MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

# Review of 2022 tasks and plans for 2023

K. Schmid

and SP-C taskholders:

E. Bernard, T. Morgan, A. Houben , A. Manhard, S. Markelj, T. Schwarz-Selinger, L. Ciupinski, F. Aumayer, D. Primezhofer, Y. Ferro, M. Lavrentiev, R. Bisson, J. Zavaznik, K. Kremer, M. Vadrucci, V. Nemanic, L. Gao

EUROfusion

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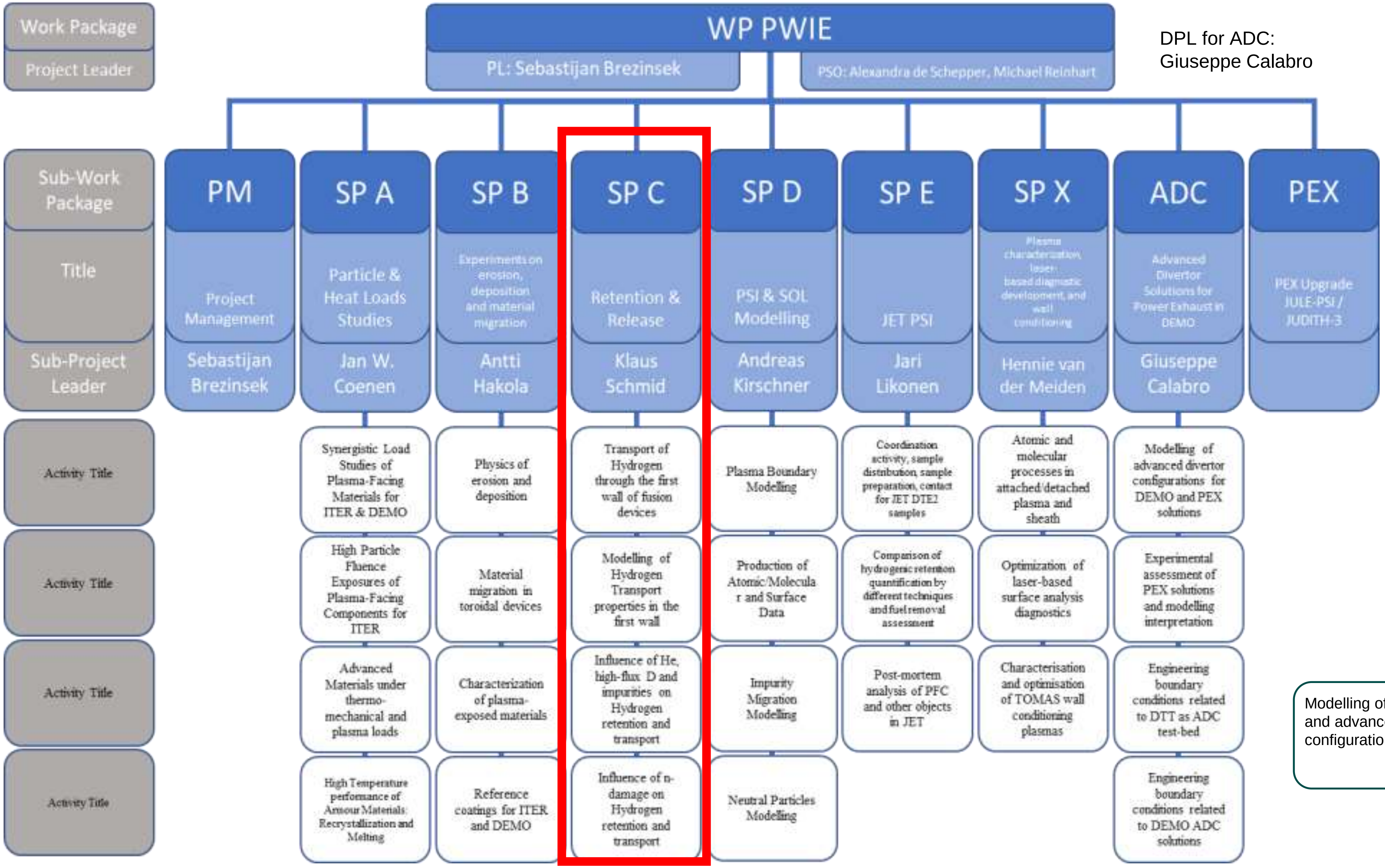
# Overview



| Work Package | WP PWIE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Project Leader | PL: Sebastijan Brezinsek<br>PSO: Alexandra de Schepper, Michael Reinhart | | | | | | | | |
| Sub-Work Package | PM | SP A | SP B | SP C | SP D | SP E | SP X | ADC | PEX |
| Title | Project Management | Particle & Heat Loads Studies | Experiments on erosion, deposition and material migration | Retention & Release | PSI & SOL Modelling | JET PSI | Plasma characterisation, laser-based diagnostic development, and wall conditioning | Advanced Divertor Solutions for Power Exhaust in DEMO | PEX Upgrade JULE-PSI / JUDITH-3 |
| Sub-Project Leader | Sebastijan Brezinsek | Jan W. Coenen | Antti Hakola | Klaus Schmid | Andreas Kirschner | Jari Likonen | Hennie van der Meiden | Giuseppe Calabro | |
| Activity Title | | Synergistic Load Studies of Plasma-Facing Materials for ITER & DEMO | Physics of erosion and deposition | Transport of Hydrogen through the first wall of fusion devices | Plasma Boundary Modelling | Coordination activity, sample distribution, sample preparation, contact for JET DTE2 samples | Atomic and molecular processes in attached/detached plasma and sheath | Modelling of advanced divertor configurations for DEMO and PEX solutions | |
| Activity Title | | High Particle Fluence Exposures of Plasma-Facing Components for ITER | Material migration in toroidal devices | Modelling of Hydrogen Transport properties in the first wall | Production of Atomic/Molecular and Surface Data | Comparison of hydrogenic retention quantification by different techniques and fuel removal assessment | Optimization of laser-based surface analysis diagnostics | Experimental assessment of PEX solutions and modelling interpretation | |
| Activity Title | | Advanced Materials under thermo-mechanical and plasma loads | Characterization of plasma-exposed materials | Influence of He, high-flux D and impurities on Hydrogen retention and transport | Impurity Migration Modelling | Post-mortem analysis of PFC and other objects in JET | Characterisation and optimisation of TOMAS wall conditioning plasmas | Engineering boundary conditions related to DTT as ADC test-bed | |
| Activity Title | | High Temperature performance of Armour Materials: Recrystallization and Melting | Reference coatings for ITER and DEMO | Influence of n-damage on Hydrogen retention and transport | Neutral Particles Modelling | | | Engineering boundary conditions related to DEMO ADC solutions | |

DPL for ADC:
Giuseppe Calabro

Modelling of standard and advanced divertor configurations for DTT

# Milestones 2022

| WP-M ID | WBS ID | WP Milestone Title | Due Date |
|---|---|---|---|
| **WM35** | SP C | Documented He retention in displacement-damaged W and its influence on H retention (ITER+DEMO) | 31.12.2022 |
| **WM36** | SP C | T-permeation from solid into gas vs. liquid phase on exit side (DEMO) | 31.12.2022 |
| **WM37** | SP C | Uptake of energetic D-ions vs. thermal D-atoms into W under first wall conditions quantified (DEMO+ITER) | 31.12.2022 |
| **WM38** | SP C | The impact of ion-induced W damage with proton-induced damage on fuel retention with the aid of depth-resolved laser-based analysis techniques compared (ITER+DEMO) | 31.12.2022 |

# SP-C tasks

- 23 Tasks

| Activity | Deliverables | Task |
|---|---|---|
| SP C.1 | D001 | Permeation (D,T) through Liquid/Solid interfaces with interface characterization (CEA) |
| SP C.1 | D002 | Dynamic measurements of deuterium retention and isotope exchange in W (DIFFER) |
| SP C.1 | D003 | Influence of ELMs on deuterium retention and outgassing in W (DIFFER) |
| SP C.1 | D004 | Gas driven permeation through and retention in W, Steel, W on Steel and W on Cu (FZJ) |
| SP C.1 | D005 | Measurement and modelling of Ion Driven Permeation in W, Cu and Fe-Ni alloys "heavy alloys" (MPG) |
| SP C.1 | D006 | Compare D permeation through W with D atoms and 300 eV/D ions (JSI, MPG) |
| SP C.1 | D007 | FIB/SEM/EDX analysis of material interfaces in multi material permeation samples (IPPLM) |
| SP C.1 | D008 | Studying the influence of (re-deposited) W on EUROFER on D retention (OEAW, VR) |
| SP C.2 | D001 | H diffusion and segregation at the Cu/W interface (CEA) |
| SP C.2 | D002 | DFT calculations of defects in W in the presence of H and He (UKAEA) |
| SP C.3 | D001 | Study the effect of O or C layers on D: bulk vs surface uptake - from 1 monolayer to a few hundred of nanometers (CEA) |
| SP C.3 | D003 | Influence of surface oxide films on the uptake of deuterium into the metallic tungsten in dependence on D ion energy and fluence (MPG) |
| SP C.3 | D003 | Influence of surface oxide films on the release of deuterium into the metallic tungsten in dependence on film thickness (MPG) |
| SP C.3 | D003 | XRD and Raman of Oxide films on W in cooperation with MPG (JSI, MPG) |
| SP C.3 | D002 | Permeation barrier properties of chromia grown on dense Cr films on Eurofer (JSI) |
| SP C.3 | D003 | Comparing He cluster nucleation in defect free and e-beam-damaged W (MPG) |
| SP C.3 | D004 | E-beam irradiation of single crystal W from MPG (ENEA) |
| SP C.3 | D002 | Influence of surface microstructure due to low energy He irradiation on D uptake studied in situ (JSI, MPG) |
| SP C.3 | D003 | Self-damaged W samples for JSI investigation (MPG) |
| SP C.4 | D001 | Simulation of neutron-damaged W by W self-damage at different dpa (6 W samples) (IPP) |
| SP C.4 | D002 | Exposition of W samples in PSI-2 D plasmas to load with D at low surface temperature (FZJ) |
| SP C.4 | D002 | Quantification of fuel content for 3 samples by NRA and TDS (MPG, FZJ) |
| SP C.4 | D002 | Quantification of fuel content for 3 samples by LIA-QMS and DP-LIBS (FZJ) |

