Bridging the gap between plasma physics and H transport in tokamak components

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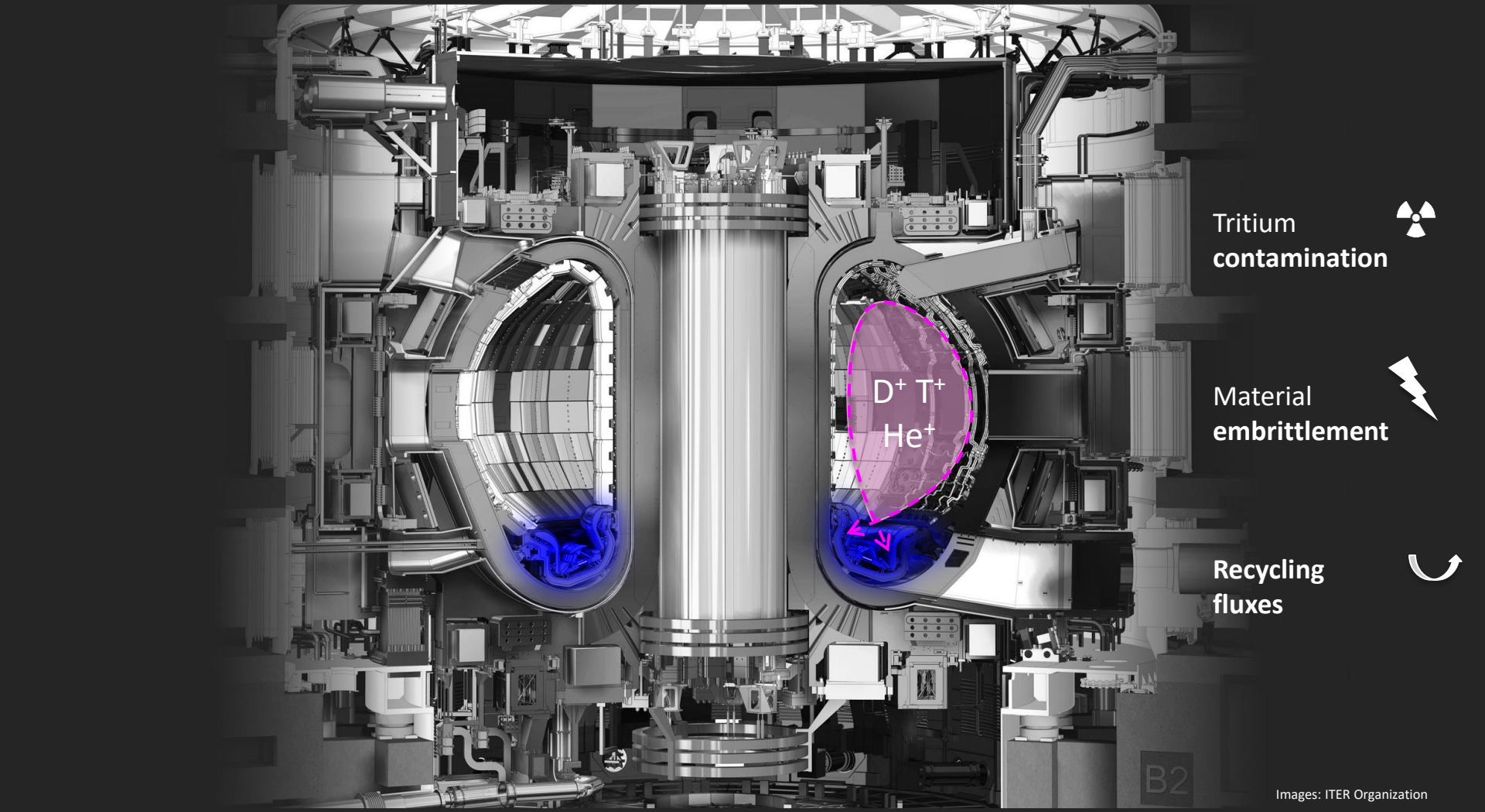


