EUROfusion

Simulations for GyM and AUG

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Linked third parties: Politecnico di Milano, ISTP-CNR

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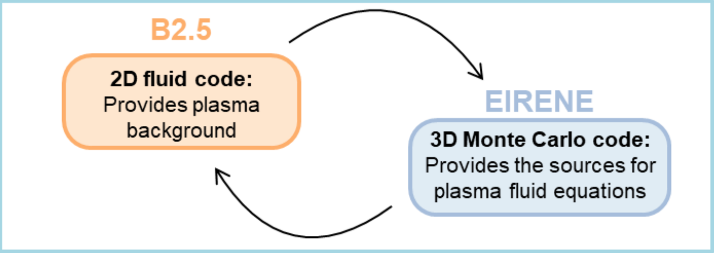
General framework of PoliMi modelling activities

SOLPS-ITER code

2D multi-fluid model

[S. Wiesen, et al., JNM 463(2015)480-4]



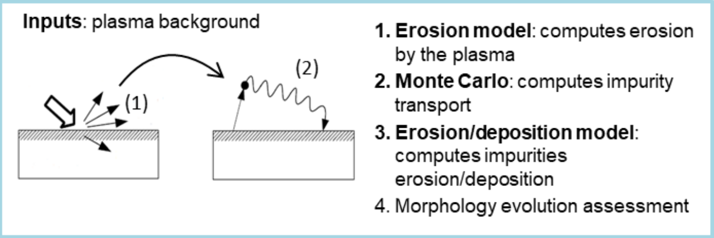
Edge relevant plasma modelling:

- Investigation of **helium plasmas** properties in tokamaks (AUG, under WP TE) and LPDs (GyM, WP PWIE)
- Investigation of **negative triangularity** plasma in TCV (WP TE)

ERO2.0 code

3D Monte Carlo and impurity transport

[A. Eksaeva, et al., NME 12(2017)253-60]

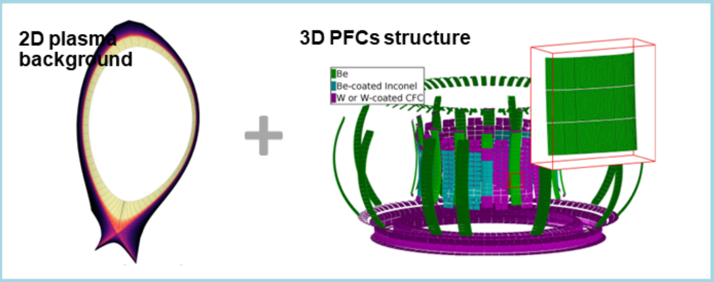


Micro-scale morphology evolution studies (under WP PWIE):

- Comparison with **analytical models**
- Interpretative simulations of the erosion of experimental samples with **different roughness**

Global coupling

of SOLPS-ITER and ERO2.0



Investigation of net and gross erosion of PFCs in tokamaks and LPDs:

- Development of **coupling procedure**
- Comparison with **erosion experiments**

Outline

1. SOLPS-ITER modelling in GyM

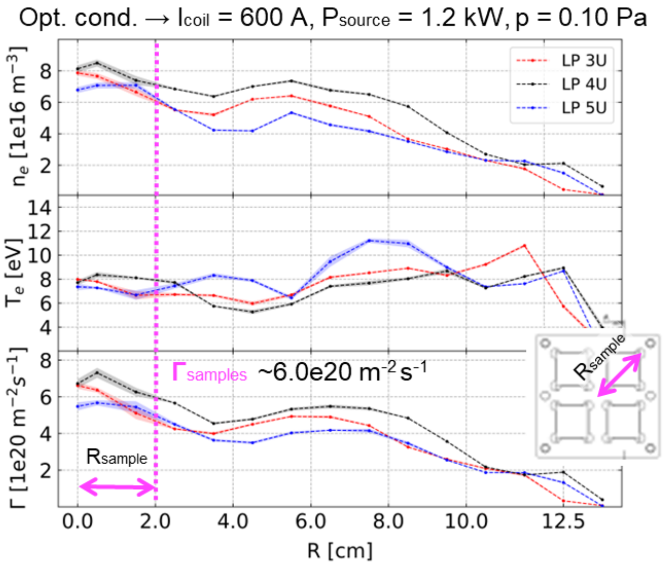
2. Global ERO2.0 simulations in GyM

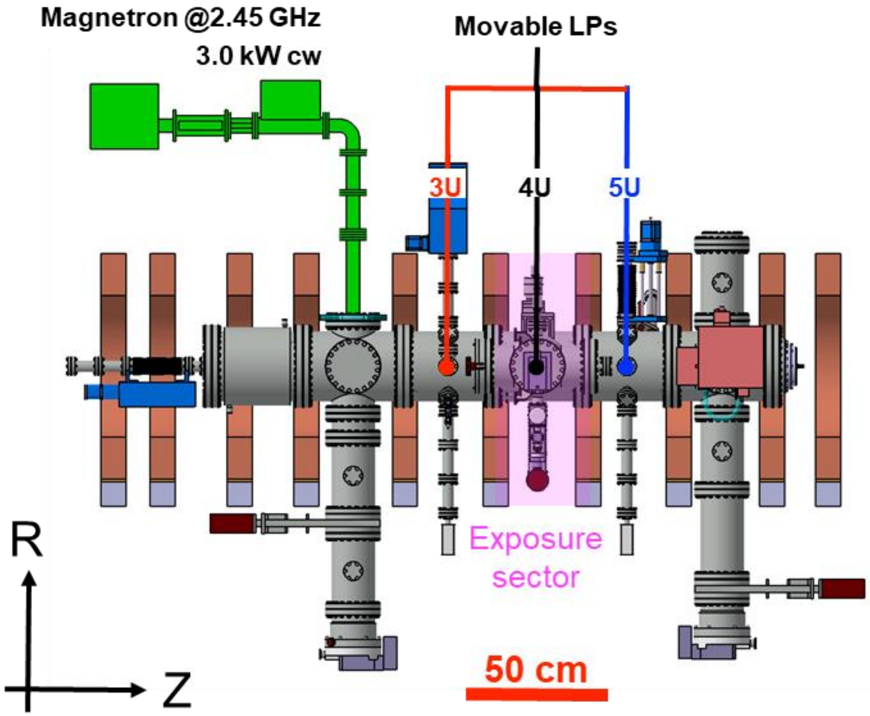
3. ERO2.0 erosion/deposition in AUG

4. ERO2.0 morphology evolution modelling

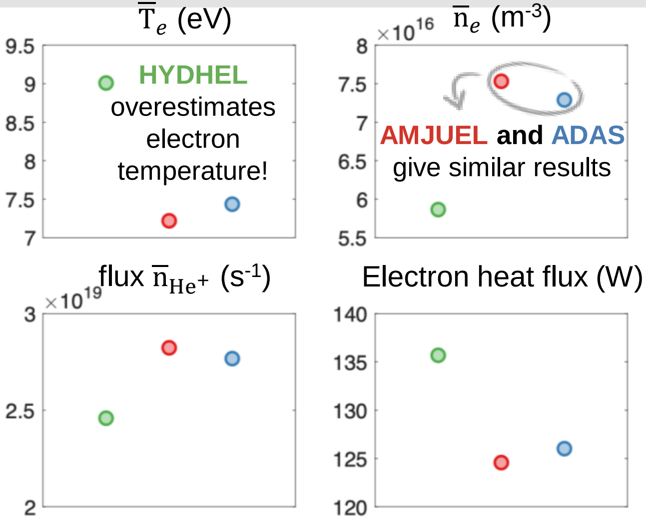
GyM linear plasma device

Vacuum vessel:	**Stainless steel** (SS): L = 2.11 m, Ø = 25 cm (optional: **SS liner with W coating**)
Pumping system:	**2 turbopumps:** p_{base} = 1E-8 mbar, p_{work} < 1E-3 mbar
Working gas:	H_2, D_2, N_2, He, Ar, He+NH_3 and mixtures