- **All tasks are assumed to complete in 2023**

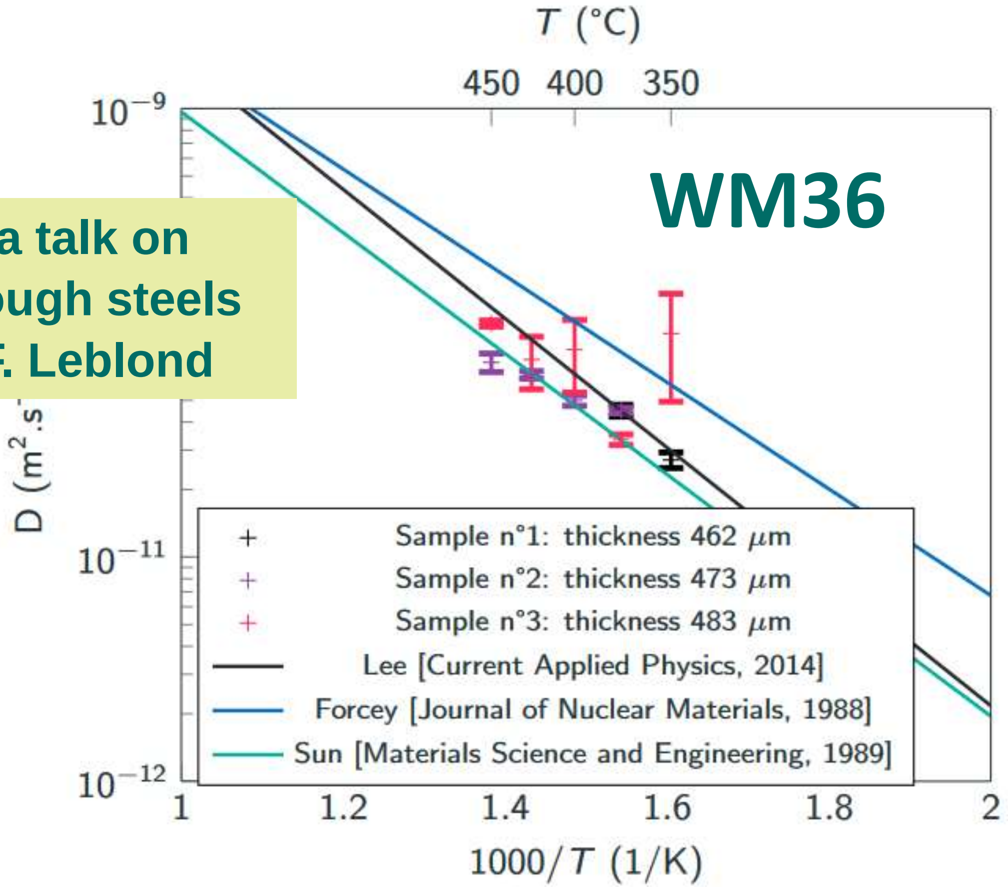
# SP C.1 Transport of Hydrogen through the first wall of fusion devices

| Task |
|---|
| Permeation (D,T) through Liquid/Solid interfaces with interface characterization (CEA) |
| Dynamic measurements of deuterium retention and isotope exchange in W (DIFFER) |
| Influence of ELMs on deuterium retention and outgassing in W (DIFFER) |
| Gas driven permeation through and retention in W, Steel, W on Steel and W on Cu (FZJ) |
| Measurement and modelling of Ion Driven Permeation in W, Cu and Fe-Ni alloys "heavy alloys" (MPG) |
| Compare D permeation through W with D atoms and 300 eV/D ions (JSI, MPG) |
| FIB/SEM/EDX analysis of material interfaces in multi material permeation samples (IPPLM) |
| Studying the influence of (re-deposited) W on EUROFER on D retention (OEAW, VR) |

# Permeation (D,T) through 316L with Liquid/Solid interfaces

- Preliminary permeation measurements on 316L were performed with the Hypertomate experiment
- Gas-driven hydrogen permeation, temperature from 350°C to 450°C

**There will be a talk on permeation through steels into water by F. Leblond**



**WM36**

- Large error bars (around 30% vs. <10% on the previous Eurofer campaign) and bad repeatability
- Surface-limited regime easily triggered, keeping us from obtaining bulk properties
- This can be prevented by adding a Pd coating on the upstream side of the samples

- Miha Cekada (JSI, Ljubljana) coated the samples for us
- The experimental campaign will resume with $H_2$, and then move on to $T_2$ and water

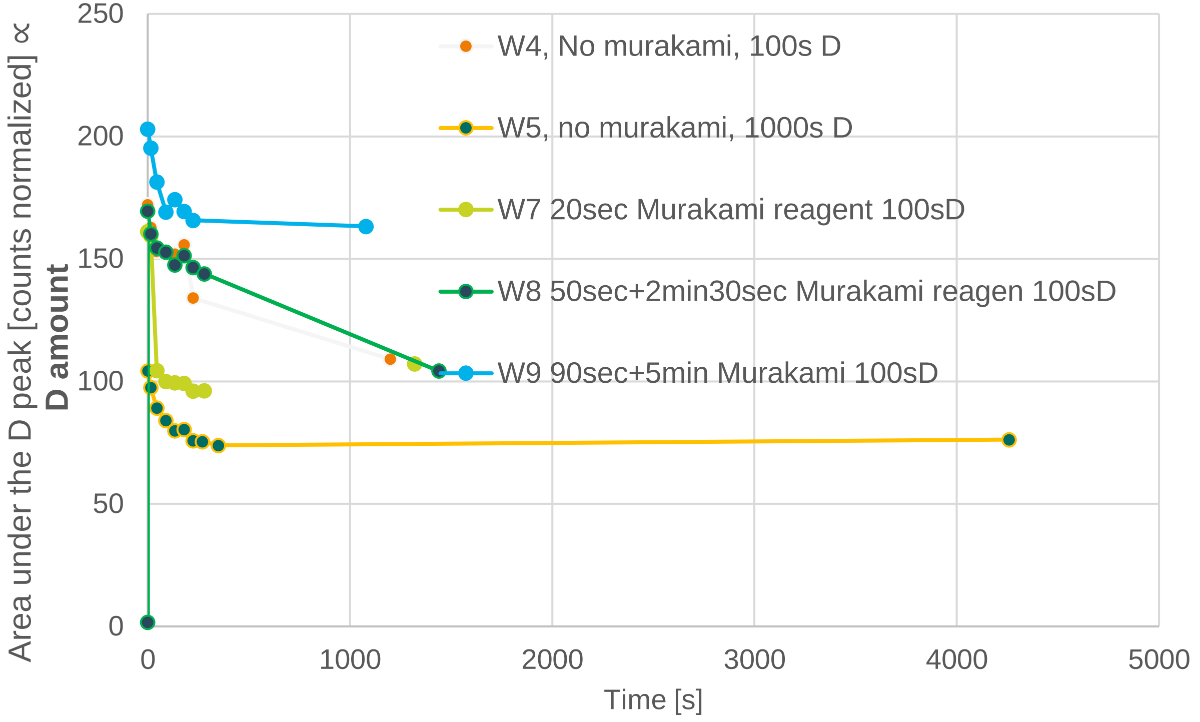
**Elodie BERNARD, CEA**

# Investigate dynamic inventory during exposure and influence of ELM like transients on post exposure retention.

❖ Dynamic outgassing (DO) from tungsten was studied with NRA, nuclear reaction analysis. DO is important for the time in between fusion shots as we need high quality vacuum.

❖ Two parameters were studied: Fluence (Do we observe saturation or does the retained amount increase with fluence?) and roughness. All samples were polished and to increase roughness a Murakami reagent was used

❖ Outgassing is observed for all the samples. 24 hours at room T seems enough to stop DO



❖ **Higher roughness seem to lead to lower retention** (W9 showed presence of C → more retention)

➢ Plasma retention studies during plasma operation, UPP will be ready for this by the end of year

DIFFER

**T. Morgan**

# Gas driven permeation through CuCrZr vs W coated CuCrZr

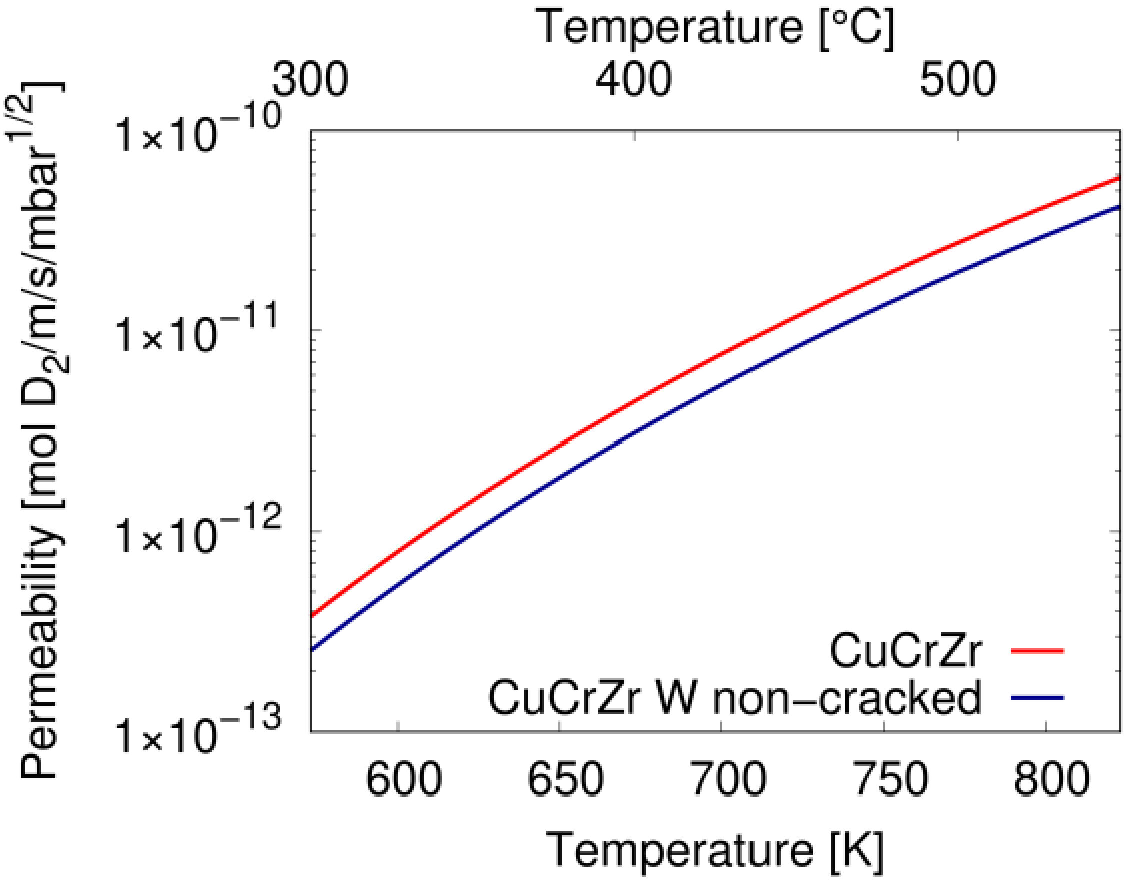
**Results and Conclusion:**

- Stable permeation measurement between 300° and 550°C, applied D pressure: 25-800 mbar
- CuCrZr permeability is similar to bulk Cu permeability, diffusion limited → published in: A. Houben *et al.*, NME **33** (2022), 101256 https://doi.org/10.1016/j.nme.2022.101256
- Reduction of permeability due to the W layer
- Permeation flux through W coated CuCrZr is diffusion limited → **no influence of interface**

