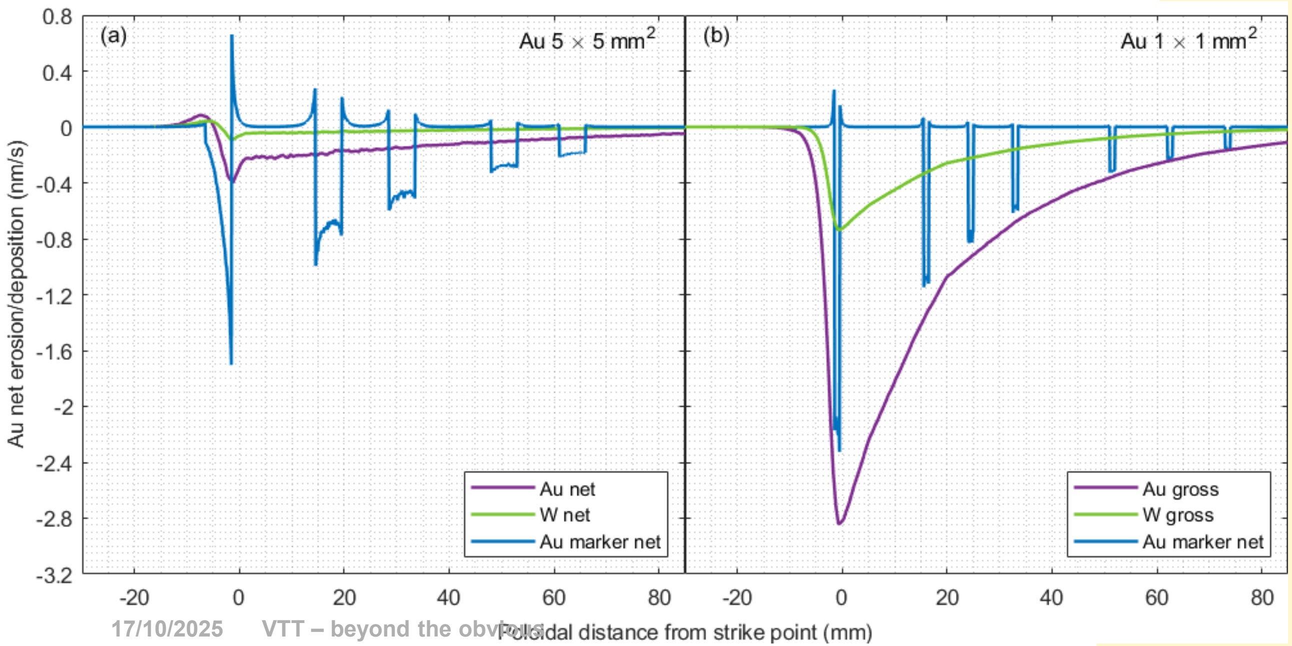
The effect of different impurities on gross erosion



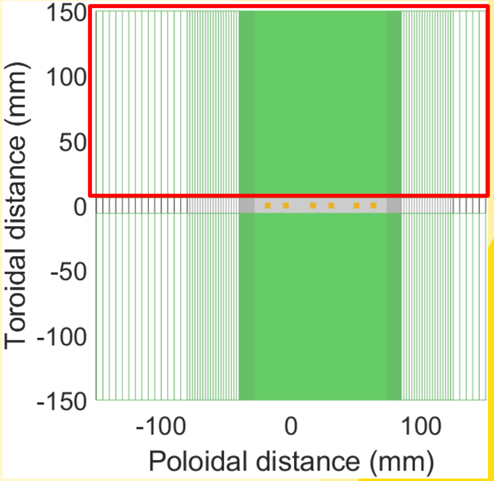
- **Gross erosion** of surfaces is primarily driven by **light B, C, and N impurities**
  - Simulation sensitive to impurity concentration → calls for further studies
- Eroded Au, Mo, or W have **minor role** in sputtering
  - Eroded material **promptly re-deposited** as low-energy particles

Au as proxy for W

- Net erosion of **toroidally extended Au** surfaces (fig. a) **3—6** times **higher** in comparison to **W**
- **Gross erosion** of **toroidally extended Au** surfaces (fig. b) **4—6 times higher** in comparison to **W**
  → Au erosion substantially higher in comparison to W. **Au suboptimal** proxy for quantitative assessment of **W erosion**