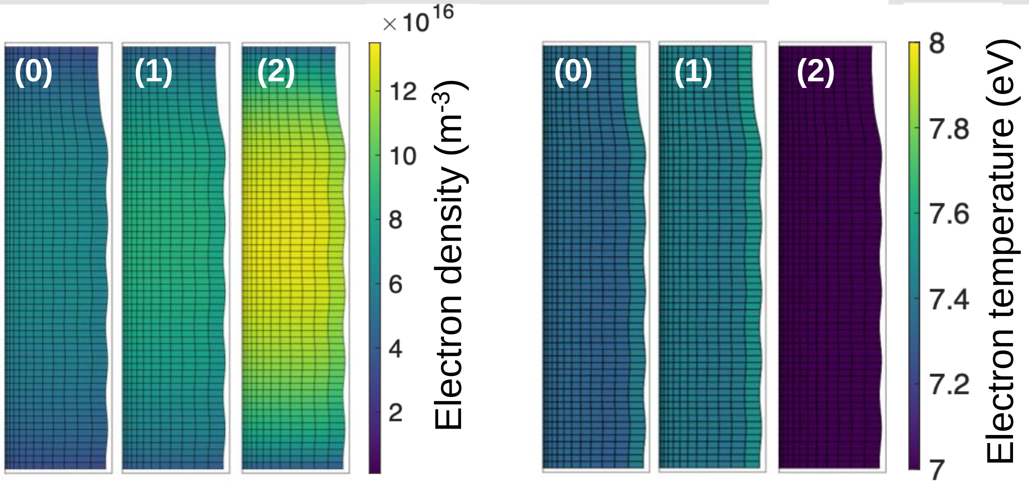




Helium databases and atomic reaction set



HYDHEL and AMJUEL from http://eirene.de/ (D. Reiter), ADAS from https://open.adas.ac.uk/



(0) Default SOLPS-ITER (1) Default SOLPS-ITER + $\mathrm{EHL_{rad}}$ (2) Default SOLPS-ITER + CX

Objective: studying He plasma properties in GyM in order to provide a plasma background for ERO2.0 simulations

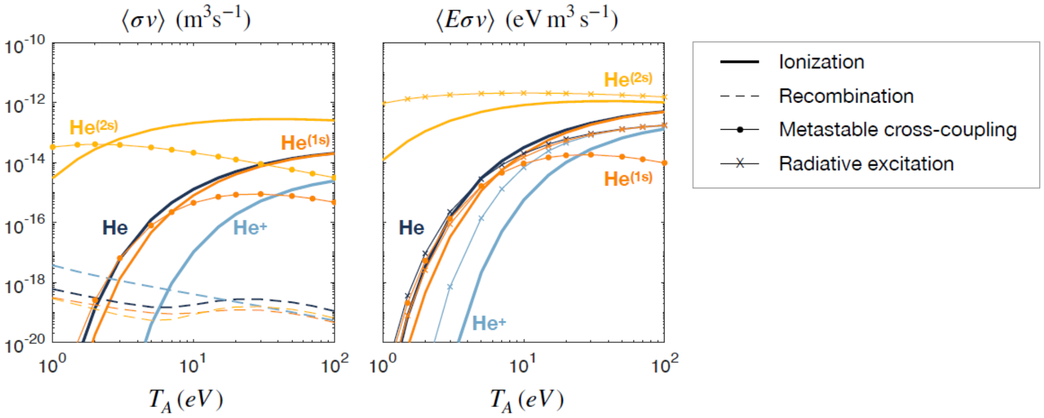
- ✓ Ionization (IZ) reaction rates from different databases (HYDHEL, ADAS and AMJUEL) can produce differences up to 20% in T_e and n_e
- ✓ Including electron neutral excitation ($\mathrm{EHL_{rad}}$) of He atoms (without resolving metastable states) leads to global increase in n_e
- ✓ Including charge exchange (CX) reactions between He-He^+ and He-He^{++} leads to increase in n_e, consistent with the collisional drag, and a reduction of T_e . Important effect in GyM due to high neutral density
- ✓ New default set of reactions and database for He plasma modelling with SOLPS-ITER

SOLPS-ITER modelling in GyM

Investigation of He metastable states (MS) in low-temperature plasmas

- Implementation of MS resolved model (ADAS rate coefficients, left figures) in the 0D model [Tonello E. et al, NF 2021], already benchmarked with SOLPS-ITER.
- Results show small difference between metastable resolved and un-resolved models in GyM conditions (right figures)

Further development: Implementation of MS in EIRENE input file



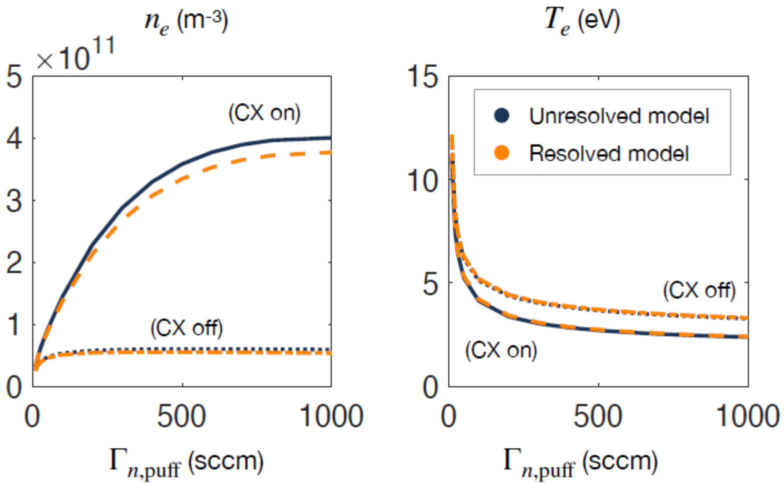


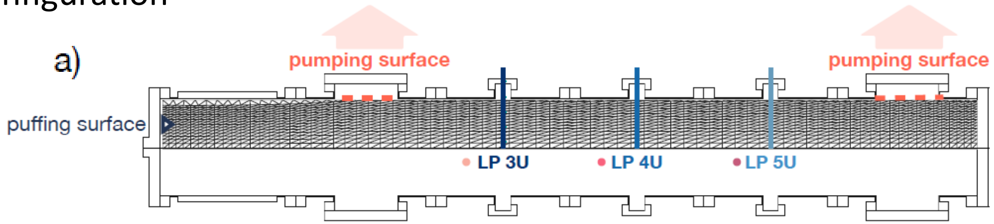
Fig. *Reaction rate coefficients (ADAS) for He with metastables resolved (left). Results of 0D model resolved vs. un-resolved (right).*