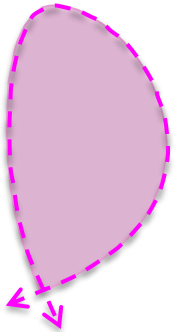
Tritium
contamination

Material
embrittlement

Recycling
fluxes

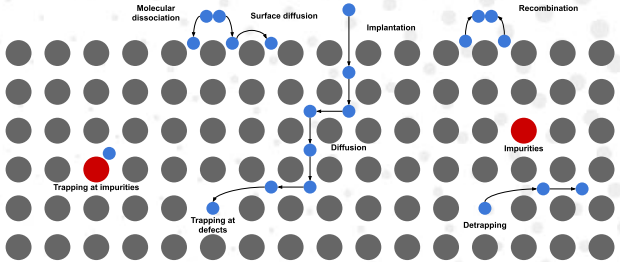
Images: ITER Organization

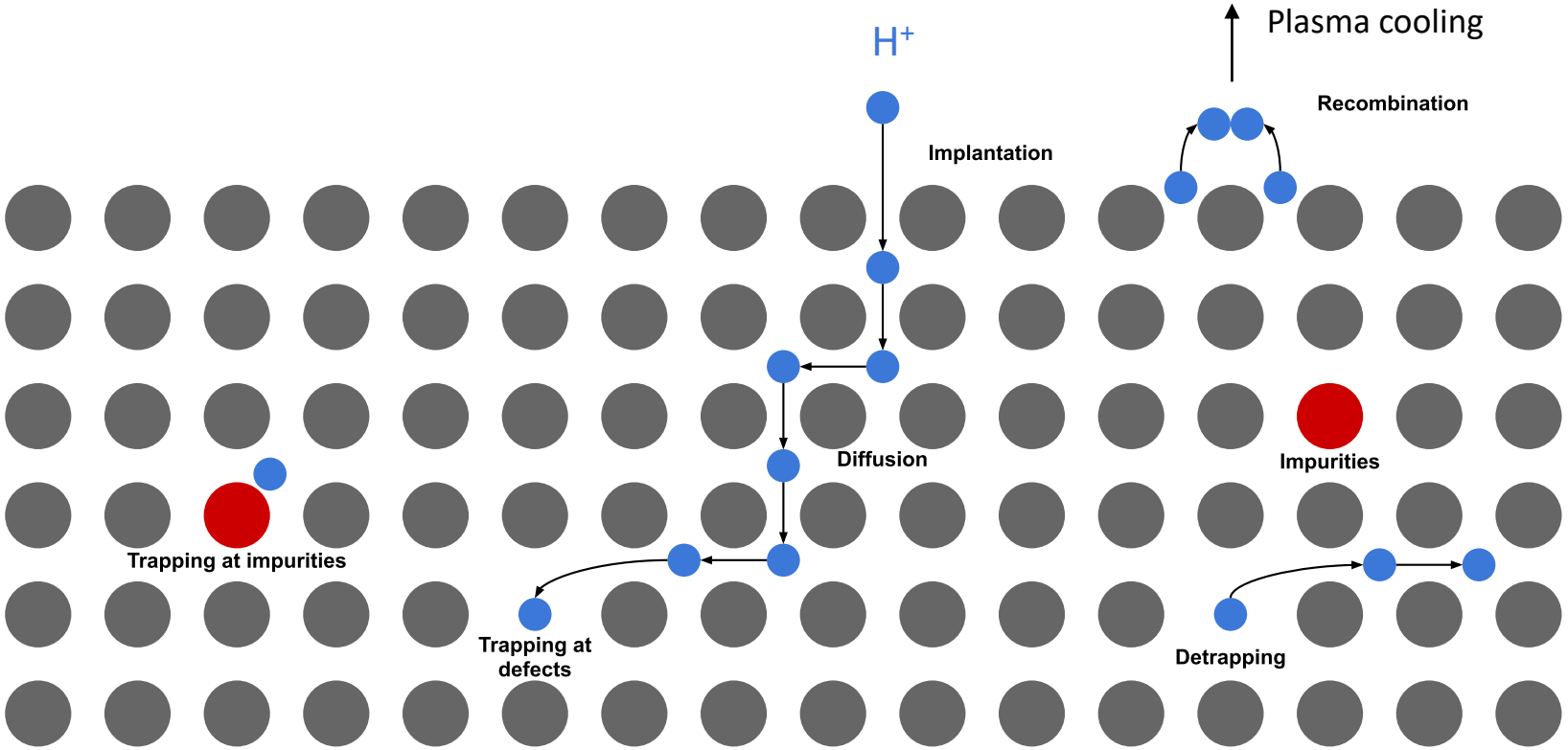
Let’s bridge the gap!

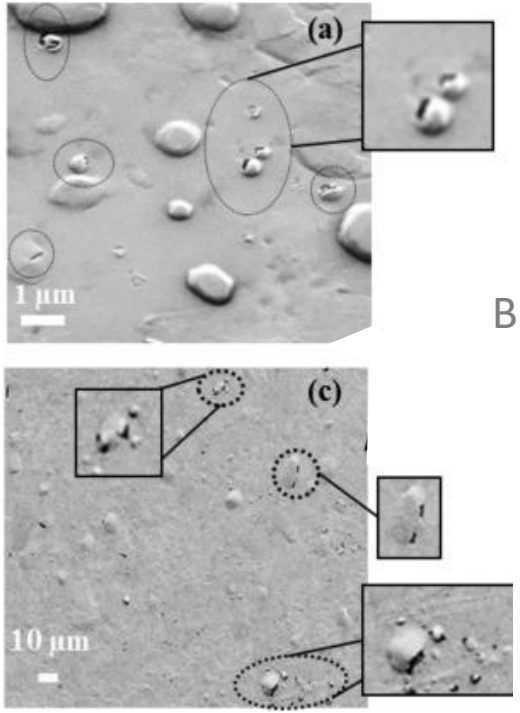


You guys know about this!

We know about that!