**Outlook:**

- Further analysis of the data: calculation of layer permeability, lag-time measurement
- FIB/SEM investigation of W layer

- Next year: Studies on the system W on steel with non-cracked W layers



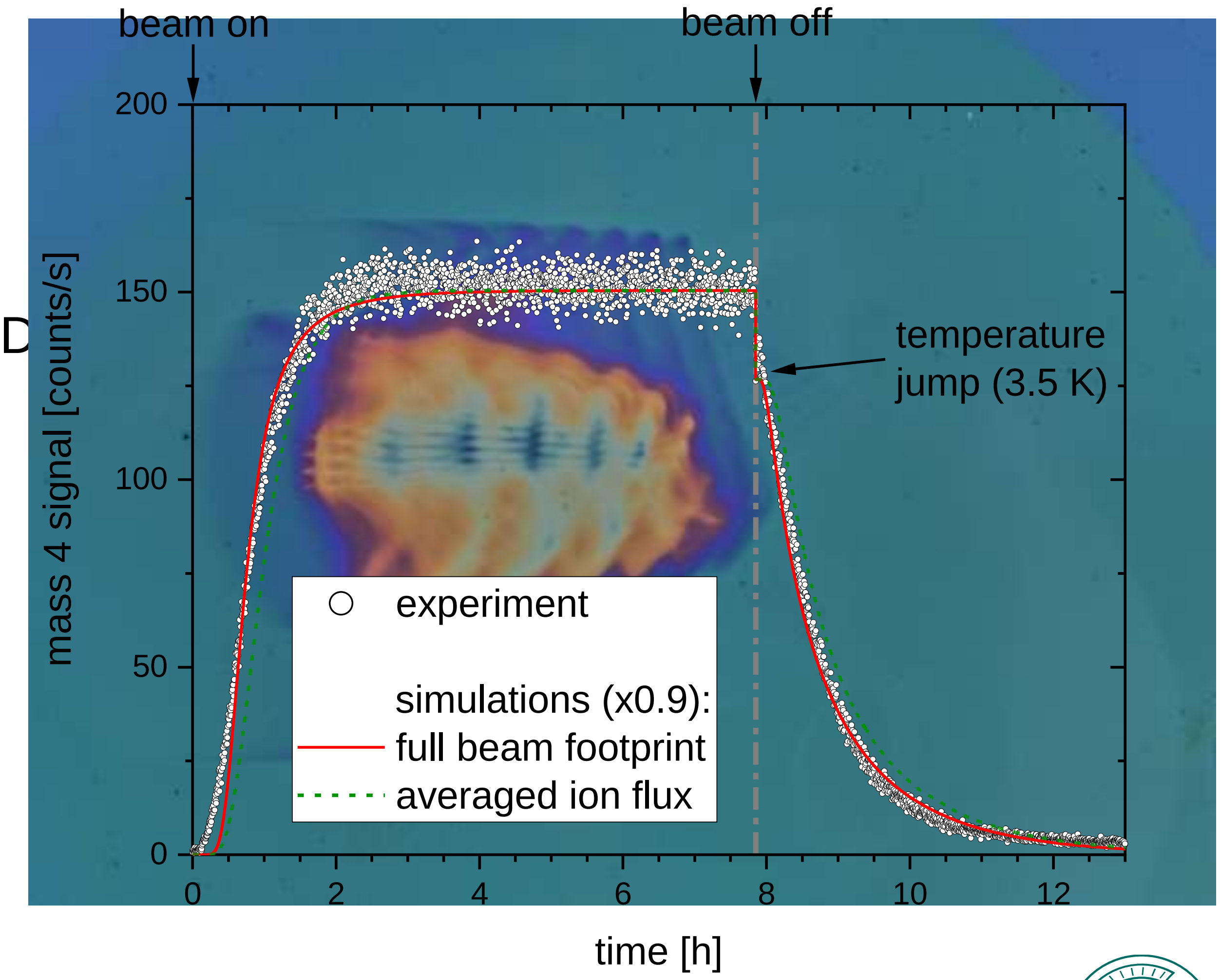
Anne Houben

# Ion Driven Permeation in W, Cu and Fe-Ni alloys

- Optimization of $D_3^+$ ion beam and precise ion flux density calibration
- Benchmark experiments: 25 µm recrystallized W

- TESSIM-X fit of experiment data: 580 K / 200 eV/D
- Includes full histogram of ion fluxes
  - Important for reproducing transients
- Includes temperature jumps at beam on/off
  - Reproduces signal jump in decay transient
- Close quantitative match of steady-state current
  - Diffusion-limited boundary conditions
  - Calibrations of ion flux and QMS accurate

*(a) visualization of beam spot by erosion of a-C:H layer*

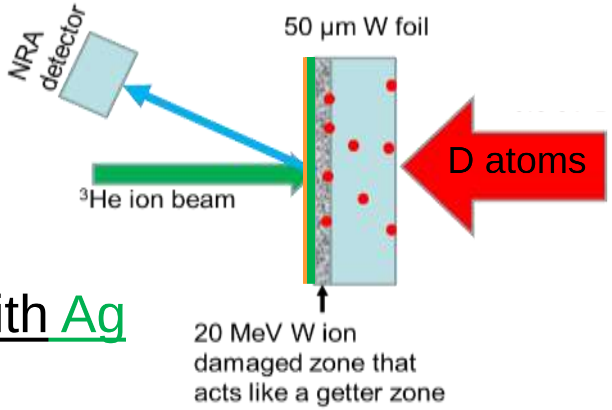


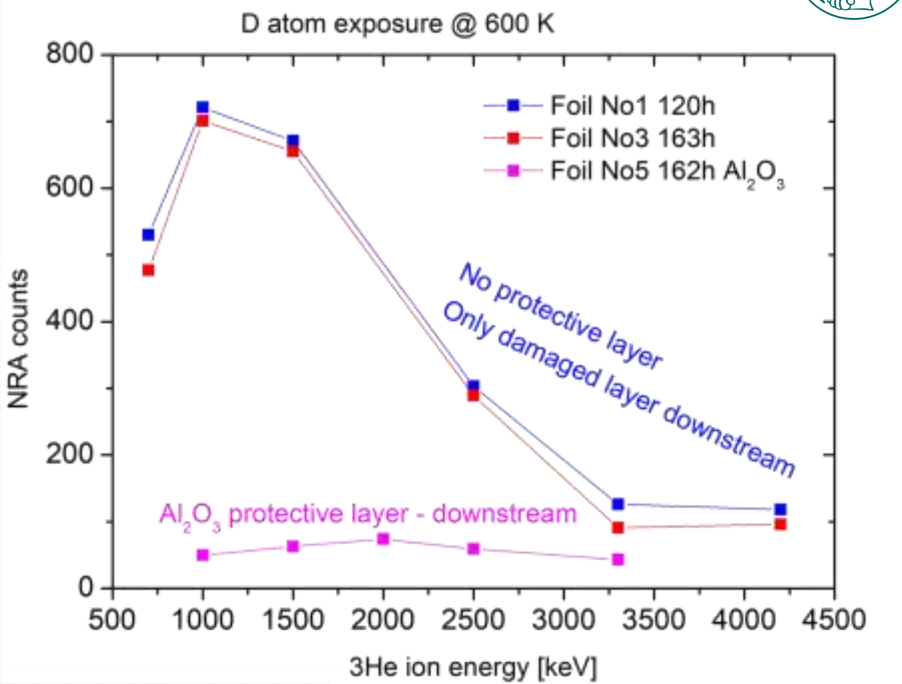
- Slowed down by challenges outside of physics (hacker attack, etc.)
- Proceed to measure W/FeNi and W/Cu layer systems and heavy alloys

# Compare D permeation through W with D atoms and 300 eV/D ions

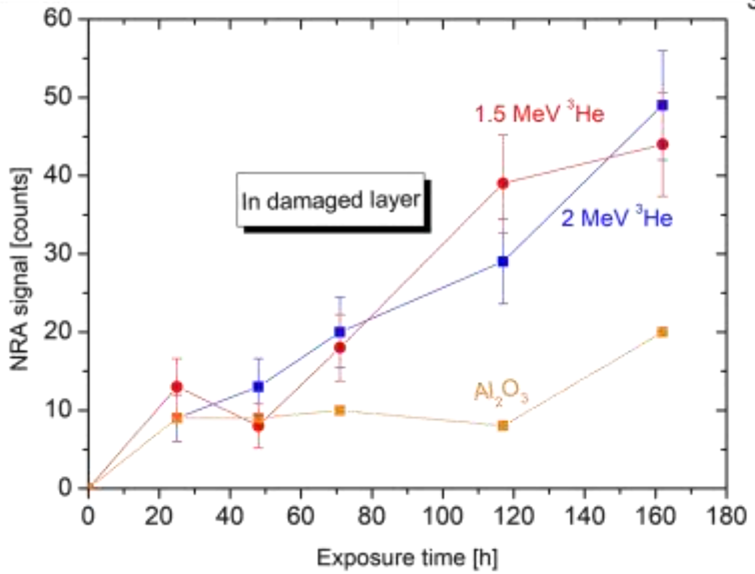
❖ Study the differences in D transport (permeation) in a W foil between 0.3 eV D atoms and 300 eV/D ions based on in situ IBA during exposure

- ✓ Exposure to D atoms on upstream side for > 120 h
- ✓ Measure D retention on the downstream side
- ➢ Deposited $Al_2O_3$ (85 nm) getter with Ag (1 µm) spacer at MPG





- ✓ First in situ measurement with D atoms @ 600 K – good separation of D in $Al_2O_3$ and in damaged layer
- ➢ Next 300 eV D ions @ 600 K
- ➢ Repeat D atom/ions at 700 K



D in damaged layer
0.015 at. % (0.3 at. % full)