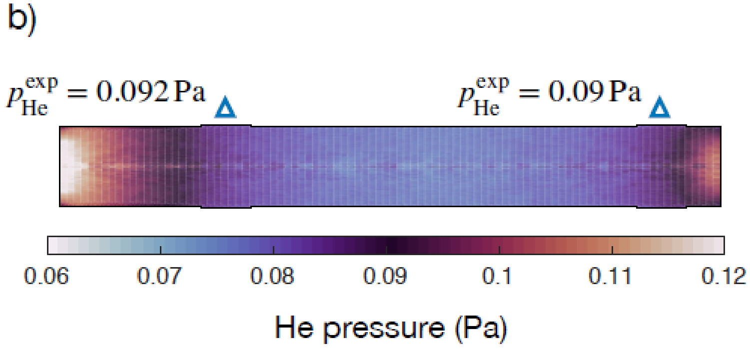
SOLPS-ITER modelling in GyM

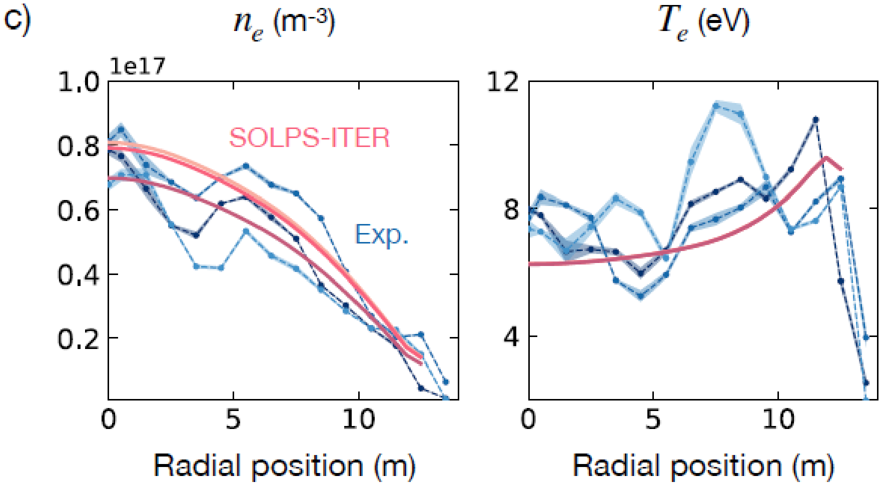
Benchmark of SOLPS-ITER simulations with experimental LP data from GyM

- Optimisation of simulation input (recycling coefficients, D_n, P_{ext}) to obtain good agreement with GyM experimental Langmuir probes (LP) data in the full machine configuration

__Fig. a)__ Setup for benchmark of experiments with SOLPS-ITER. __b)__ Helium gas pressure. __c)__ Comparison between SOLPS-ITER simulations and exp. LP results.







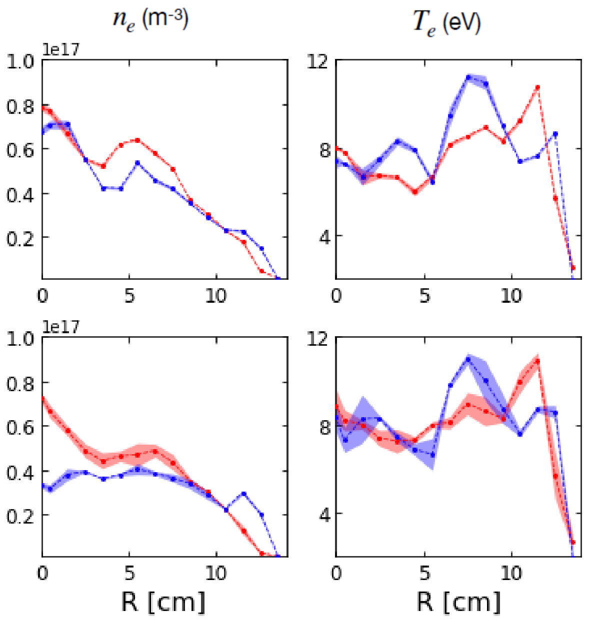
SOLPS-ITER modelling in GyM

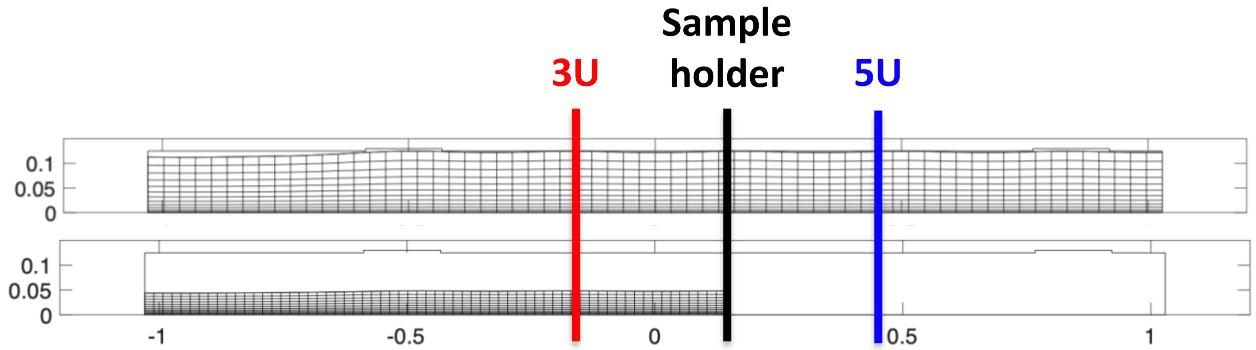
Next steps:

- Experimental LP data show **effect of sample holder presence** on plasma density beyond it (**LP 5U**)
- Up to now, SOLPS-ITER could not simulate plasma at **high radius** and **beyond sample holder** in this configuration
- **B2.5 extended mesh** could allow this modelling (SOLPS-ITER training workshop @KU Leuven next November)