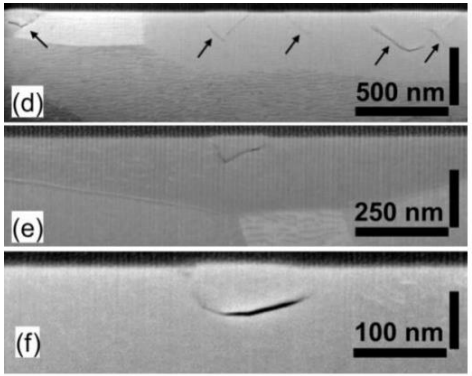

H+
Plasma cooling
Recombination
Implantation
Diffusion
Impurities
Trapping at impurities
Trapping at defects
Detrapping



Ouaras *et al,* JNM (2015)

Blistering

Hydrogen induced cracks (HIC)



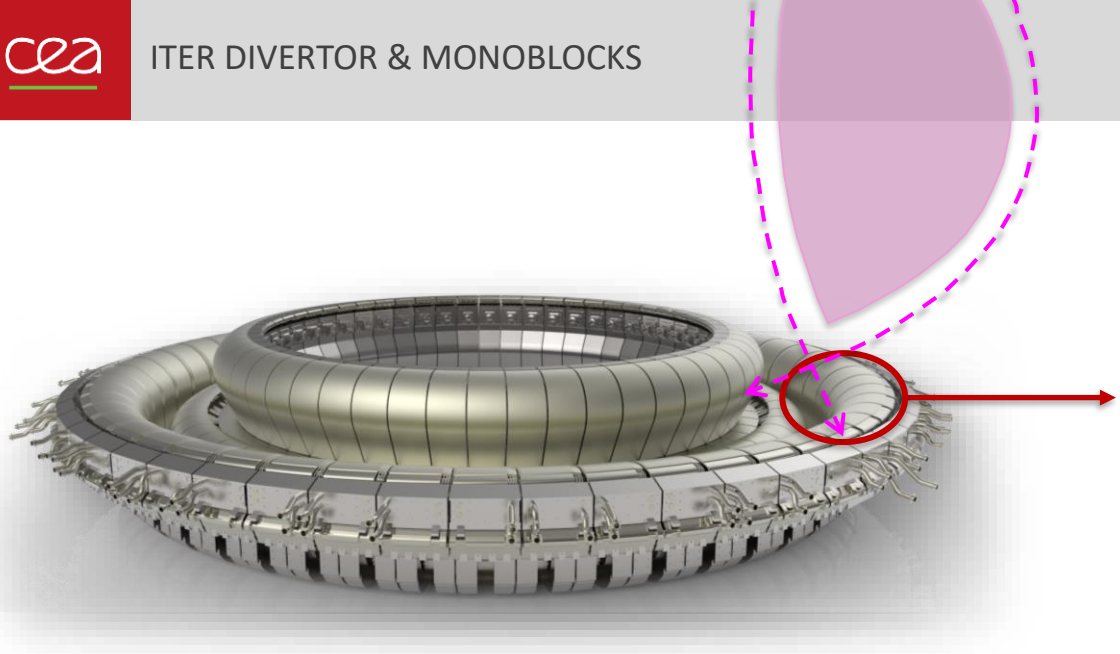
Gao *et al,* Nucl Fusion (2019)

We need to keep track of
hydrogen in materials!

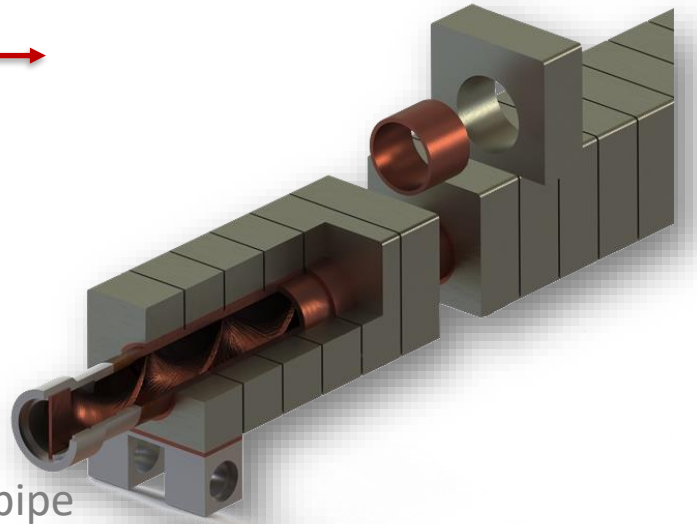
$$\begin{cases} \dfrac{\partial c_{\mathrm{m}}}{dt} = \overbrace{\nabla(D \cdot \nabla c_{\mathrm{m}})}^{\text{diffusion}} - \sum_i \dfrac{\partial c_{\mathrm{t},i}}{\partial t} \\ \dfrac{\partial c_{\mathrm{t},i}}{dt} = \underbrace{k \cdot c_{\mathrm{m}}(n_i - c_{\mathrm{t},i})}_{\text{trapping}} - \underbrace{p \cdot c_{\mathrm{t},i}}_{\text{detrapping}} \end{cases}$$

McNabb & Foster - Trans. Metall. Soc Trans. Metall. Soc. (1963)

- c_{m}, $c_{\mathrm{t},i}$ mobile and trapped H concentration
- D diffusion coefficient
- k, p trapping and detrapping rates
- n_i trap density



W substrate



- Simulation problem:
  - **Multi-materials**
  - **Multi-dimensional**
  - **Multi-physics**

