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A multi-physics modeling approach to predicting erosion, re-deposition andgas retention in fusion tokamak divertors

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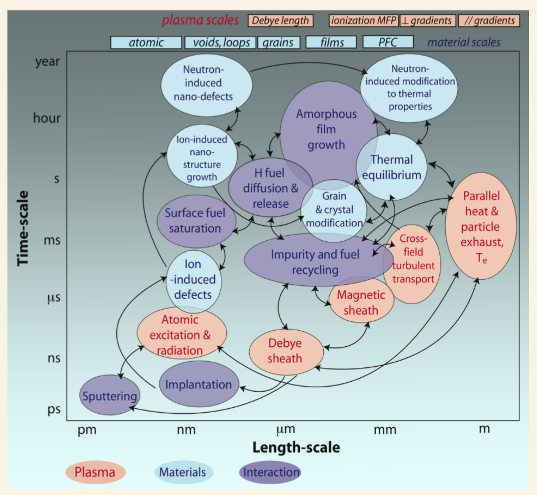
INTRODUCTION

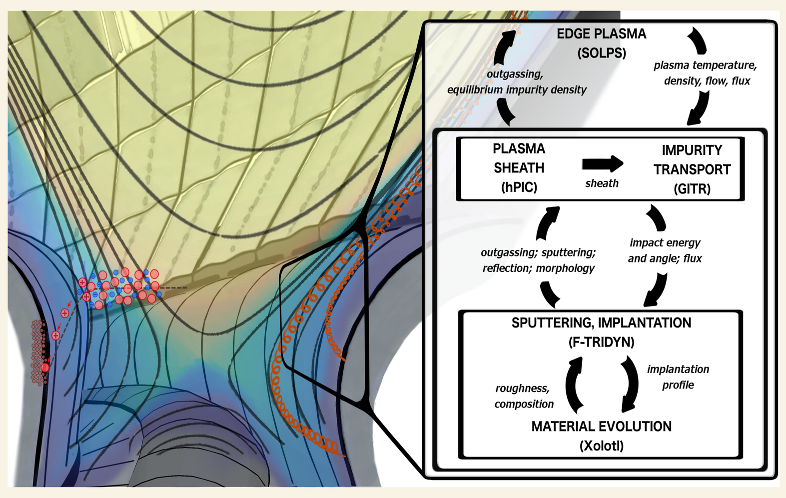
- Plasma-material interactions (PMI) are multi-physics and multi-scale in nature



- PMI compromise both material and plasma performance
  - Mutually degrade
  - Erosion, fuel retention, morphology changes…
- It's a multi-scale physics problem
  - Address it with multiple, high-fidelity models

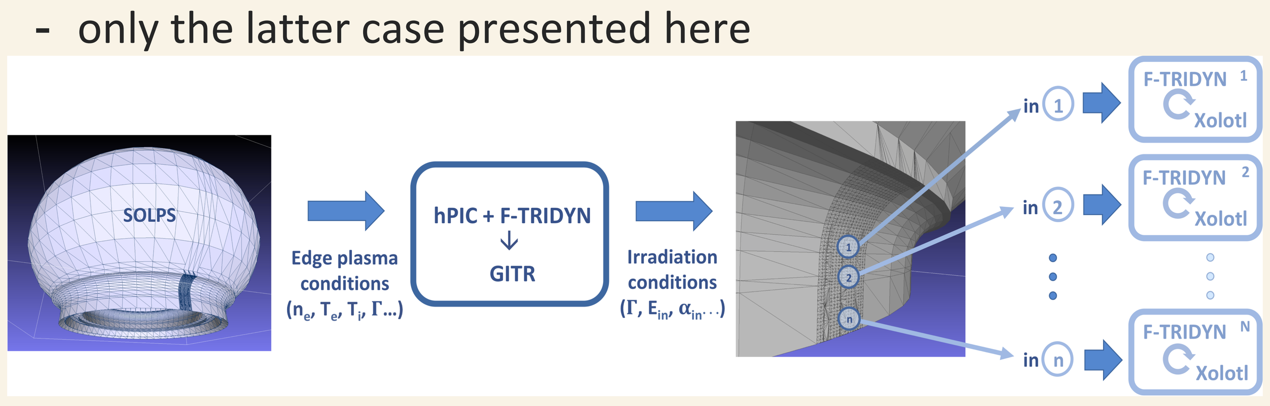
We developed a new integrated model for PMI