(i) Full machine (no sample holder

(ii) Sample holder inserted





B2.5 mesh

(i) Full machine configuration

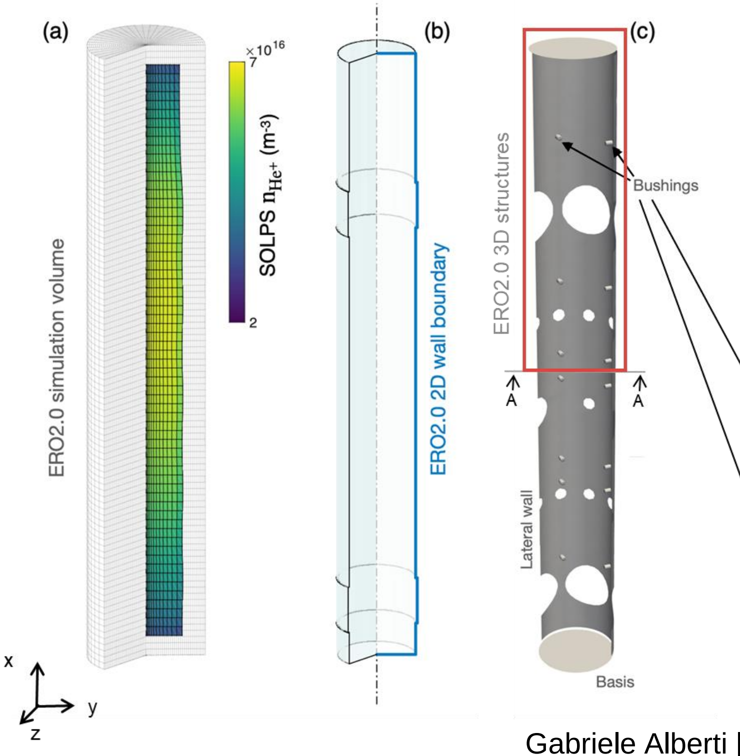
(ii) Sample holder configuration

Outline

1. SOLPS-ITER modelling in GyM
2. Global ERO2.0 simulations in GyM
3. ERO2.0 erosion/deposition in AUG
4. ERO2.0 morphology evolution modelling

Global ERO2.0 simulations in GyM

Objective: Exploiting the coupling between SOLPS-ITER and ERO2.0 in a linear plasma device to study erosion of internal walls and impurity migration in GyM helium plasma

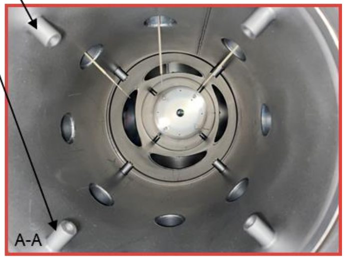


(a) 3D plasma background for ERO2.0

- 2D SOLPS-ITER plasma background interpolated on the (x, y) plane of 3D ERO2.0 mesh
- *Axial symmetry* is assumed

(b) 2D ERO2.0 domain boundary

- 2D SOLPS-ITER plasma background is extrapolated up to this boundary
- *Axial symmetry* is assumed



(c) 3D GyM wall structures

- Used by ERO2.0 to assess erosion/deposition of walls (bases and lateral wall of vacuum chamber and bushings)
- Drawn in CAD: *no axial symmetry* required

Global ERO2.0 simulations in GyM

Varied parameters:

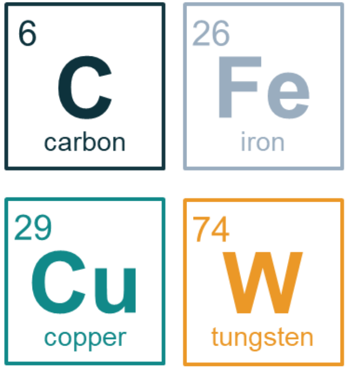
GyM vacuum chamber material

6 C carbon	26 Fe iron	29 Cu copper	74 W tungsten
Common fusion material	**Main component of GyM steel**	**Proxy of other ligants in GyM steel**	**Common fusion material**

Bias voltage applied to the walls

Bias voltage [V]
0
- 20
- 100
- 200

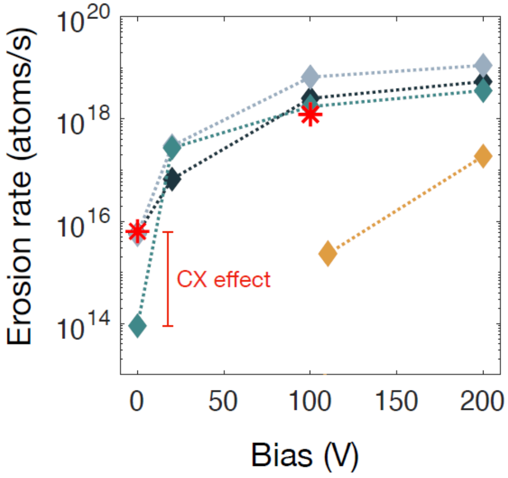
Global ERO2.0 simulations in GyM



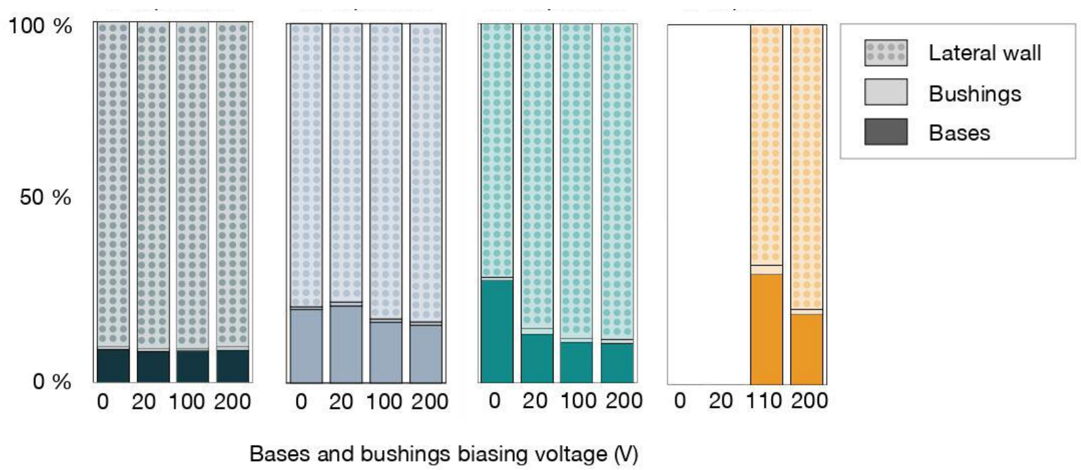
Main results:

- Lowest erosion for **W** (not eroded for V_{bias} < 110 V), highest for **Fe**
- **Bases** and **bushings** are main **erosion sources**, **lateral wall** main **deposition zone**
- Deposition on lateral wall generally increases at high V_{bias}

Gross erosion



Deposition



Global ERO2.0 simulations in GyM

Under review for Nuclear Fusion

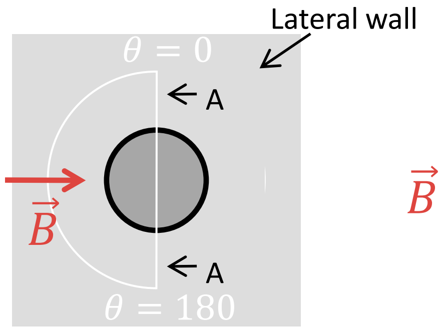
Angular distribution of erosion is studied on lateral surfaces of bushings:

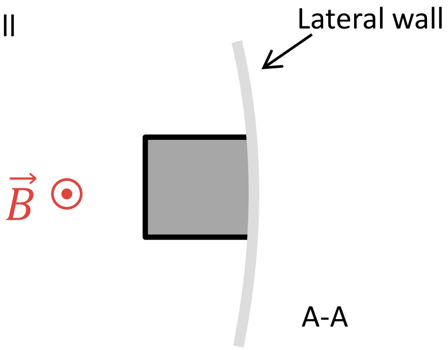
a. $\vec{B}$ impinges on lateral side of GyM bushings: full distribution for He plasma ions incidence angle (no sheath-tracing model is used)