Toroidally extended Au/W surface (changed from W to Au in some simulations)



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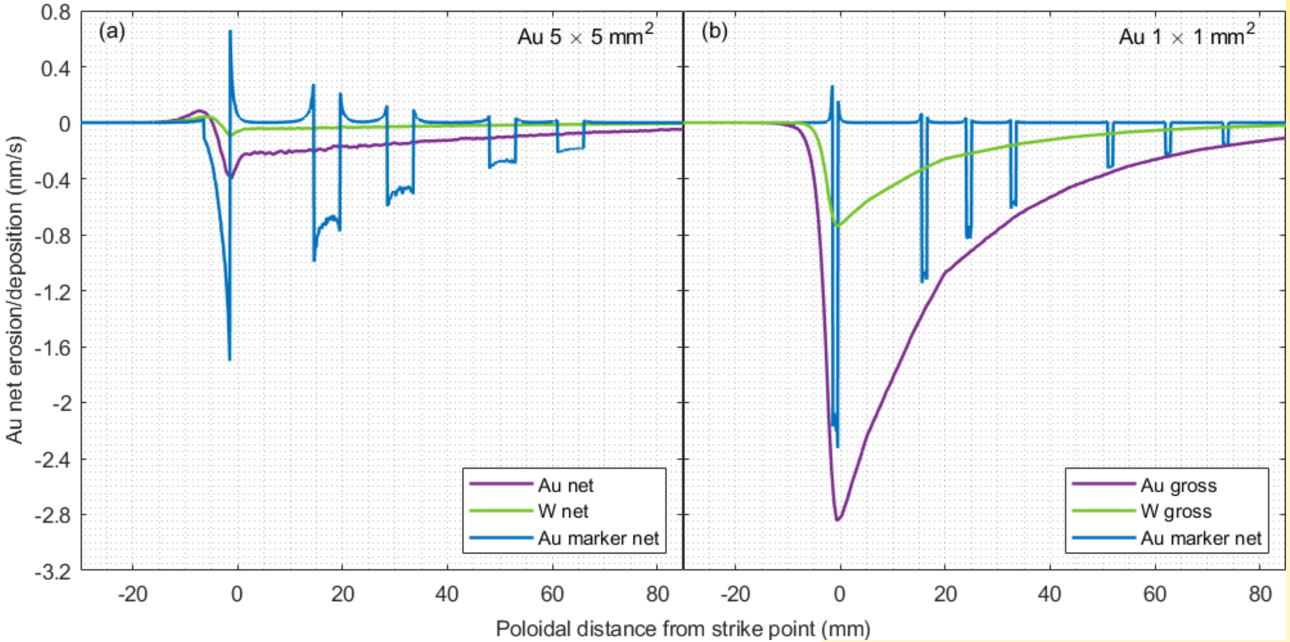
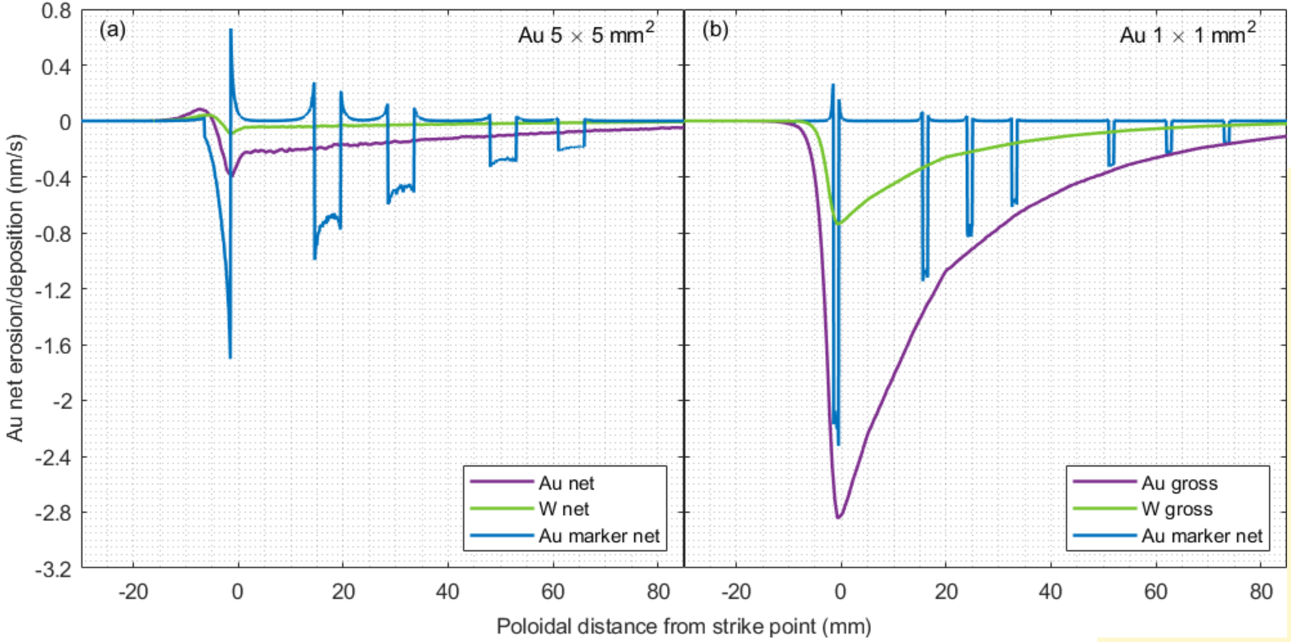