D in $Al_2O_3$
1.3e15 D/cm$^2$

**WM37**

Jožef Stefan Institute

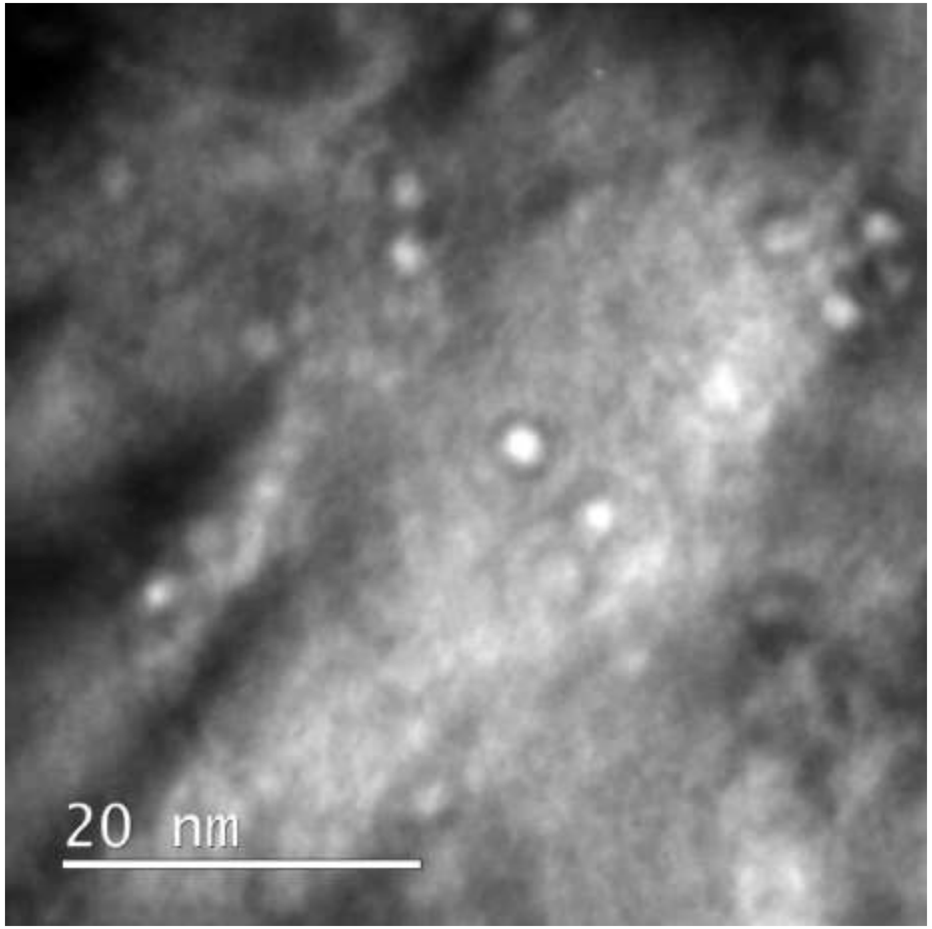
➢ Need for next year – transport in H-filled W?

S. Markelj

# SP C.1 Transport of Hydrogen through the first wall of fusion devices
## TEM analysis of void formation in self-damaged W

- TEM characterization of samples prepared by Dr. Zibrov
  - Helium nanobubbles and voids after self-damage

- We developed sample preparation techniques which enables nanobubbles observations (succesfully repeated on several specimens)
- Samples are milled with FIB followed by argon ions smoothening



➢New state-of-the-art high resolution analytical transmission electron microscope arrived at WUT! We are open to new collaborations!

Warsaw University of Technology

IPPLM

# TU Wien (ÖAW) + Uppsala University (VR)

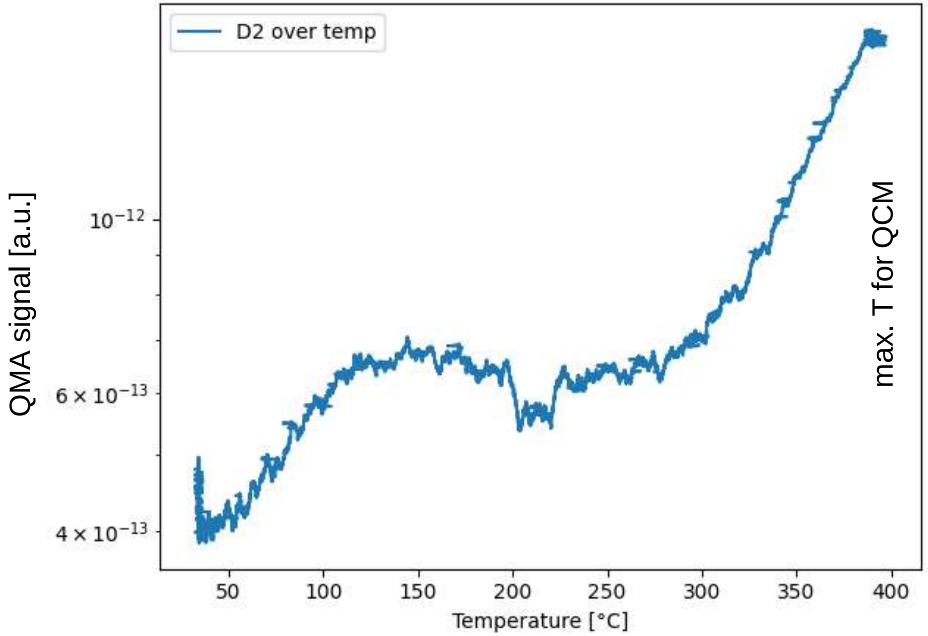
- **TDS and QCM measurements on EUROFER preimplanted with D**

- TU Wien:
  2 implantations of 2 keV $D_2^+$ under 0° in EUROFER
  a) TDS experiment without redeposited W layer
  b) TDS experiment with redeposited W layer

- TDS: small low temperature peak at 150°C (423K)
- Good agreement with [1] (different ion energy though)
- Rising TDS slope towards 400°C limit (limit by QCM)
- QCM: both implantation and outgassing can be compared in terms of mass change (see table)

- **Evaluation ongoing**, but <u>no delay of task expected</u>

Representative TDS data



| Experimental Case | D/m² implanted | D/m² outgassed |
|---|---|---|
| without redeposited W | 5.6 E+20 | Currently eval. |
| with redeposited W | 4.0 E+20 | Currently eval. |

[1] Hollingsworth et al., Nucl Fusion 60 (2019), 016024

**Christian Cupak** cupak@iap.tuwien.ac.at

# SP C.1 Transport of Hydrogen through the first wall of fusion devices

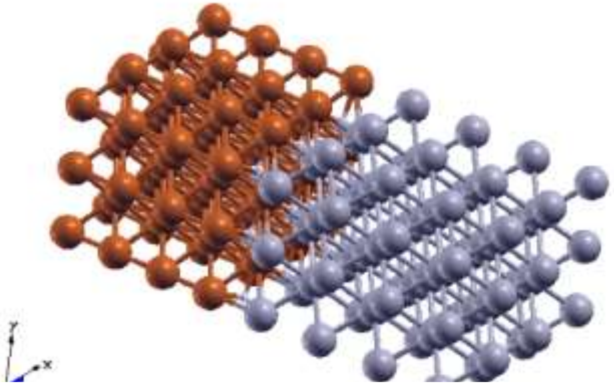
## ❖ Plan for 2023

| Association | Title | Deliverables |
|---|---|---|
| CEA | Permeation (D,T) through Liquid/Solid interfaces with interface characterization | T Gas/Gas permeation vs T Gas/Liquid on EUROFER w/wo O-layers |
| DIFFER | "Dynamic measurements of deuterium retention and isotope exchange in W" | Evaluation of influence of plasma parameters and surface temperature on trapping and de-trapping post-exposure |
| DIFFER | Influence of ELMs on deuterium retention and outgassing in W | Compare pre-damaged (ELM-like laser pulse)  W with simultaneously damaged (laser) W |
| MPG | Measurement and modelling of Ion Driven Permeation in W, Cu and Fe-Ni alloys "heavy alloys" | Ion-driven permeation through layered model systems: W on FeNi and FeNi ond W |
| JSI | study permeation on H-prefilled W foil | D permeated amount compared to non-H-filled W |
| IPP_LM | TEM analyis of material interfaces in W/Cu and W/EUROFER samples | TEM analysis of damaged W-samples |
| ÖAW | Studying the influence of (re-deposited) W on EUROFER on D retention | Variation of TDS with W-layer thickness on EUROFER |

# SP C.2 Modelling of Hydrogen Transport properties in the first wall

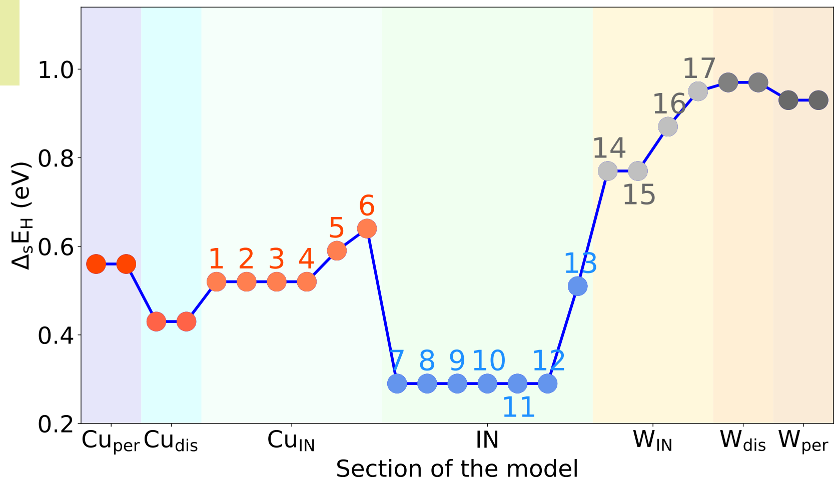
| Task |
|---|
| H diffusion and segregation at the Cu/W interface (CEA) |
| DFT calculations of defects in W in the presence of H and He (UKAEA) |

# H diffusion and segregation at the W/Cu interface



- **Deliverable**: Energy landscape of H at a W/Cu material interface
- A DFT model of the W/Cu interface was built
  - -> orientation: W(001) with the Cu(001) surface
  - -> the structural distortion at the surface was determined
- Hydrogen solubility
  - -> it was determined in perfect Cu and W
  - -> it was also determined in **pure** distorted Cu and W (with the same geometry distortion as at the interface).
  - -> we are calculating the solution energy of H *close to* and *at* the interface (see graph)
- The effect of the interface is to create a sink where Hydrogen's Isotope will possibly accumulate

**There will be a talk on DFT modeling of the W/Cu interface by Y. Ferro**



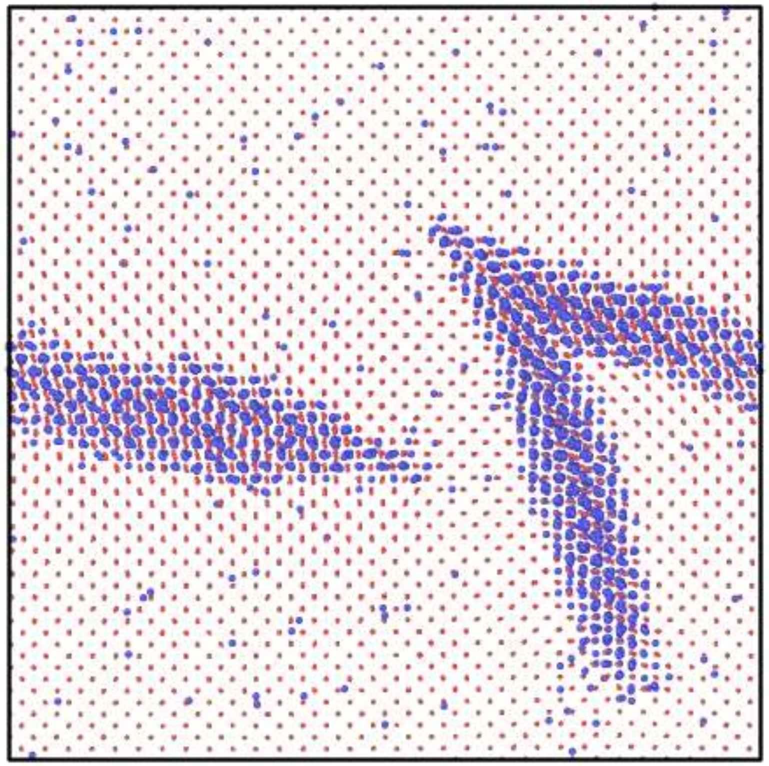
- **What next ?**
  - -> The full energy path could reveal high energy barriers for diffusion, they will be computed
  - -> The effect of hydrogen accumulation could also be investigated for the year after.