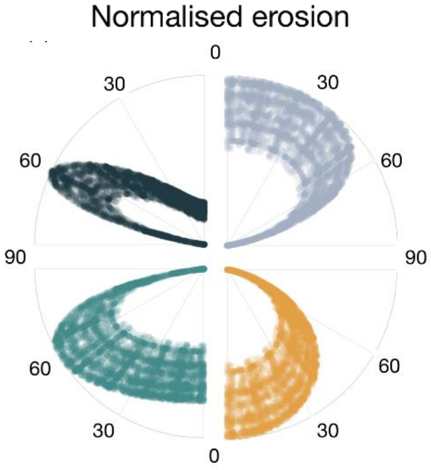
b. poloidal plot shows erosion normalised to the peak values for each material

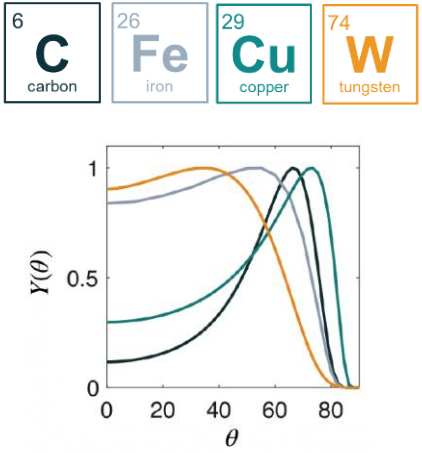
The angular position of the peak depends on two opposite effects: Y increases towards grazing incidence (higher erosion); the flux decreases towards grazing incidence (lower erosion)

The variation of $Y(\theta)$ depends on the material: e.g. for W mild $Y(\theta)$ dependence = maximum erosion at normal incidence ($\theta = 90°$)









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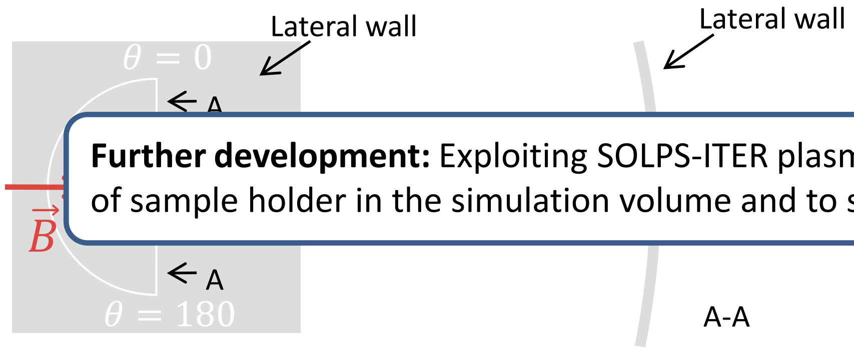
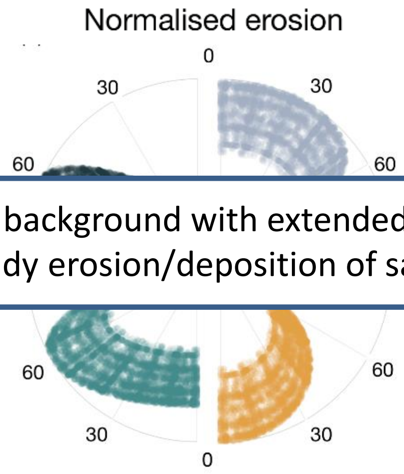
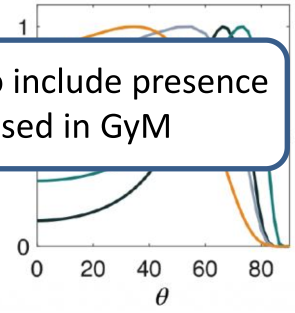






Further development: Exploiting SOLPS-ITER plasma background with extended B2.5 grid to include presence of sample holder in the simulation volume and to study erosion/deposition of samples exposed in GyM

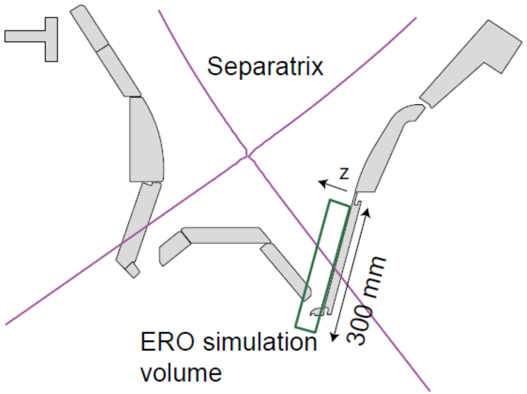
Outline

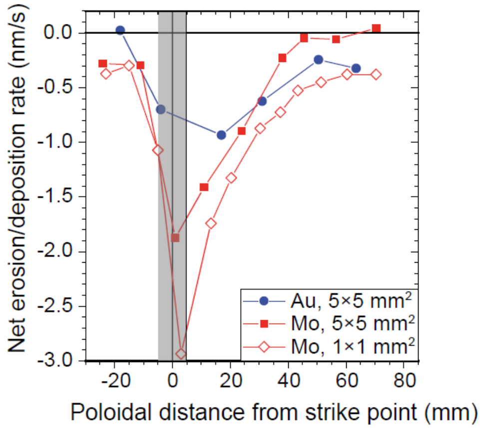
1. SOLPS-ITER modelling in GyM
2. Global ERO2.0 simulations in GyM
3. ERO2.0 erosion/deposition in AUG
4. ERO2.0 morphology evolution modelling

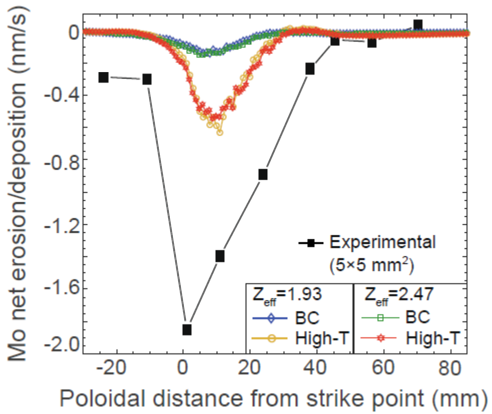
Previous AUG erosion/deposition experiments

- Eight **L-mode D-plasma** discharges (#35609-35617)
- Measured erosion of **Mo** and **Au** markers close to outer strike point (OSP)
- ERO1.0 modelling to simulate markers erosion/deposition in **small volume around markers**
- **W**, **C**, **B** and **N** impurities considered in plasma for ERO modelling

Objective of our work: Exploiting ERO2.0 extended simulation volume to estimate role of impurities eroded from FW on divertor markers erosion