CuCrZr cooling pipe

Cu interlayer

Images: ITER Organization

FESTIM

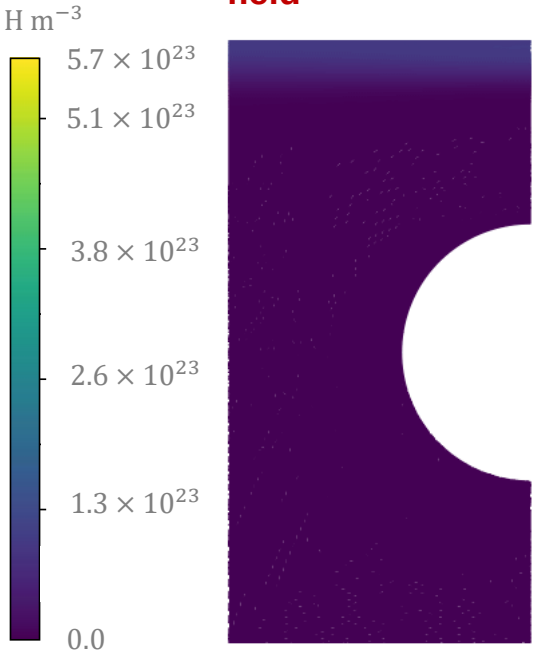
- Finite Element Simulation of Tritium In Materials
- Finite Element Methods
- 1/2/3D
- Multiphysics
  - Hydrogen transport
  - Heat transfer
- Multi-materials

FENICS PROJECT

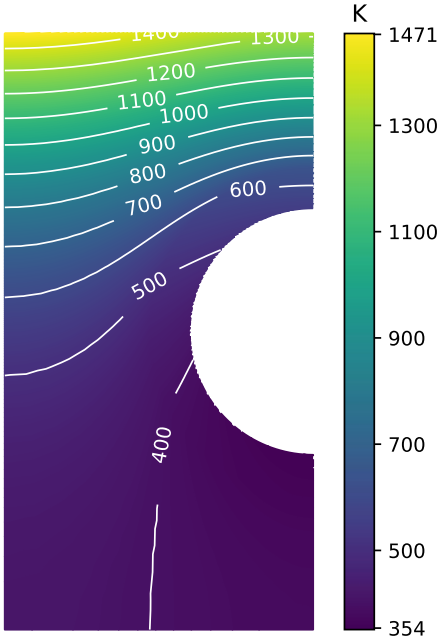
For more info:

Delaporte-Mathurin *et al,* NME (2019)