- Steady state plasmas only → one-way coupling
- Time-scale separation → run codes sequentially
- Modest data exchange → file-based coupling



The resulting integrated model is applied to simulate PMI in the ITER divertor

- The model was benchmarked against PISCES experiments
- It is here applied to exposure of the ITER divertor to He-operation and burning D-T plasmas
  - only the latter case presented here

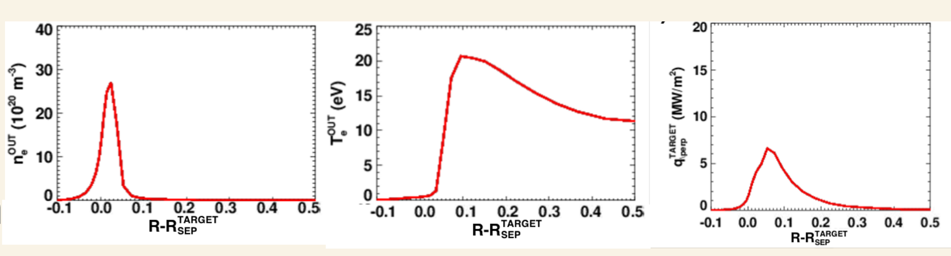


- *SOLPS:* 2-fluid model of edge plasma + kinetic neutrals; D-T plasma + He, Ne, Be (CX-only) ; provides edge plasma profiles
- *hPIC*: 1D3V PIC code; multi-species (D, T, He, Ne); 36 locations across the divertor; outputs impact energy-angle distributions
- *GITR*: W sputtering, ionization & transport in the divertor; in 3D, 2.5M particles, $O(10^6)$ time-steps; calculates W re-distribution
- *F-TRIDYN*: binary collision approximation code; provides sputtering and reflection yields, and implantation profiles
- *Xolotl*: cluster dynamics code; evolves the surface height and sub-surface gas concentrations due to clustering, trapping…

RESULTS

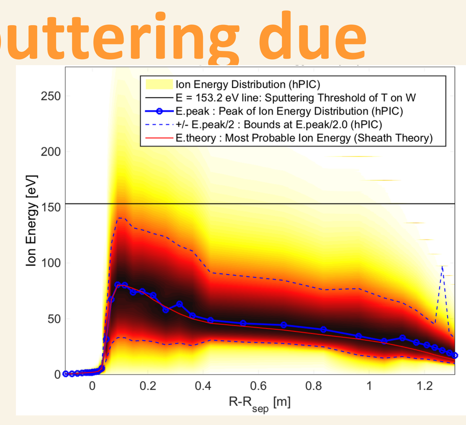
SOLPS-predicted plasma profiles are representative of a partially detached divertor

- P_{in}=100MW; P_{rad}=73 MW, mainly by Ne, in the divertor; q ~7 MW/m² at the target
- The plasma profiles consistent with a partially detached divertor



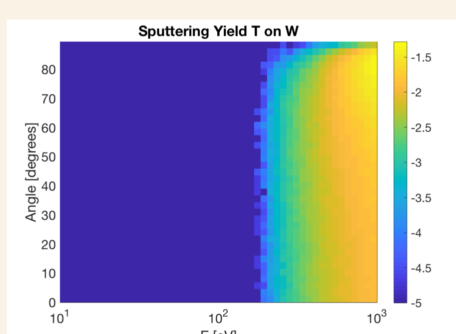
hPIC reveals that light ions contribute to sputtering due to the high-energy tail

- Peak of hPIC's distribution is consistent with the most probable energy expected from classical sheath theory
- Particles with E_{in} in the high-energy tail, as predicted by hPIC, contribute to sputtering of W by light species