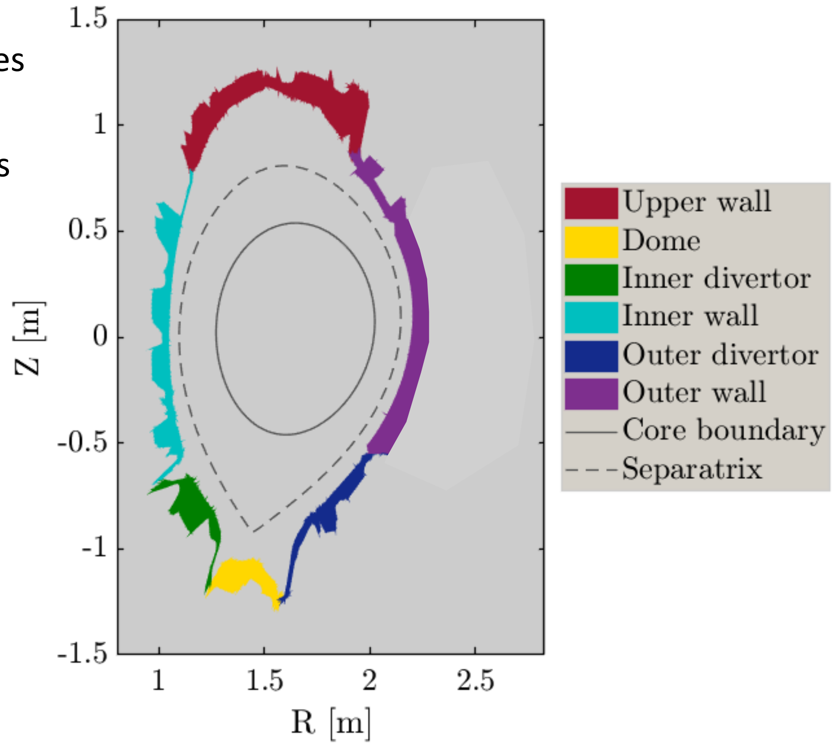
ERO2.0 erosion/deposition in AUG

Simulations setup

- **D plasma** from SOLPS-ITER with C (1.0%) and W (0.01%) impurities
- **80° sector** with **periodic BC**
- **3D full-W** wall divided into 6 parts to distinguish impurity sources
- Inner **core** boundary at 0.7 r_{sep}
- Single time step of 1s

Analyzed parameters

- Plasma **shadowing** effects (**- 50%** of erosion)
- Migration studied from each FW component individually
- **Extrapolation method** of SOLPS-ITER solution to the wall
- Plasma w/o **W** impurities
- Multiple time steps



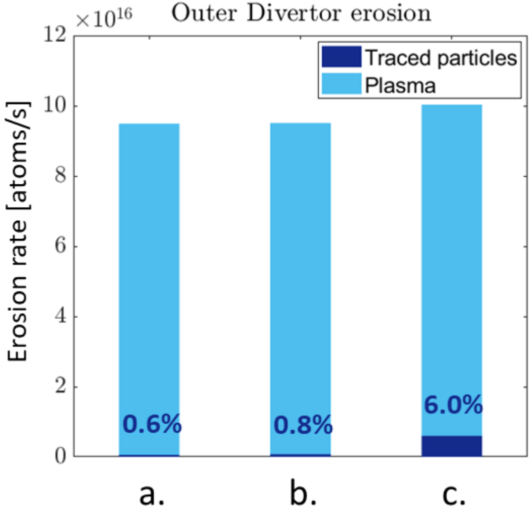
ERO2.0 erosion/deposition in AUG

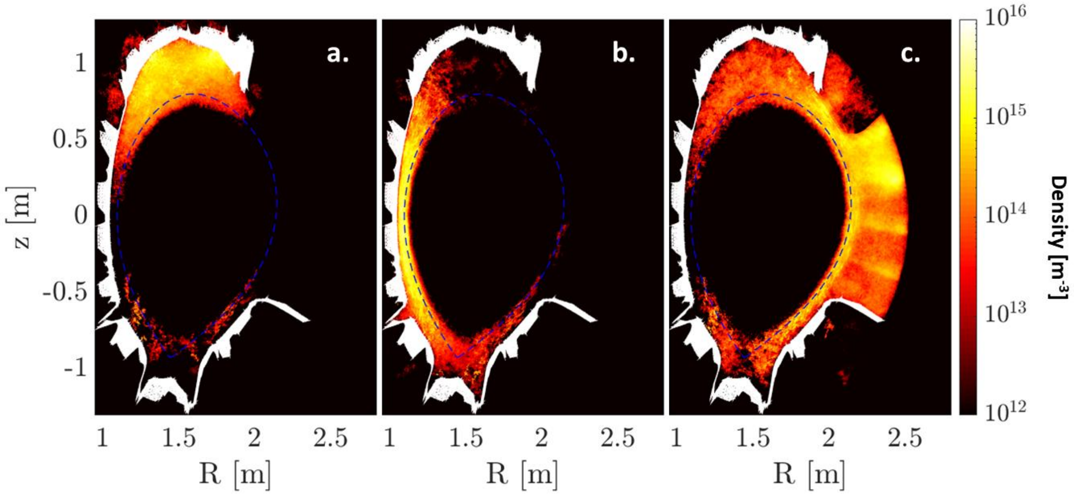
Contribution to divertor erosion from different PFCs

3 different simulations: a) **Upper** wall erosion, b) **Inner** wall erosion, c) **Outer** wall erosion

- Highest contribution to **outer divertor** erosion due to **plasma**, W particles eroded from **outer wall** contribute to about **6%** (only outer wall considered in the following)
- Highest probability of reaching **core** for **inner wall W** impurities