- **Net erosion** of **5 × 5 mm²** markers **2—6 times higher** in comparison to **toroidally extended Au** surfaces
  → 5 × 5 mm² markers **too small in toroidal direction** for **net erosion studies** due to re-deposition of eroded Au largely toroidally downstream from the marker surfaces

Au as proxy for W



- **Agreement within 20%** **between net erosion of 1 × 1 mm²** Au markers and **gross erosion** of **toroidally extended Au** surfaces
  - → 1 × 1 mm² markers **suitable** for gross erosion studies

⇒ **Net and gross erosion of W overestimated** by factors of 15—20 and 3—4 by **Au markers** due to material and geometry effects

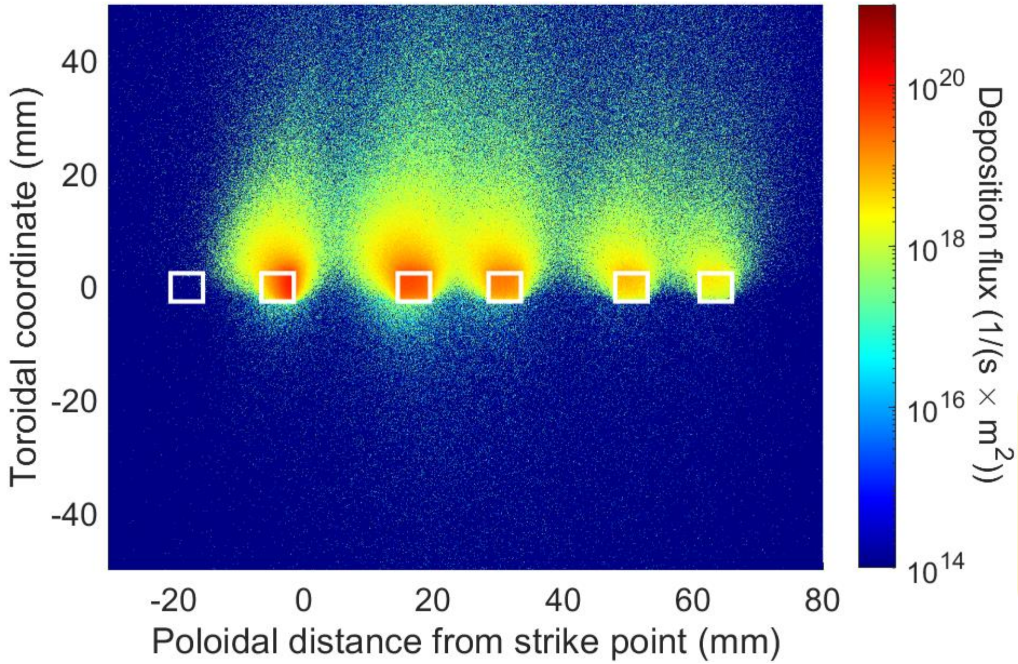
Conclusions

⇒ Erosion of Au markers near the outer strike point of AUG simulated using ERO2.0 and SDTrimSP