H concentration field

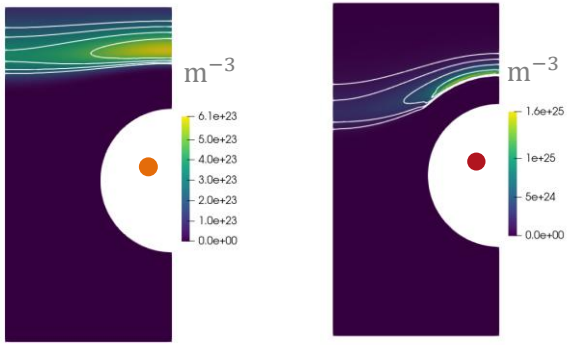


Temperature

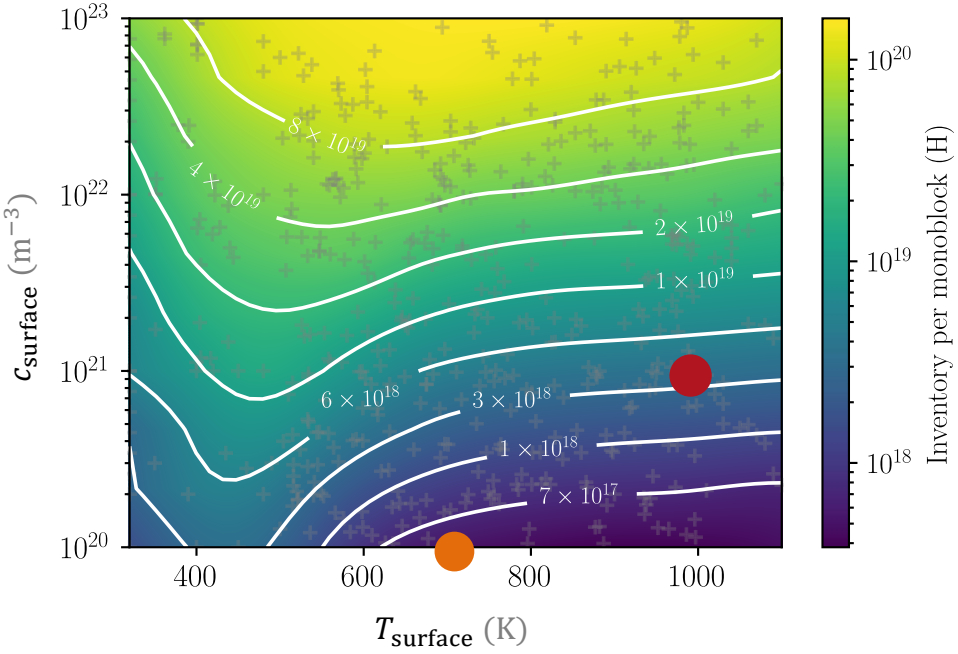


- Higher retention in cold regions
- Inventory [H] = $\int$ concentration dV

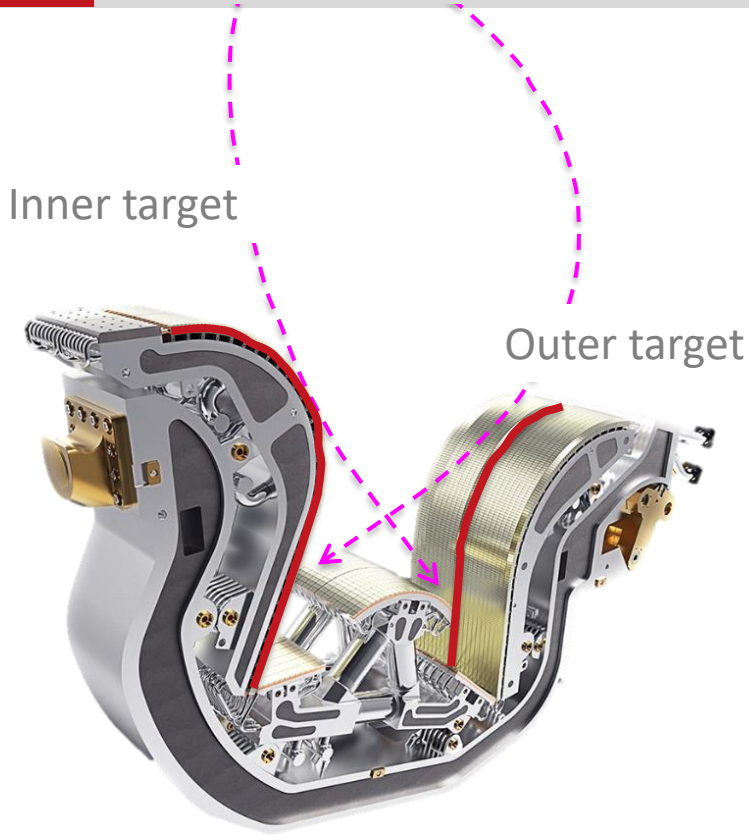
Influence of surface temperature and concentration



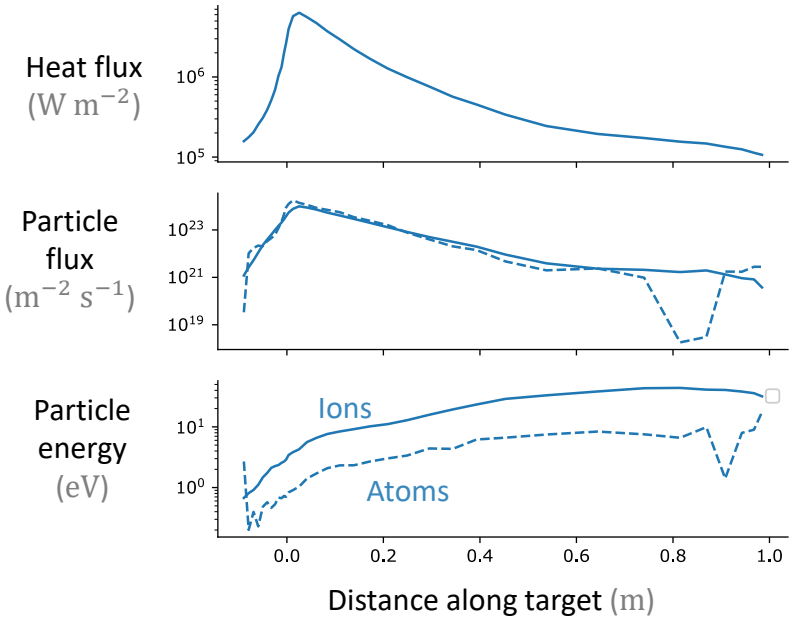
- 600+ computation points
- inventory $= f(T_{\text{surface}}, c_{\text{surface}})$



Can this be applied to the whole divertor?