Aix Marseille université

& **CEA**

# DFT calculations of defects in W in the presence of H

- ❖ Investigated dependence of diffusion of hydrogen in tungsten on hydrogen concentration
- ❖ Molecular dynamics simulations using LAMMPS package on large W-H system and ab initio calculations using VASP program on systems with up to 1000 atoms
- ❖ Molecular dynamics results found dramatic decrease of hydrogen diffusion coefficient at concentrations above 2 at. %
- ❖ This decrease was found to be the result of formation of large almost two-dimensional hydrogen clusters
- ❖ Possibility of formation of clusters was further studied in ab initio calculations. It was found that indeed two-dimensional clusters are energetically stable



Final snapshot of molecular dynamics run of 65536 W atoms (red) and 4096 H atoms (blue). Temperature T = 1000 K, P = 0.

- ➢ Physical model using kinetic Monte Carlo simulations will be created to investigate hydrogen clustering under the realistic fusion conditions
- ➢ Possibility of interstitials in tungsten to serve as clustering seeds will be studied

CCFE
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**M.Yu. Lavrentiev, S.L. Dudarev, M. Boleininger**

# SP C.2 Modelling of Hydrogen Transport properties in the first wall

- **Plan for 2023**

| Association | Title | Deliverables |
|---|---|---|
| CEA | H diffusion and segregation at the Cu/W interface | Diffusion properties of hydrogen at the W/Cu interface: activation barriers for MRE modeling |
| UKAEA | DFT calculations of defects in W in the presence of H | Formation of Defects in the presence of H and/or He |

# SP C.3 Influence of He, high-flux D and impurities on Hydrogen retention and transport

| Task |
|---|
| Study the effect of O or C layers on D: bulk vs surface uptake - from 1 monolayer to a few hundred of nanometers (CEA) |
| Influence of surface oxide films on the uptake of deuterium into the metallic tungsten in dependence on D ion energy and fluence (MPG) |
| Influence of surface oxide films on the release of deuterium into the metallic tungsten in dependence on film thickness (MPG) |
| XRD and Raman of Oxide films on W in cooperation with MPG (JSI, MPG) |
| Permeation barrier properties of chromia grown on dense Cr films on Eurofer (JSI) |
| Comparing He cluster nucleation in defect free and e-beam-damaged W (MPG) |
| E-beam irradiation of single crystal W from MPG (ENEA) |
| Influence of surface microstructure due to low energy He irradiation on D uptake studied in situ (JSI, MPG) |
| Self-damaged W samples for JSI investigation (MPG) |

# Task: Study the effect of O layers on D retention: from 1 monolayer to few 100s nm

- Strategy: repeated D implantation on one $WO_3$ sample grown at 1073 K

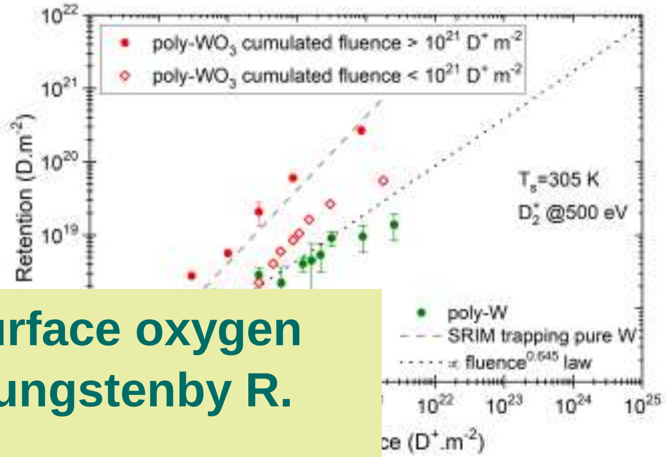
**2021**

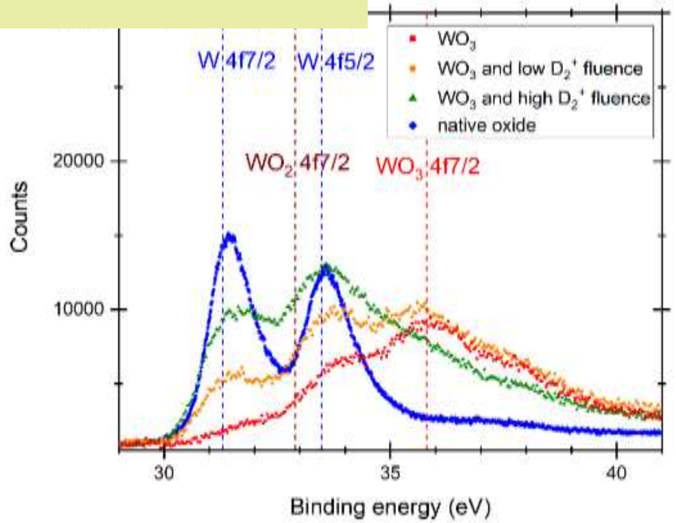
- oxide with 150 nm thickness: D retention ?
- D retention increases with fluence
- At a given fluence, the cumulated fluence increases D retention → layer evolution ?

**There will be a talk on Surface oxygen versus native oxide on tungstenby R. Bisson**

**2022**

- oxide with thickness below 100 nm: D retention ?
- D retention dependence with fluence ?
- XPS analysis of the 150 nm thick oxide after high cumulated fluence shows loss of oxygen
  → sample surface toward the native poly-W
- Completion of the system upgrade for oxide growth at lower thickness
- oxide growth below 100 nm ongoing





*SP-C-1: Transport of Hydrogen through the first wall of fusion devices (from 03-AMU)*

**T. Angot, R. Bisson, C. Martin, M. Minissale – PIIM/AMU-CNRS**

# Energy and fluence dependence of D uptake through thin surface oxide films on tungsten - Results

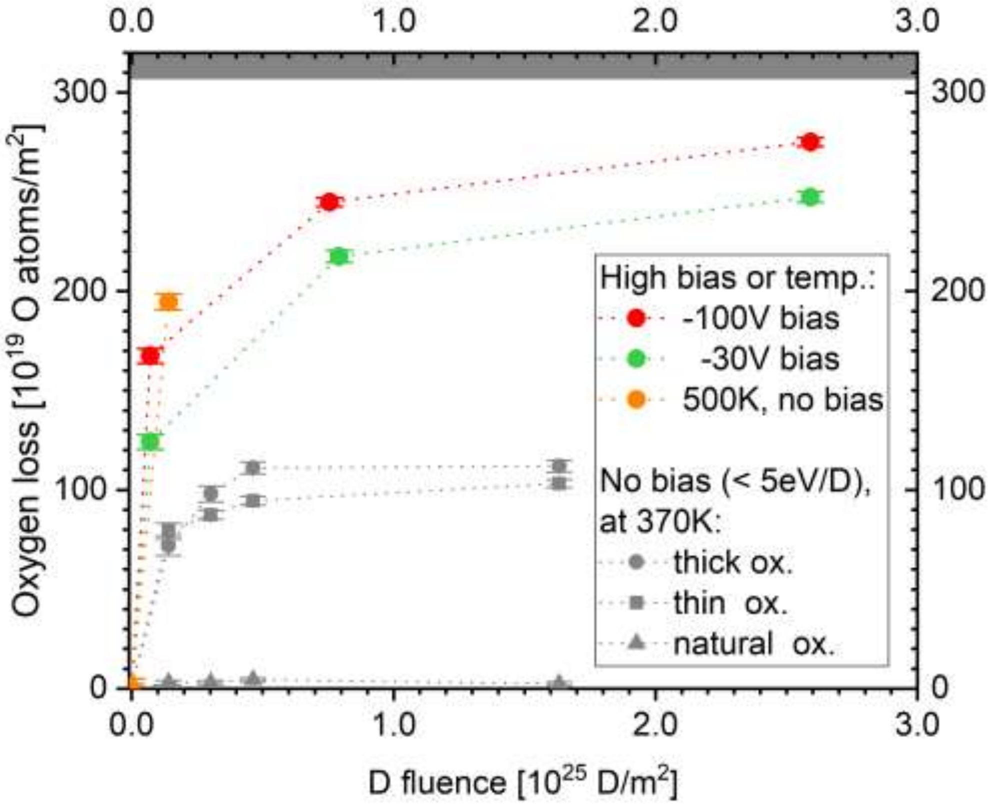
❖Asses role of oxide in laboratory experiments:
Does it affect predications for reactor?

There will be a talk on the influnce of WO on uptake and release by K. Kremer

❖**5eV/D: 30 nm oxide form stable D uptake barrier!**

❖**15, 38 eV/D: Oxide reduction degrades barrier**

❖Extrapolation to **natural oxide** (1-2 nm):
→ **Affects only D uptake studies with low fluence ($< 10^{23}$ D/m²)**



Oxygen loss depending on fluence for different plasma conditions

➢Second publication to uptake/oxide reduction on its way

➢In-situ studies with oxide free surface planned

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Kristof Kremer

# D release through thin surface oxide films on tungsten depending on oxide thickness - Results

❖Asses role of oxide in laboratory experiments:
Does it affect pre

**There will be a talk on the influnce of WO on uptake and release by K. Kremer**

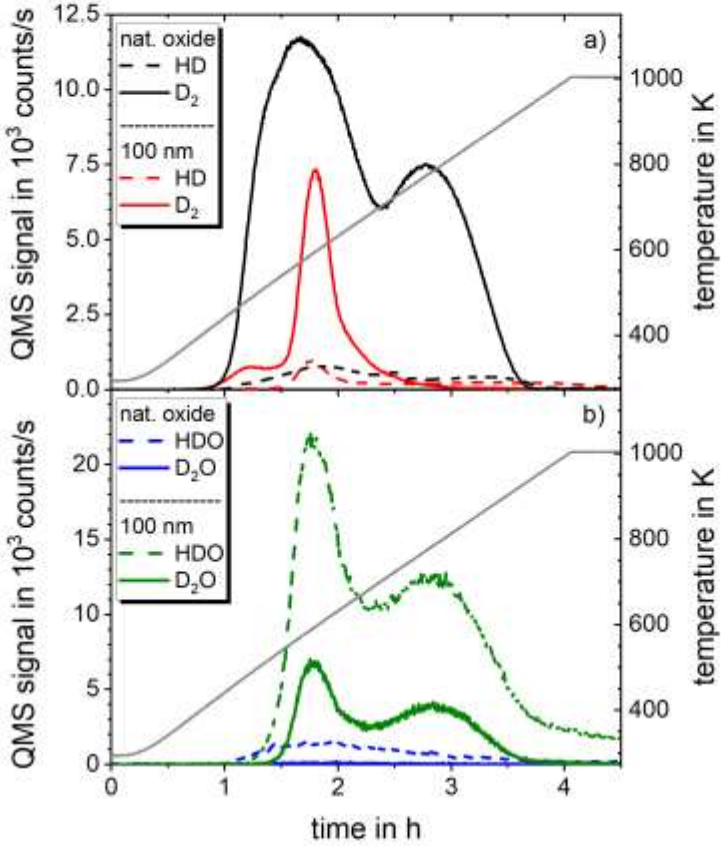
❖Oxide shifts first release peak:
→ Affects calculation of D binding energies

❖Chemical reaction above 500 K:
→ D mainly released as heavy water
→ Needs to be included for correct D amount!