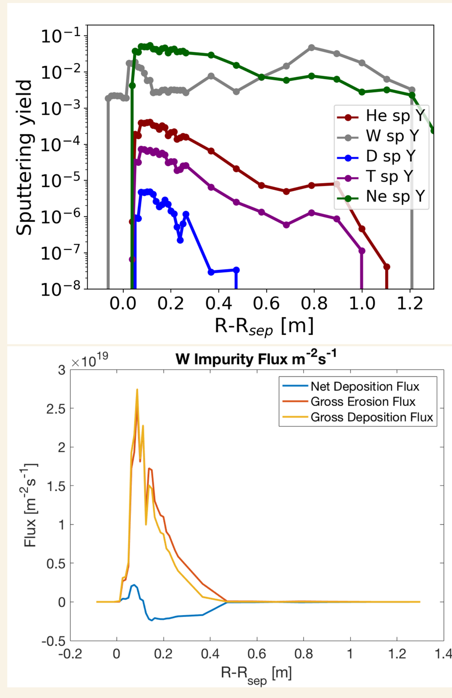
F-TRIDYN provides a high-resolution reduced model of sputtering and reflection

- To turn these fluxes and distributions into a W source, we build a reduced model for reflection and sputtering
- Based on $O(10^4)$ combinations of impact species, energy and angle



GITR models the W migration in the ITER divertor, showing strong local re-deposition

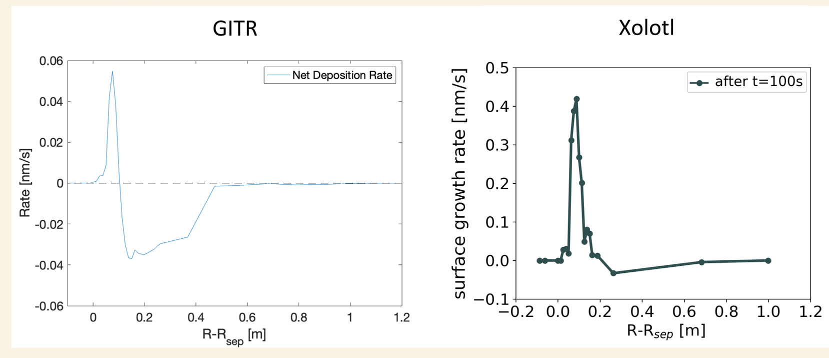
- Neon dominates surface sputtering, except near the strike point
- W erosion and re-deposition are strongly correlated: 93% prompt and local re-deposition
- Transport by local E fields and re-deposition in low T_i results in net deposition around the strike point and net erosion further along the target.



Similar surface height in Xolotl, with differences from sub-surface gas dynamics

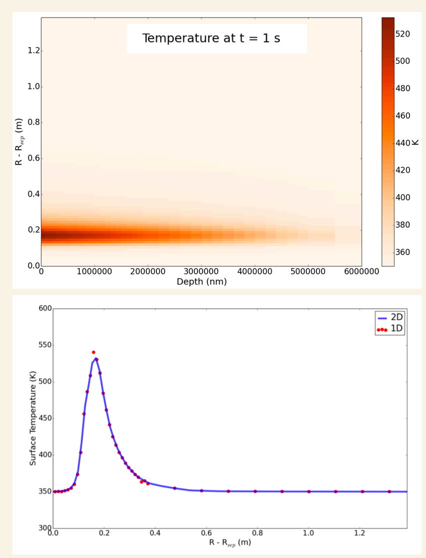
Higher surface growth around the strike point as modeled in Xolotl due to trap mutation and surface growth induced by He clusters

- Larger growth in Xolotl around the strike point, due to He clustering & trap mutation (low T_i shallow He implantation)
- Surface height in Xolotl resembles that of GITR further along the target, as trap mutation is less likely (Ti~40eV, deep He implantation)



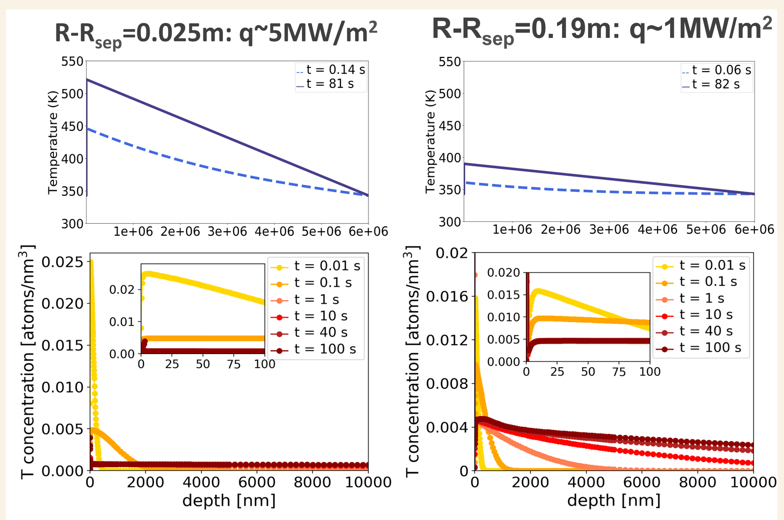
Heat fluxes increase the surface temperature up to 200K