	a. Upper wall	b. Inner wall	c. Outer wall
Core reflection [%]	5.7	46.8	12.7



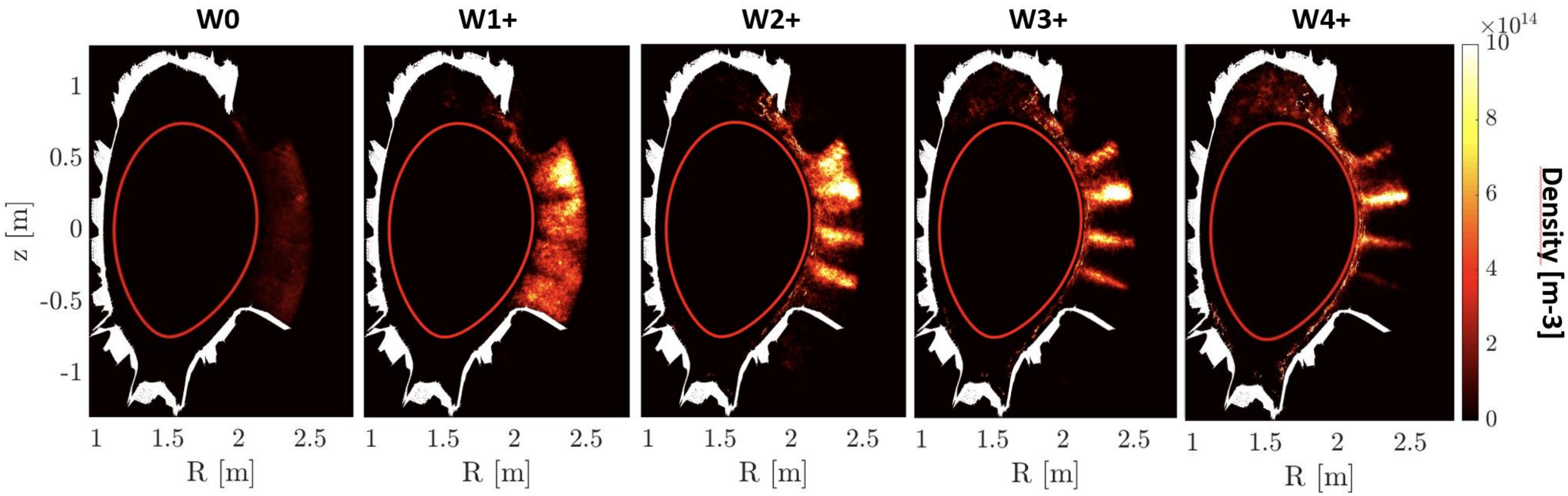


ERO2.0 erosion/deposition in AUG

Effect of particle charge on impurity migration

W particles eroded from outer wall

- Lower ionized W impurities more localized near production areas
- Particles in **higher ionization states** can migrate towards different PFCs (main contributors to outer divertor erosion)

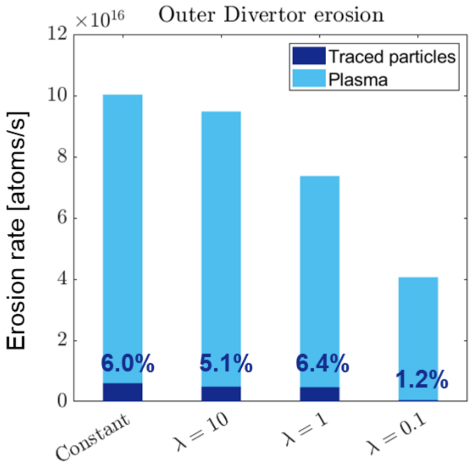


ERO2.0 erosion/deposition in AUG

Effect of extrapolation method of SOLPS-ITER plasma to 3D walls

4 different simulations, varying from constant extrapolation to exponential decay with different characteristic lengths λ (10, 1 and 0.1)

- **Outer wall** erosion deeply affected by extrapolation method (about **factor 200 reduction**, compared to < factor 3 for outer divertor)
- As a consequence, **contribution of outer wall impurities** on divertor erosion **decreases at lower λ**
- Probability of reaching **core boundary** for outer wall impurities **increases at lower λ** due to lower plasma density and temperature at edge



	Constant	λ = 10	λ = 1	λ = 0.1
Divertor erosion rate [$10^{16}/m^2$ s]	3.46	3.28	2.55	1.40
Outer wall erosion rate [$10^{16}/m^2$ s]	26.4	23.2	7.90	0.14
Core reflection [%]	12.7	14.8	32.8	215

ERO2.0 erosion/deposition in AUG

Effect of W impurities in the plasma

- **Removing W** impurities (0.01%) in D plasma deeply affects **divertor** erosion (**> factor 10 reduction**, compared to < factor 2 for outer wall)
- As a consequence, the **contribution of** W particles eroded from **outer wall** to divertor erosion **increases** (14.4% against previous 6.0%)

	w/o W in plasma	with W in plasma
Divertor erosion rate [$10^{16}/m^2$ s]	0.24	3.46
Outer wall erosion rate [$10^{16}/m^2$ s]	16.3	26.4
W from FW contribution [%]	14.4	6.0

Effect of multiple time steps

Up to 10 time-steps for a total of **10s discharge** simulated

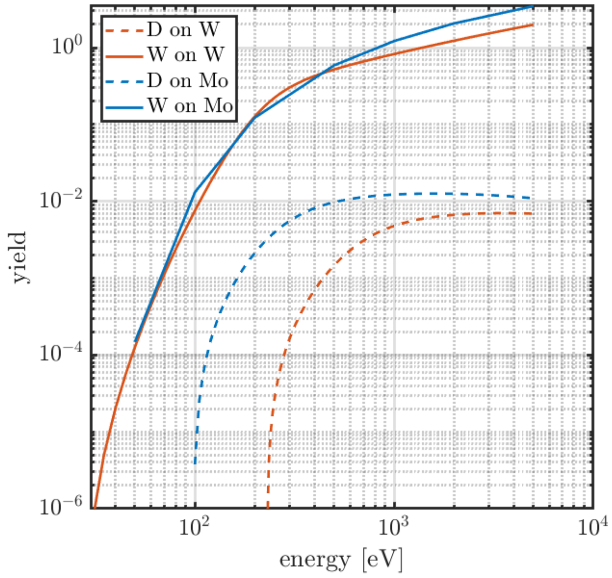
- **No significant differences** observed for the reported global results (local effects observed, especially regarding erosion of plasma shadowed areas)

ERO2.0 erosion/deposition in AUG

Molybdenum (Mo) as outer divertor material

- **Mo** presents 30 times higher erosion wrt **W**, especially due to D-plasma
- Almost **doubled erosion due to W from FW** for Mo
- **Erosion %** due to FW W **decreases for Mo**

	W divertor	Mo divertor
Divertor erosion rate [10^{16}/m² s]	0.24	8.27
W from FW contribution [%]	14.4	0.8



Further developments:

- Comparison with experimental data and ERO1.0 modelling
- Consider also erosion from CX neutrals

Outline

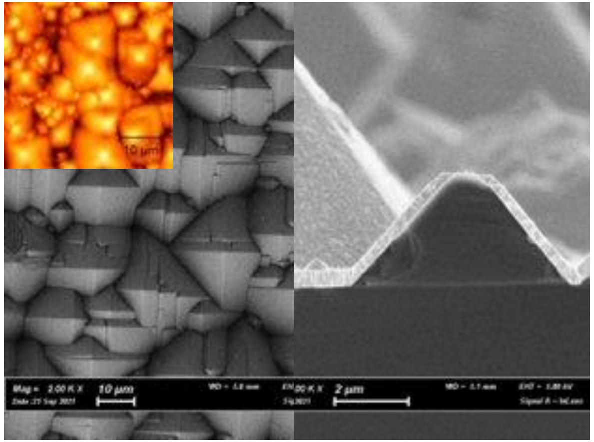
1. SOLPS-ITER modelling in GyM
2. Global ERO2.0 simulations in GyM
3. ERO2.0 erosion/deposition in AUG
4. ERO2.0 morphology evolution modelling

ERO2.0 morphology evolution modelling: experimental results

Motivation : Previous work showed the dependence of ERO2.0 morphology evolution on few numerical parameters, e.g. time step and mesh resolution

Samples production and exposure

- pyramidal surfaces produced by chemical etching of Si wafers (@ ISTP-CNR) with different average surface roughnesses (300-600-900 nm)
- Deposition of compact W coating by means of HiPIMS technique (@ PoliMi)
- New exposure @ 350 eV to enhance samples erosion



Before and after exposures

- weighing to evaluate erosion using balance @ CNR-Mi
- AFM for topography evolution @ ISTP
- SEM morphology evolution @ PoliMi
- SEM statistical analysis of coating thickness variation in cross section @ PoliMi

He^+ energies [eV]	30	80	150	200	250	350

New exposure!