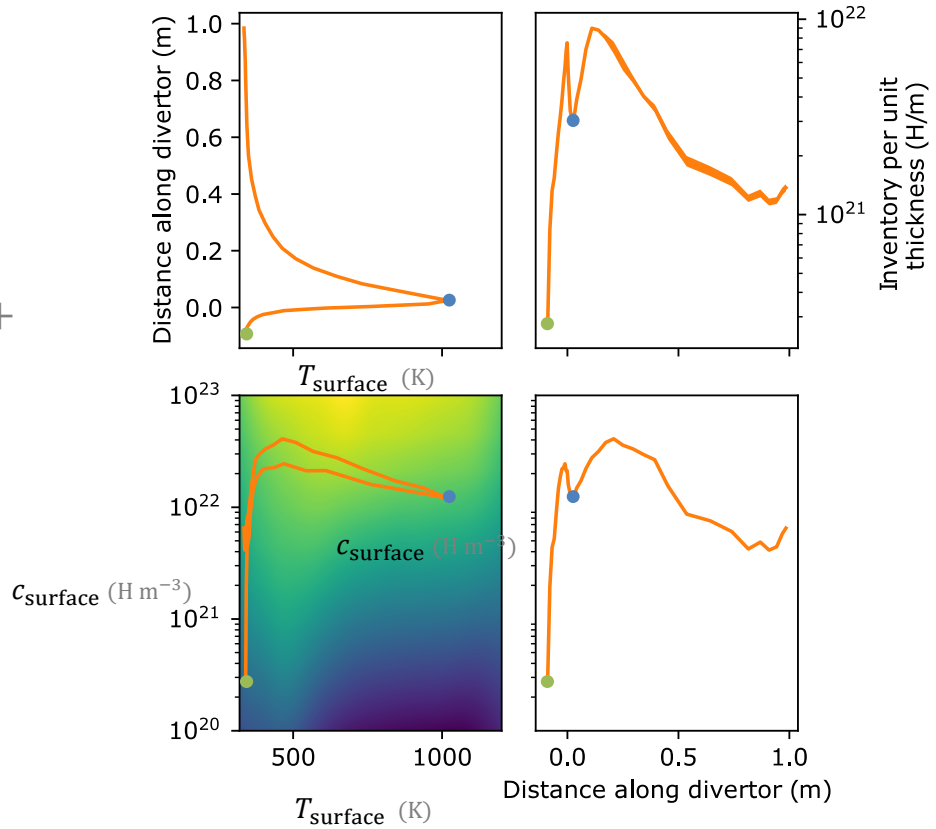


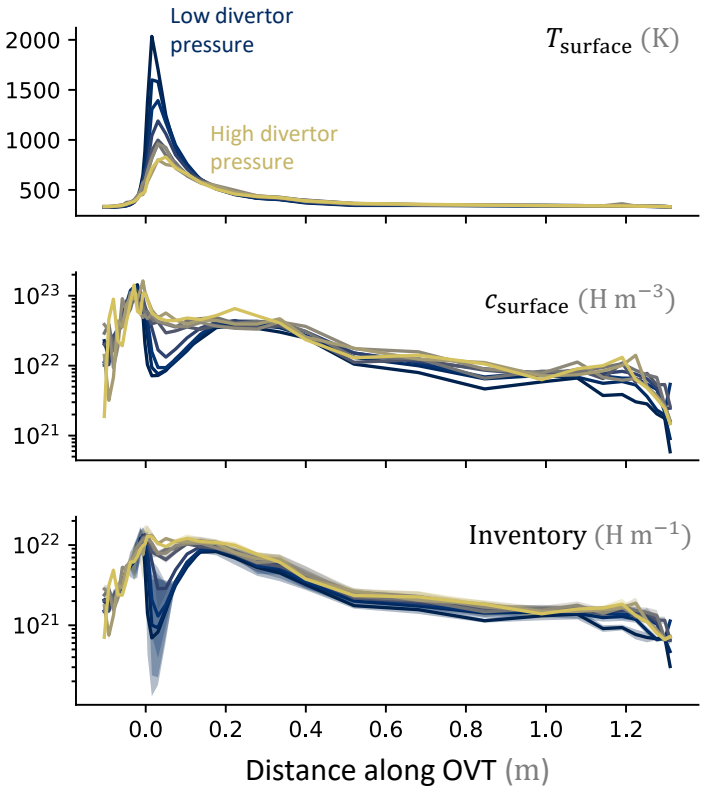
From SOLPS



Images: ITER Organization

- $T_{\text{surface}} = 1.1 \times 10^{-4}\ \varphi_{\text{heat}} + 323$
- $c_{\text{surface}} = (1 - r_{\text{atoms}}) \frac{R_{p\,\text{atoms}}\ \varphi_{\text{atoms}}}{D(T_{\text{surface}})} + (1 - r_{\text{ions}}) \frac{R_{p\,\text{ions}}\ \varphi_{\text{ions}}}{D(T_{\text{surface}})}$
- Where R_p , r depend on particle energy
- inventory $= f(T_{\text{surface}}, c_{\text{surface}})$





- Max $T_{surface}$ at strike points
- Lower inventory at strike point
- 14 g of H in ITER divertor after 25 000 pulses

Paper to be submitted…

Not your cup of tea?

Don’t worry…

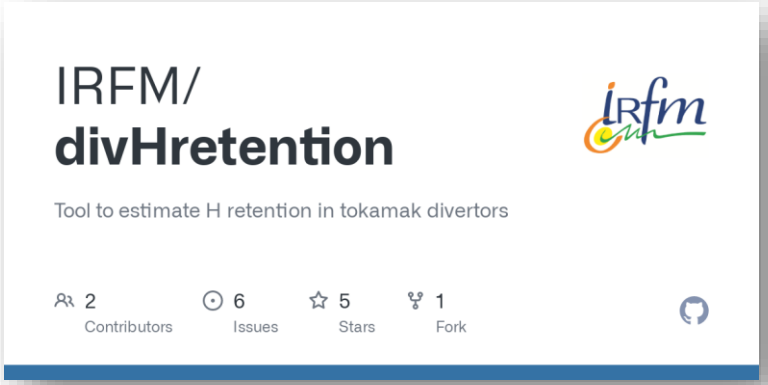
- Python
- Open source

- divhretention.readthedocs.io/en/latest/

- github.com/IRFM/divHretention

- Missing a feature?