❖**Oxide films affect D release if ratio O/D > 5%**
❖Even natural oxide films can have an effect!

➢Investigation of oxide reduction process and heavy water formation with TDS at 500 K

First results published in:
K. Kremer et al., Nuclear Materials and Energy, Volume 30, 2022, 101137, ISSN 2352-1791



TDS for natural (1-2 nm) and 100nm thick oxide
→ shift of first release peak
→ heavy water production

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# Task name: XRD and Raman of Oxide films on W

## What we did:

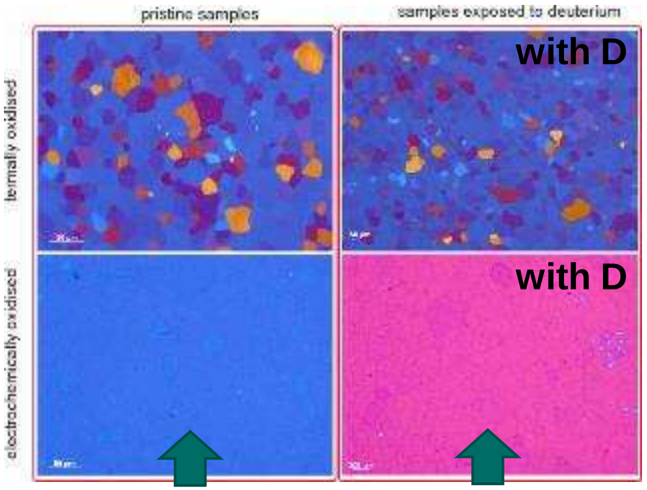
- ❖ XRD, SEM, FIB and vibrational study of thermal and electrochemical WOx before & after D loading

## How we did:

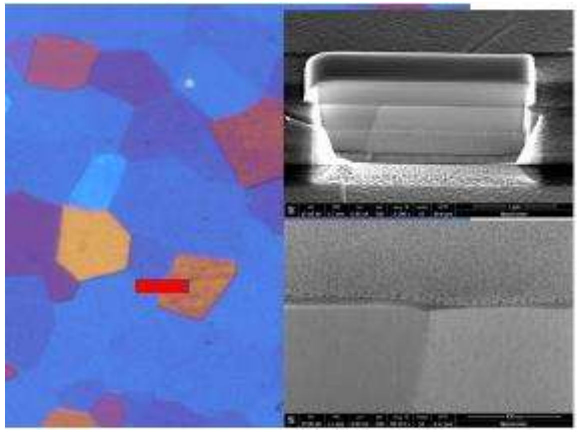
- ❖ XRD, GI-XRD, FTIR and μ-Raman spectroscopy

## KEY answers obtained:

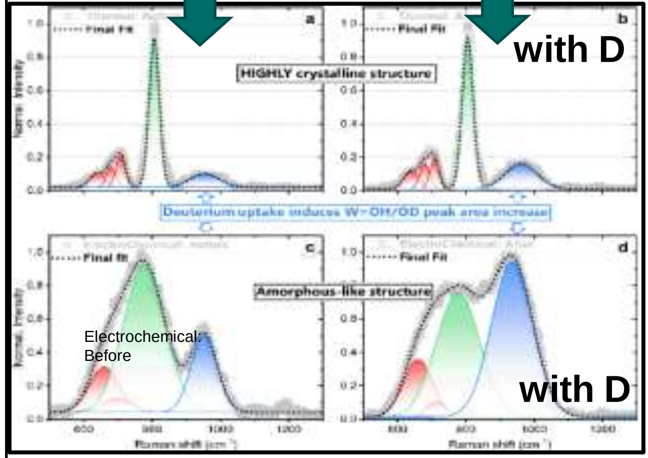
- ❖ crystallinity: **highly crystalline „thermal“ WOx**, and **amorphous electrochemical WOx**
- ❖Annealing of am. electrochem. WOx results in mixtures of WOx and differs from “thermal” WOx
- ❖Deuterium uptake/retention is more favorable by electrochemical WOx
- ❖interaction with D results in W-hydroxides => more pronounced in electrochemical WOx



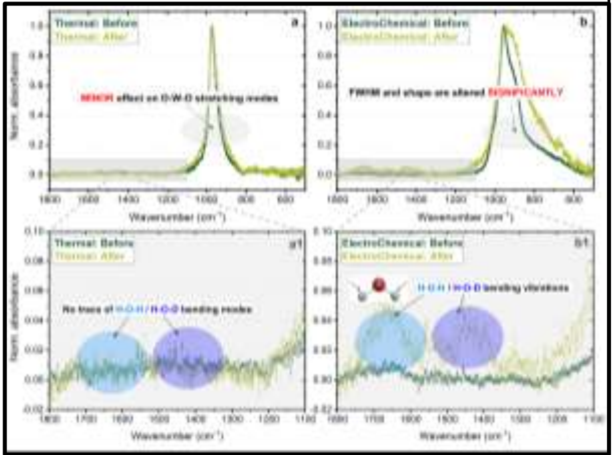
**pristine WOx ====> with D**



**OL / FIB identical location thickness studies**



**Raman**



**FTIR**

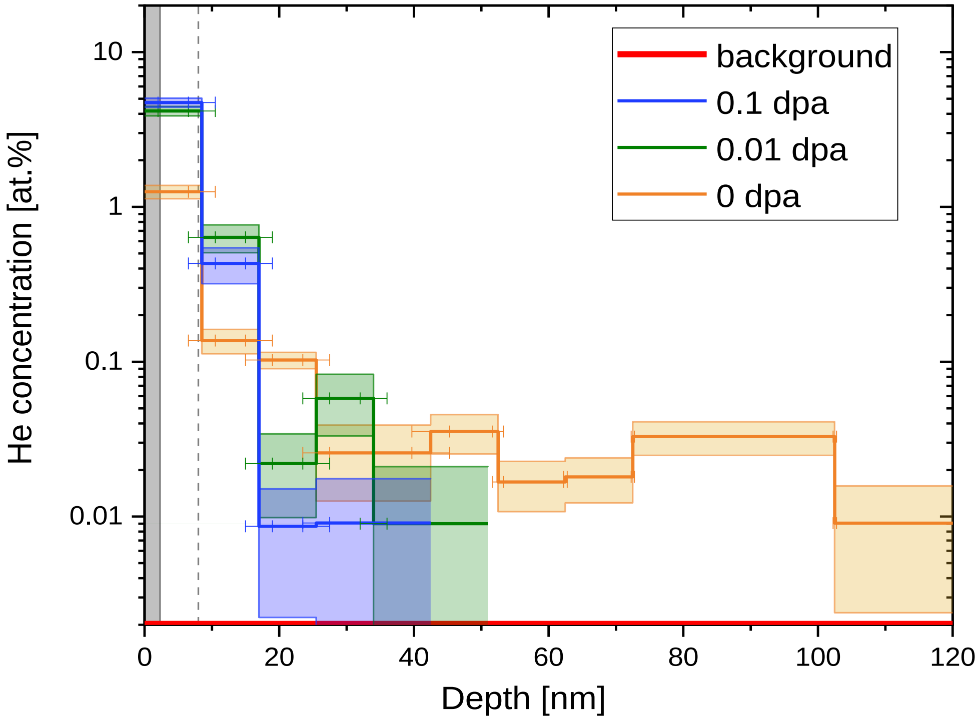
## Next goals:

- ➢TEM annealing studies to reveal and understand WOx structural transformations influencing crystallinity, thickness and propensity towards D.

**Kristof Kremer (IPP), Janez Zavašnik (IJS)**

# Establishing He exposure and analysis procedure

- ❖ 2400 K annealed, polycryst. W
- ❖ Creation of displacement-damage with 20 MeV W
- ❖ Exposure to low flux He plasma ($10^{18}$ He/m$^2$s) at low energy (100 eV) to avoid creation of additional defects (energy transfer 8.3 eV << $E_{displacement}$)
- ❖ Depth-resolved DB-PAS at shows no additional defects
- ❖ Total He retention from Elastic Recoil Detection (ERDA) analysis: He retention depends on damage level
- ❖ Depth profiling by anodic oxidation and dissolution of the oxide together with ERDA shows larger retention near the surface and **less deep penetration of He when displacement damage is present**
- ❖ Manuscript submitted to Nucl. Mater. Energy



Influence of displacement damage on He depth profiles for low-flux, low-energy He exposure