Below and above sputtering threshold for He on W (105-110 eV)

(F. Ferroni, et al., JNM 458 (2015) 419-24)

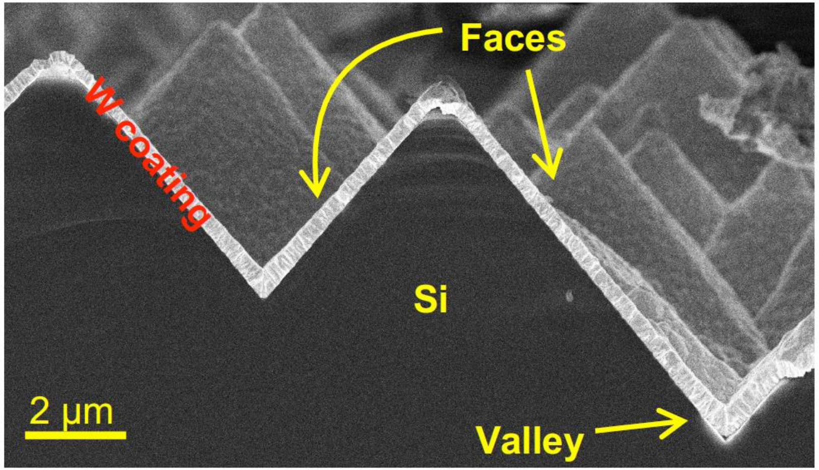
ERO2.0 morphology evolution modelling: experimental results

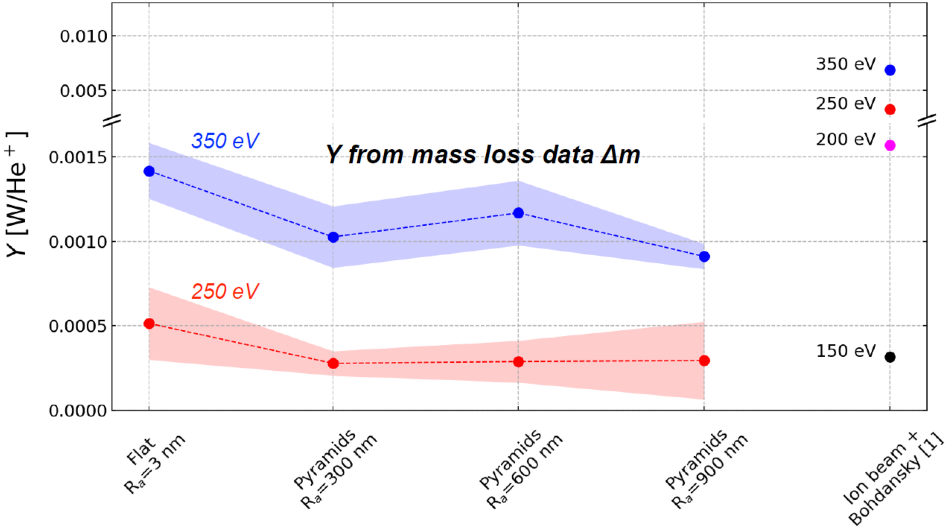
Net erosion statistical analysis

- $\Delta s_{flat} > \Delta s_{pyra}$ as expected in literature
- $\Delta s_{faces} > \Delta s_{valleys}$: possible deposition of sputtered particles from faces to valleys
- Further work needed to reduce uncertainty

350 eV	Flat	Pyr. Ra = 900 nm	
		Faces	Valleys
$\overline{\Delta s}[nm]$	60.7	49.4	34.6
$\sigma_{\Delta s}[nm]$	17.0	29.9	35.9

Less erosion than expected from Y_{sputt}!



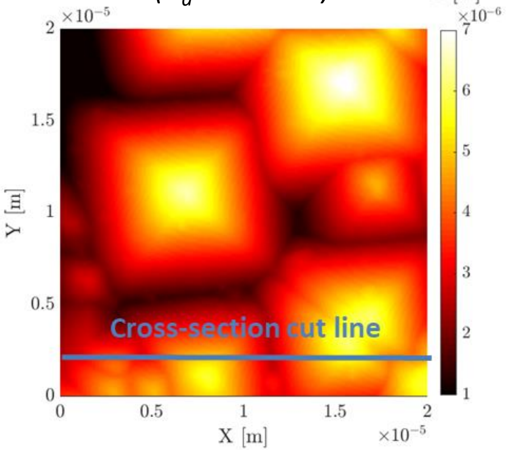


ERO2.0 morphology evolution modelling: ERO2.0 modelling

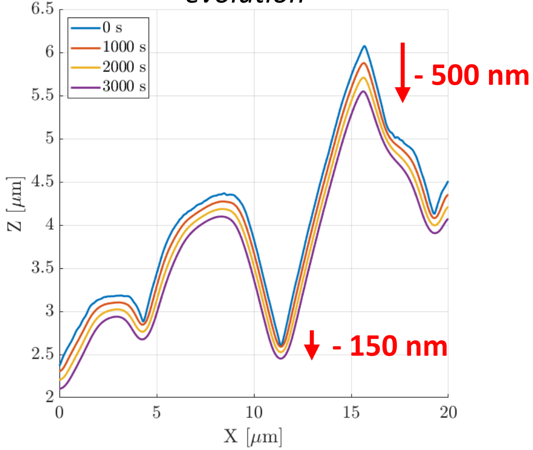
- ERO2.0 **overestimates erosion** of all samples, in agreement with available sputtering yields
- ERO2.0 predicts **more morphology variations than observed** in experiments (fig. b)
- $\mathbf{Y_{rough}/Y_{flat}}$ well reproduces experimental data for all roughnesses (fig. c)

Strategy: fixing physical parameters for quantitative agreement with flat surface and vary numerical ones to morphology evolution of pyramids

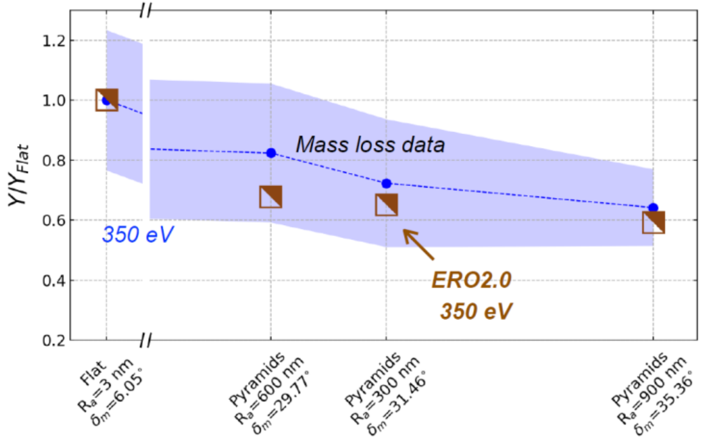
a) AFM-topography (R_a = 900 nm)



b) ERO2.0 morphology evolution



c) Y_{rough}/Y_{flat} compared to experimental data



Thank you for your attention!

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