- The thermal coupling between locations is negligible
  - We run multiple, independent 1D locations
  - May change in the full power operation of 500 MW
- For 100 MW discharge, increases in T_{surf} of up to 200K, which affects sub-surface gas dynamics
  - No threat of melting-recrystallization (no transients)



T diffuses faster with increasing T_{surf}, which is correlated with the local heat flux

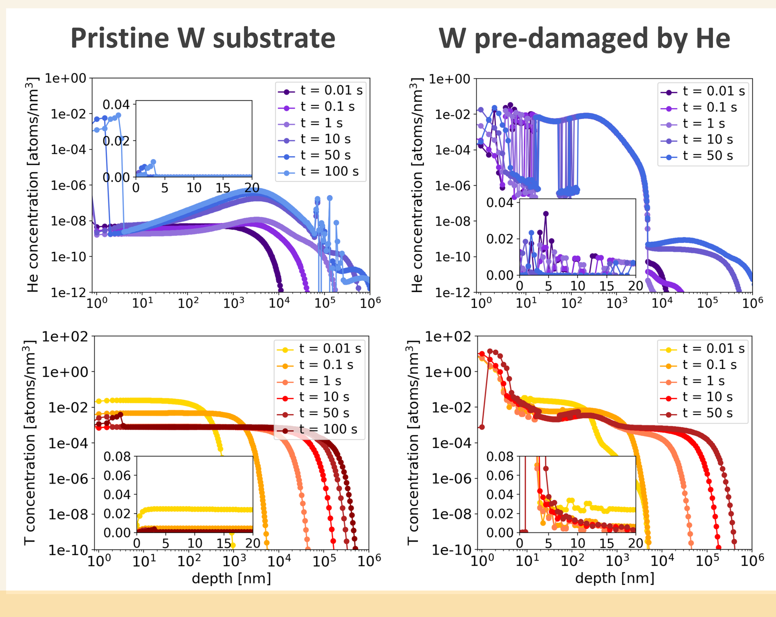
- The peak in concentration takes the value expected for $T=T_{surf}(t)$
- Gases diffuse faster, mainly outgassing
- Results for D follow the trends of T, and are thus not shown here



Pre-exposure to He forms a barrier for T permeation

At $R-R_{sep}$=0.025m, q~5 MW/m²

- The pre-implanted He clusters, leaving V-clusters (voids) that refill with He and trap T (D)
- V and He clusters (which trap T) form a permeation barrier and limit the T_{surf} dependence of the near-surface T concentration (in this T_{surf} and *q* ranges)



Summary & Future Plans

Integrated multiple, high-fidelity codes to model PMI to simulate 100 MW, burning plasma discharge, revealing:

- Neon dominates both radiation and W erosion, although the high-energy IEAD tail contributes to erosion by light ions
- >90% local W re-deposition leads to net deposition near the strike point, net erosion at $R-R_{sep}$>0.2m – with additional surface growth due to sub-surface gas dynamics in areas of low plasma temperature
- Hight heat flux (T_{surf}) decreases near surface T concentration
- Pre-exposure to He plasma leads to increased near-surface T concentration (trapped in bubbles/voids), but also decreases T permeation
- Seeking opportunities to **experimentally validate** our PMI model
- Work towards understanding effects of **mixed materials**, e.g. W-Be & extending predictions of microstructure to thermal-mechanical properties
- Working in the SciDAC to include the **feedback** from PMI **onto plasma** ; e.g. to Develop capability to model **ELMs**

Further details:
https://science.osti.gov/-/media/fes/pdf/program-documents/FY2018_PMI_Theory_Milestone_Final_Report.pdf

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