**WM35**

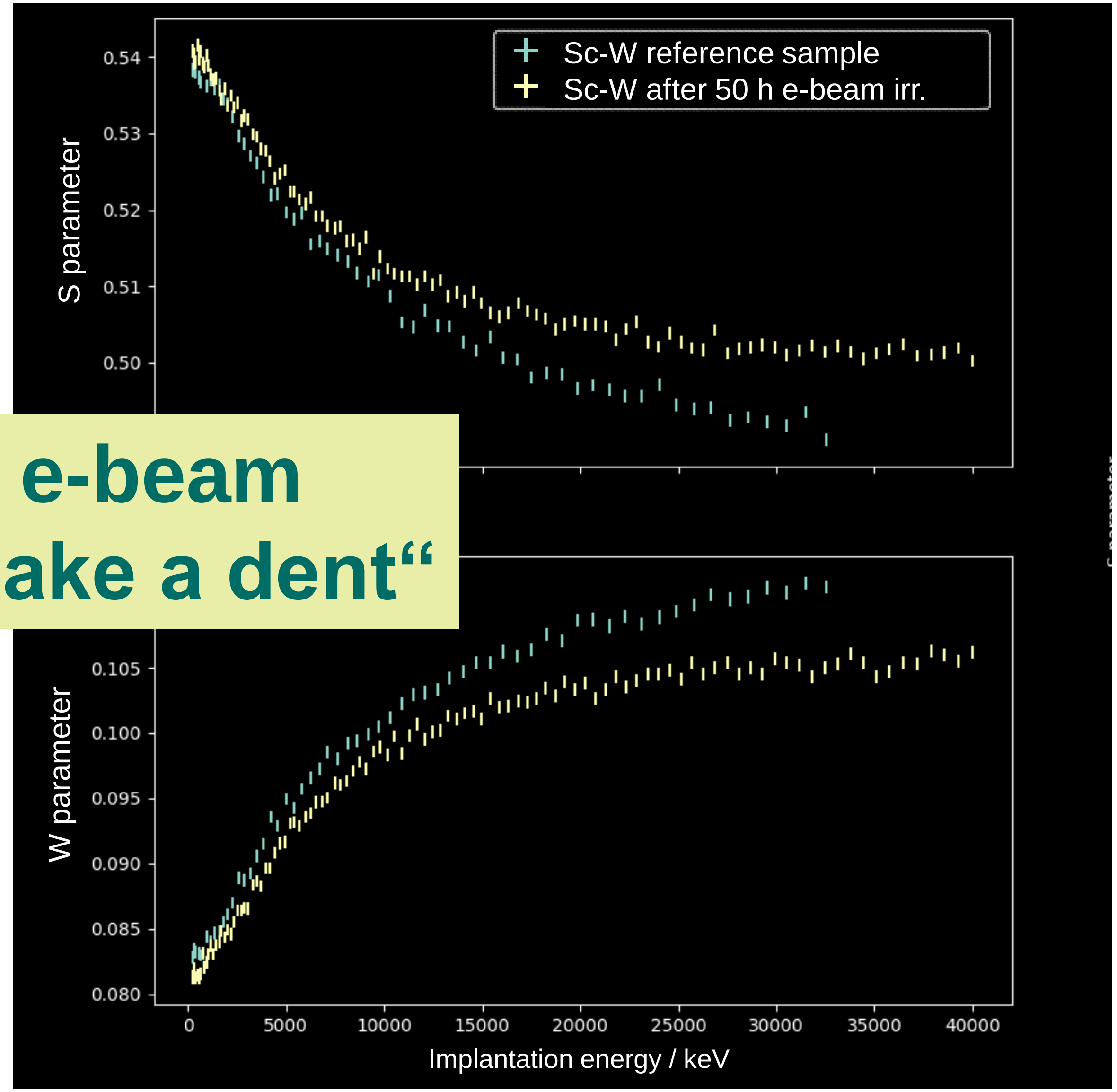
**Annemarie Kärcher**

# Difference in He retention in defect-free and e-beam damaged W

- Preparation of tungsten single crystals (sc-W) and pre-characterization at MLZ Heinz Maier-Leibnitz Zentrum with depth-resolved DB-PAS
- Exposure for 10 and 50 h of e-beam at ENEA to create homogeneously distributed mono-vacancies (4.5 MeV, 0, 0.3, 1.2×10$^{-4}$ dpa)
  Second batch of exposures plann
- Post-characterization by depth re

| **Sample** | **mean diffusion length** [nm] |
|---|---|
| sc-W after 50 h e-irradiation | 48 ± 1.3 |
| sc-W after 10 h e-irradiation | 54 ± 1.5 |
| sc-W (reference) as prepared | 58 ± 2.3 |

- ➢ Procedure for pending He exposure established
- ➢ Sensitivity for ERDA setup increased
- ➢ TDS up to 2600 K achieved
- ➢ Post DB-PAS measurements under way



**50h of e-beam „hardly make a dent“**

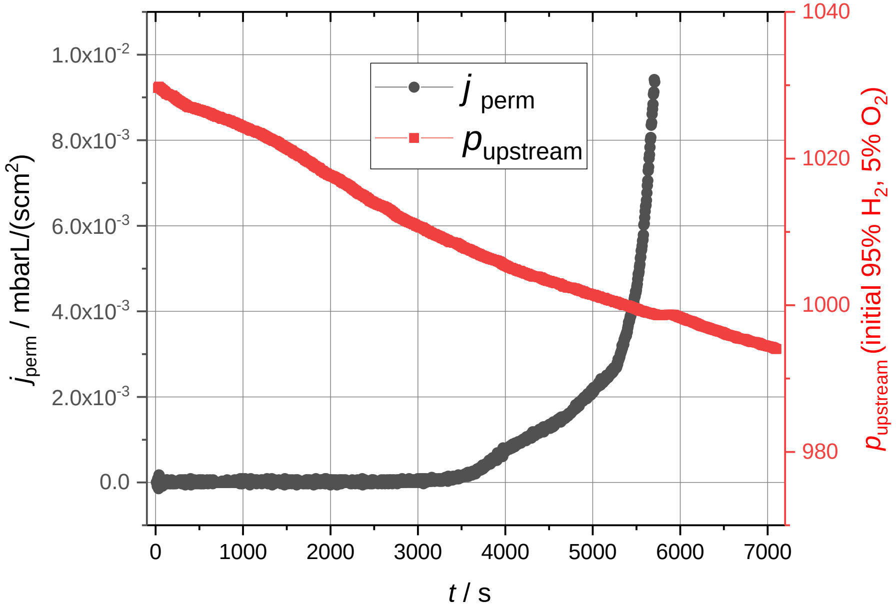
Depth resolved S and W parameter obtained by DB-PAS of 50 h irradiated sc-W

# Permeation barrier properties of chromia grown on dense Cr films+Eurofer

- Oxides influence H/D/T permeation rate through metal, but the suppression mechanism is not well explained yet.

- Native and mixed oxide grown in pure $O_2$ is transparent for $H_2$.
- Gas-driven hydrogen permeation through Eurofer membrane was monitored in exposure to $95\%H_2/5\%O_2$ gas mixture at 400°C.

- **An impermeable film is immediately formed in this gas mixture, but becomes permeable again in pure $H_2$.**



- The most probable explanation is that during the catalytic reaction, an ultrathin layer prevents hydrogen dissociation. Verifying chemical reactions at the surface is extremely challenging and proven only on Cr, but not yet on Fe.

Catalytic reaction maintained Eurofer impermeable for ~1h, *PRF*>1000

- All the planned experiments for 2022 have been realised.

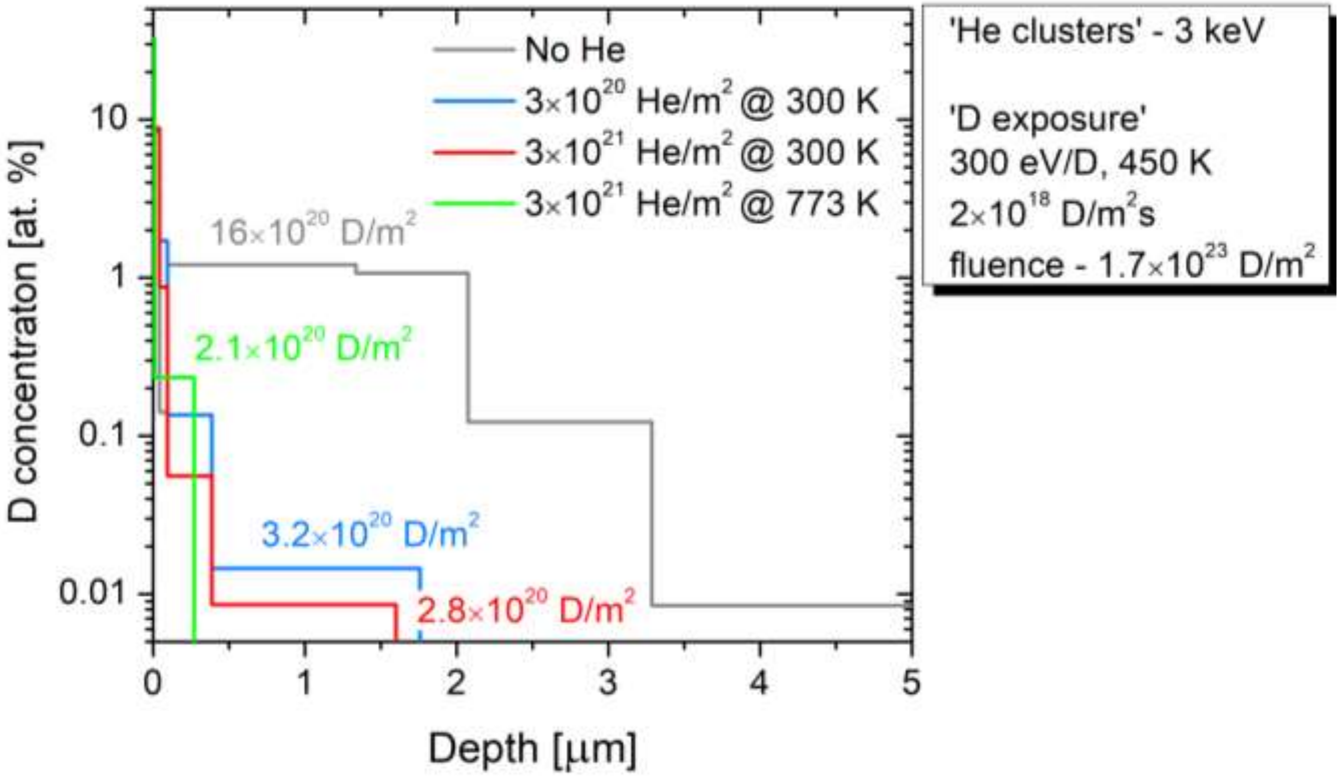
**Jozef Stefan Institute**

**Vincenc Nemanič, Marko Žumer, Janez Zavašnik, Matjaž Panjan**

# Influence of surface microstructure due to low energy He irradiation on D uptake

- ❖ Irradiate W by 3 keV He ions @ 773 K (He cluster/bubbles), self-damage by 20 MeV W to 2 microns and finally expose to 300 eV/D ions at 450 K to study D uptake (last year @ RT)
- ❖ NRA: D depth profiles in He irradiated samples and no He reference sample
- ✓ Total D retention 7 times less in the He irradiated samples compared to only W irradiated
- ✓ High D surface concentration – as for the RT case
- ✓ Very small amount of D beyond 40 nm
- ✓ He on the surface – barrier for D / increased recycling?
- ✓ Retained D/m² ≈ implanted He/m²
  (similar as for MeV He implantations by Bauer et al. 2019)