→ Contributions are most welcome!

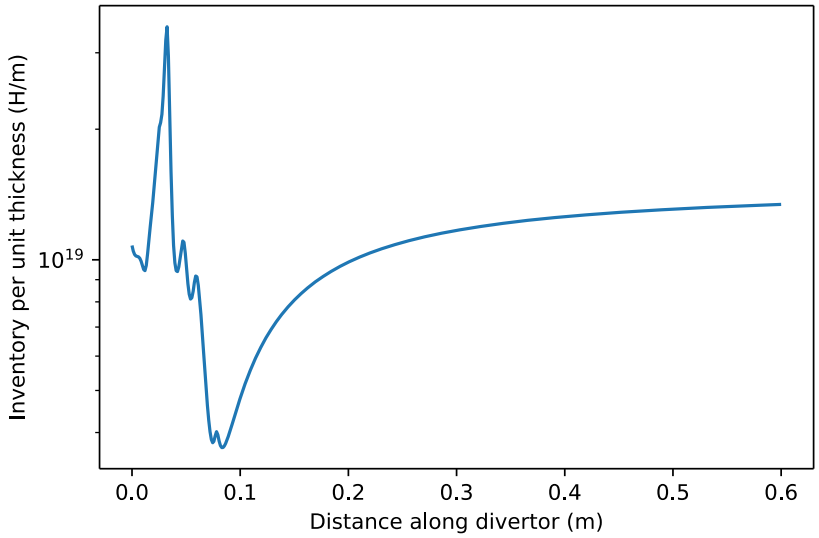


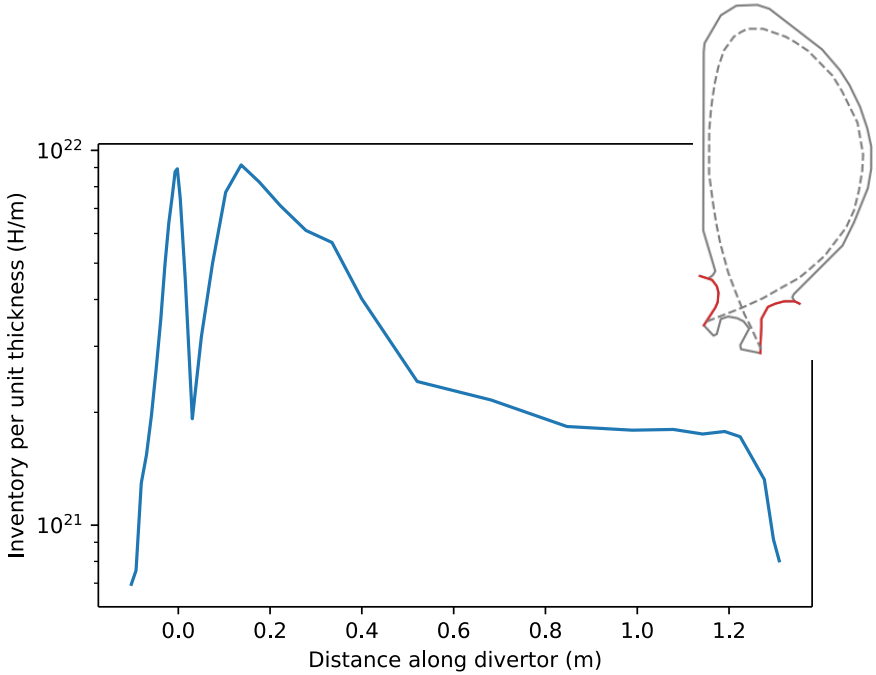

```
pip install divHretention
```

- To use, please cite:

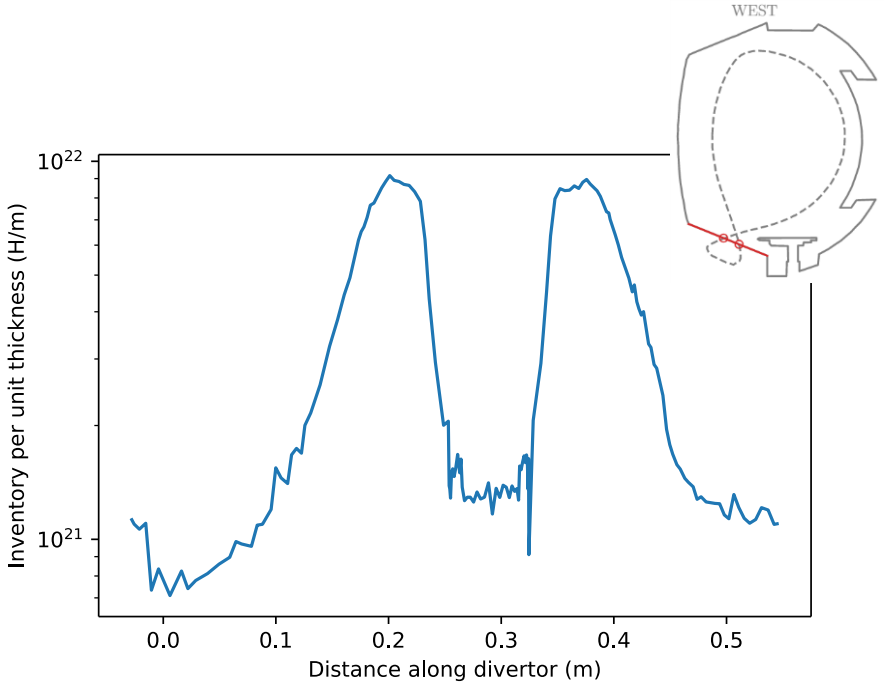
Delaporte-Mathurin *et al,* Nature Scientific Reports (2020)

```python
import matplotlib.pyplot as plt
import numpy as np
from divHretention import compute_inventory


x = np.linspace(0, 0.6, num=500)  # arc length (m)
T = 320 + 1000*np.exp(-50*x)  # surface temperature (K)
concentration = 5e21*np.exp(-50*x)  # surface concentration(Hm-3)

# compute the inventory (H/m) and standard deviation at 10 000s
inv, sig = compute_inventory(T, concentration, time=1e4)

plt.plot(x, inv)
plt.yscale("log")
plt.xlabel("Distance along divertor (m)")
plt.ylabel("Inventory per unit thickness (H/m)")
plt.show()
```