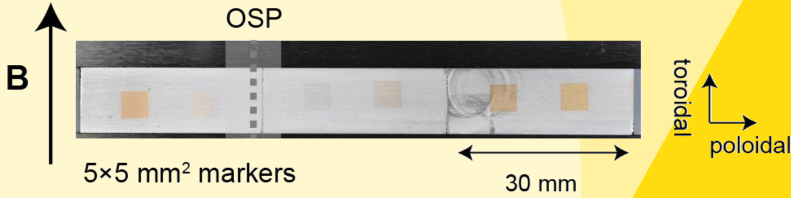
- ✓ Improved agreement between simulated and measured net erosion of Au particularly due to adoption of new sputtering and reflection data created with SDTrimSP
- ✓ Net erosion was found to be caused mostly by light impurities of the background plasma
- ✓ Au was found to be a poor proxy for quantitative assessment of W erosion; 5 × 5 mm² markers too small in toroidal direction for studying net erosion.
  - ➢ New experiments are needed with better proxy materials, such as Pt, and improved marker geometries for net erosion studies

Backup slides

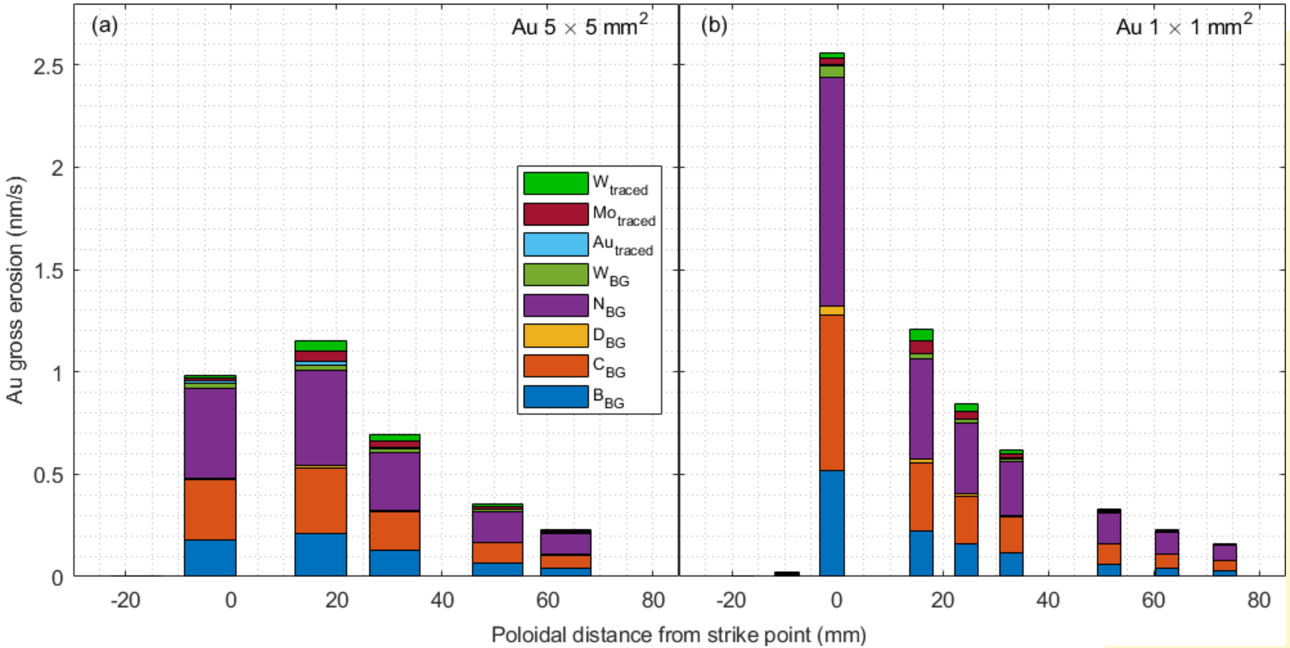
Deposition of particles



- Narrow net **deposition peaks** next to markers due to **re-deposition** of material eroded from marker **edges**
- **Migration** of **particles** is primarily in the **toroidal direction**



Impact of impurities



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