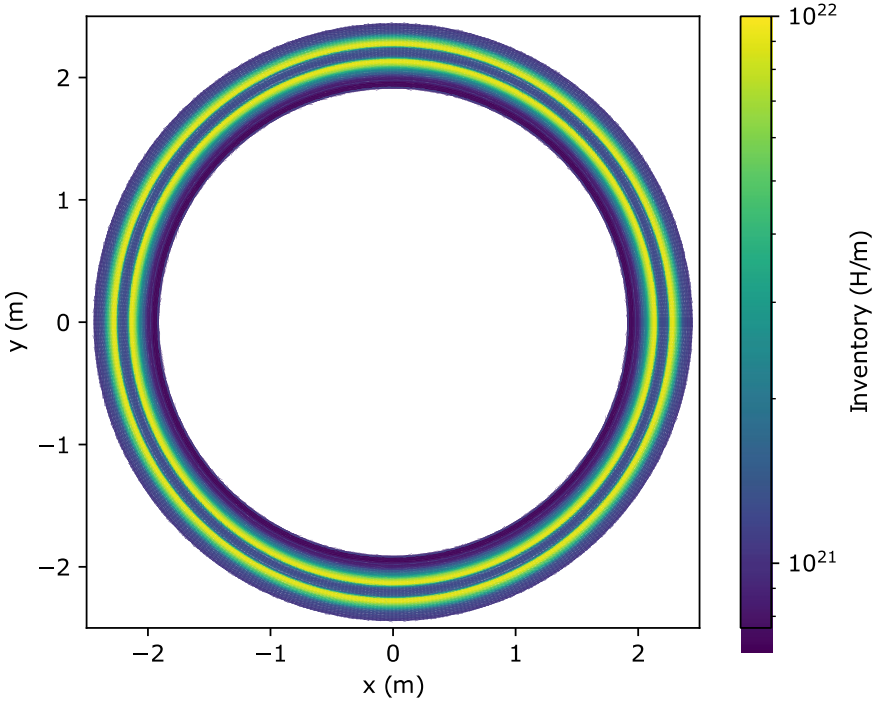



```python
from divHretention import Exposition

import matplotlib.pyplot as plt

filename = "2399_outer_target.csv"
res = Exposition(filename, filetype="ITER")


plt.plot(res.arc_length, res.inventory)
plt.xlabel("Distance along divertor (m)")
plt.ylabel("Inventory per unit thickness (H/m)")
plt.yscale("log")
plt.show()
```

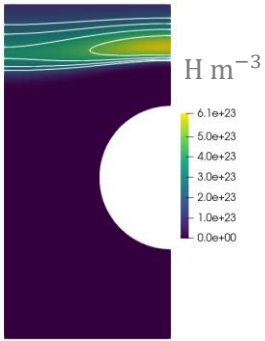



```python
from divHretention import Exposition

import matplotlib.pyplot as plt

filename = "West-LSN-P3.58e+21-IP2.5MW.csv"
res = Exposition(filename, filetype="WEST")


plt.plot(res.arc_length, res.inventory)
plt.xlabel("Distance along divertor (m)")
plt.ylabel("Inventory per unit thickness (H/m)")
plt.yscale("log")
plt.show()
```


WEST


2
1
0
−1
−2
y (m)
−2
−1
0
1
2
x (m)
10^{22}
10^{21}
Inventory (H/m)

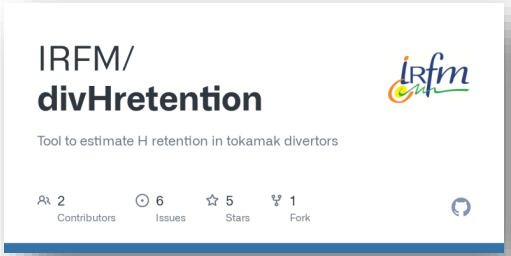
- A new method has been developed to estimate the inventory of H in tokamak divertors



- Based on Finite Element simulations of monoblocks with **FESTIM**

- **divHretention**: an open-source tool written in python and easy to use

github.com/IRFM/divHretention



Thank you for your attention

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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