**There will be a talk on the influence on near surface He by S. Markelj**

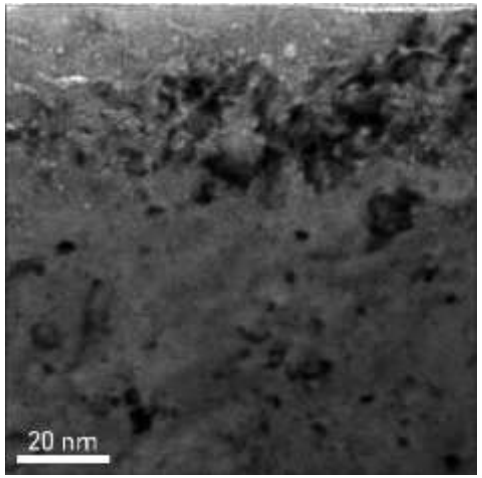


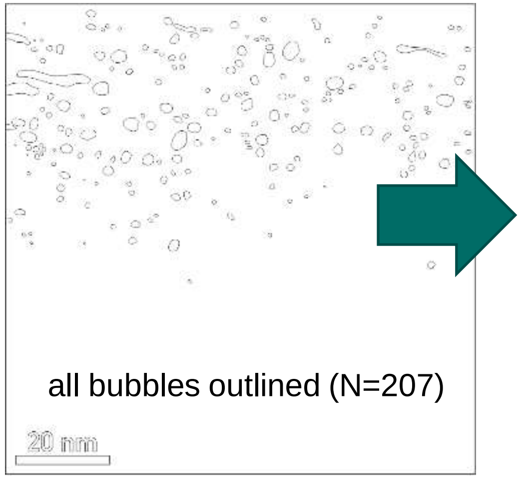
Sabina Markelj / Thomas Schwarz-Selinger

# Influence of surface microstructure due to low energy He irradiation on D uptake

- Irradiate W by 3 keV He ions @ RT and 773 K (He cluster/bubbles), self-damage by 20 MeV W to 2 microns and finally expose to 300 eV/D ions at 450 K to study D uptake

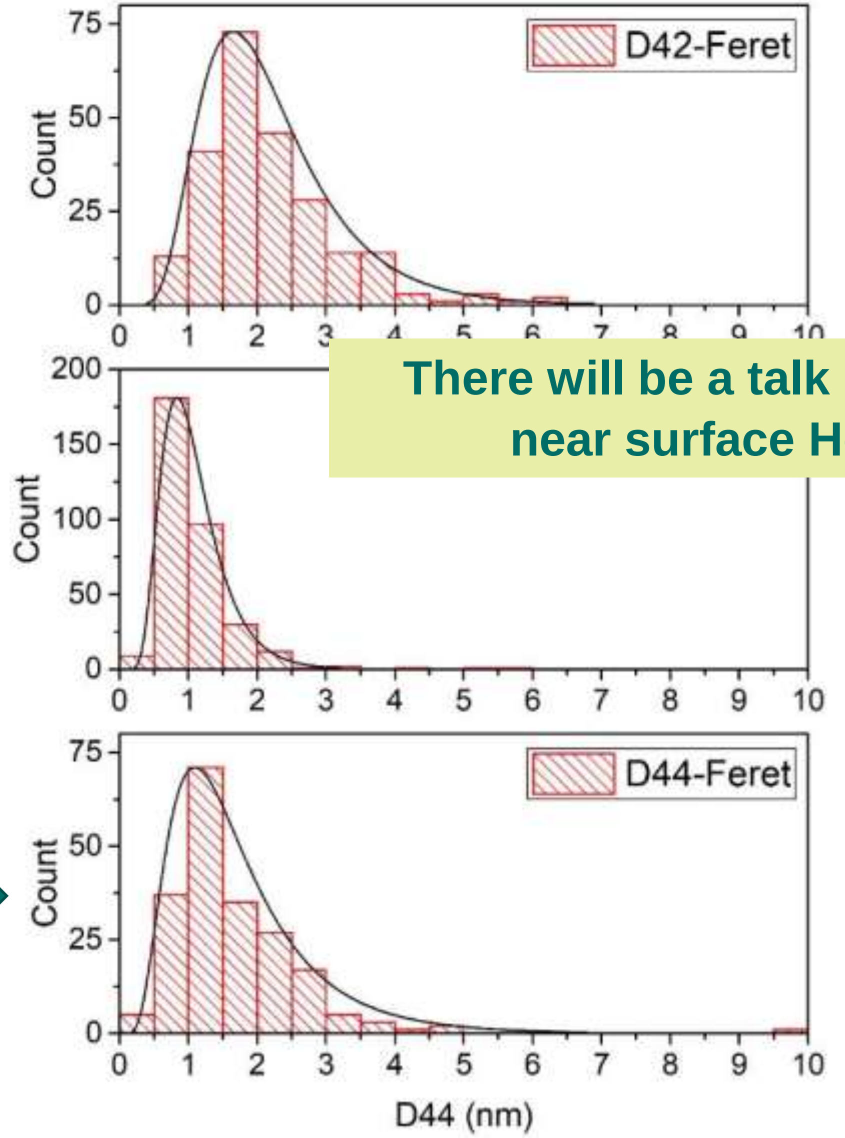
- TEM analysis of all three samples: nm-size bubbles in the first few nm bellow the surface
- Smaller bubbles observed for the higher fluence





all bubbles outlined (N=207)

He bubble size:



$3{\cdot}10^{20}$ He/m$^2$ @ RT

$3{\cdot}10^{21}$ He/m$^2$ @ RT

$3{\cdot}10^{21}$ He/m$^2$ @ 773 K

**There will be a talk on the influence on near surface He by S. Markelj**

**Andreja Šestan / Janez Zavašnik**

# SP C.3 Influence of He, high-flux D and impurities on Hydrogen retention and transport

## ❖ Plan for 2023

| Association | Title | Deliverables |
|---|---|---|
| CEA | Study the effect of O or C layers on D: bulk vs surface uptake | #1 Influence of storage time on retention with O-layers on W<br>#2 Fluence dependence on retention with C-layers on W |
| JSI | TEM analysis of He loaded self-damage W | Investigate presence of He-bubbles |
| MPG | Exposure of poly crystalline W to He plasmas to study He cluster formation | Retained He in W at low energies (< 100 eV) as function of flux (<10^19 He/m2) |
| JSI | Study of hydrogen permeation barrier in situ grown by oxygen/hydrogen mixture | Permeation reduction factor on chromia and Eurofer formed by oxygen/hydrogen mixture |

# SP C.4 Influence of n-damage on Hydrogen retention and transport

| Task |
|---|
| Simulation of neutron-damaged W by W self-damage at different dpa (6 W samples) (IPP) |
| Exposition of W samples in PSI-2 D plasmas to load with D at low surface temperature (FZJ) |
| Quantification of fuel content for 3 samples by NRA and TDS (MPG, FZJ) |
| Quantification of fuel content for 3 samples by LIA-QMS and DP-LIBS (FZJ) |

# Reference D-containing W samples for LIBS

❖ What we did and why:

LIBS exhibit great potential on in situ determination of fuel retention after proper signal calibration.
Reference D-containing W samples are required to further explore the LIBS technique.

❖ Which experiments/calculations were performed

1. Recrystallization of 12x double-forged W samples: eliminating the effect form unknown intrinsic defects
2. Self-damage (10.8 MeV W, 0.23 dpa) for 9x samples: to create high-density defects for D trapping
3. D 1e25/m$^2$ loading at PlaQ (5eV/D, 370K, 4x) & PSI-2 (40eV/D, 390K, 4 samples): D decoration
4. Partial degassing of 2-PlaQ-loaded samples
5. NRA D depth profiling of 4-PlaQ-loaded samples

❖ **Brilliant Results: to be expected in Nov. / Dec. 2022**

**WM38**

➢ Things will be done within this year:

1. Partial degassing of 2-PSI2-loaded samples
2. NRA D depth profiling of 4-PSI2-loaded samples
3. Dual-pulse LIBS measurements of all 8 samples
4. TDS of all 8 samples
5. Summary of the task

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

JÜLICH Forschungszentrum

**T. Schwarz-Selinger, Liang GAO, E. Wüst**

# SP C.4 Influence of n-damage on Hydrogen retention and transport

## ❖ Plan for 2023

| Association | Title | Deliverables |
|---|---|---|
| FZJ | Gas driven permeation through and retention in W, Steel, W on Steel and W on Cu | Permeation though p-damaged EUROFER |
| FZJ | Development of co-deposited D-W, He-W and D-He-W layers in magnetron-sputter device with good reproducibility | D, He or D&He contents in co-deposited D-W, He-W and D/He-W layers cross-checked by NRA, TDS, and DP-LIBS |
| MPG | Annealing of displacement damage of EUROFER below 600K | Trap site concentration as function of annealing temperature below 600K |
| MPG | Annealing of trap sites in He containing displacement damaged EUROFER | Temperature needed to anneal trap sites in He containing displacement damaged EUROFER |
| JSI | Uptake of atomic D into displacement damaged EUROFER | Uptake of atomic D as function of time |

# Conclusions

**All tasks are underway/completed and no delays are expected**

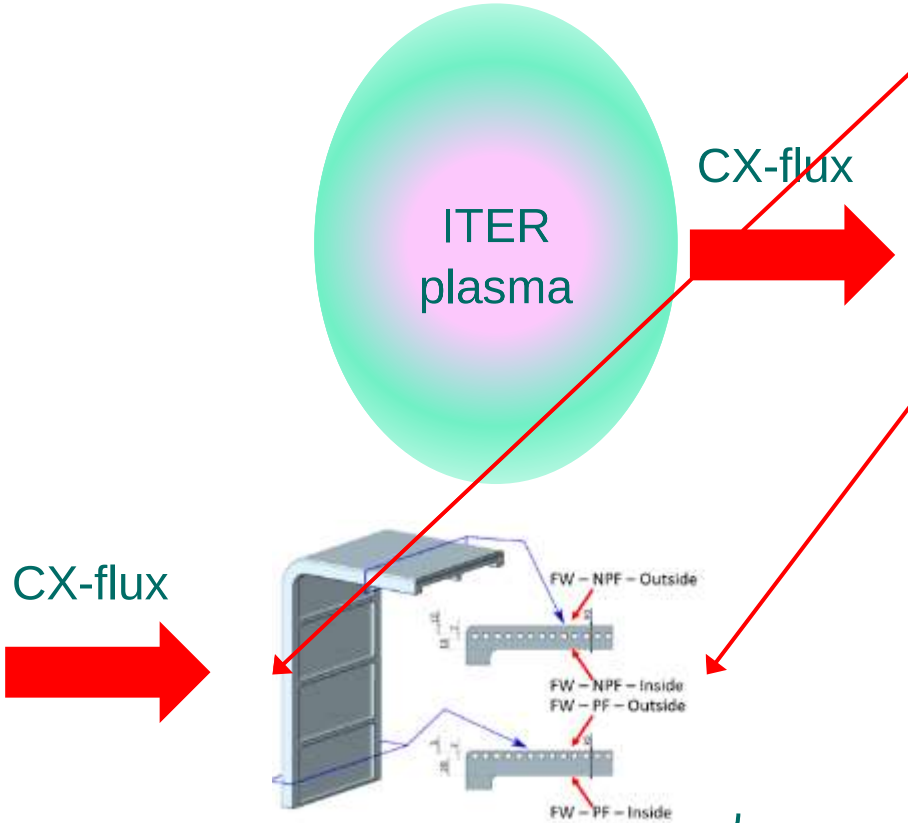
# Plans for 2023

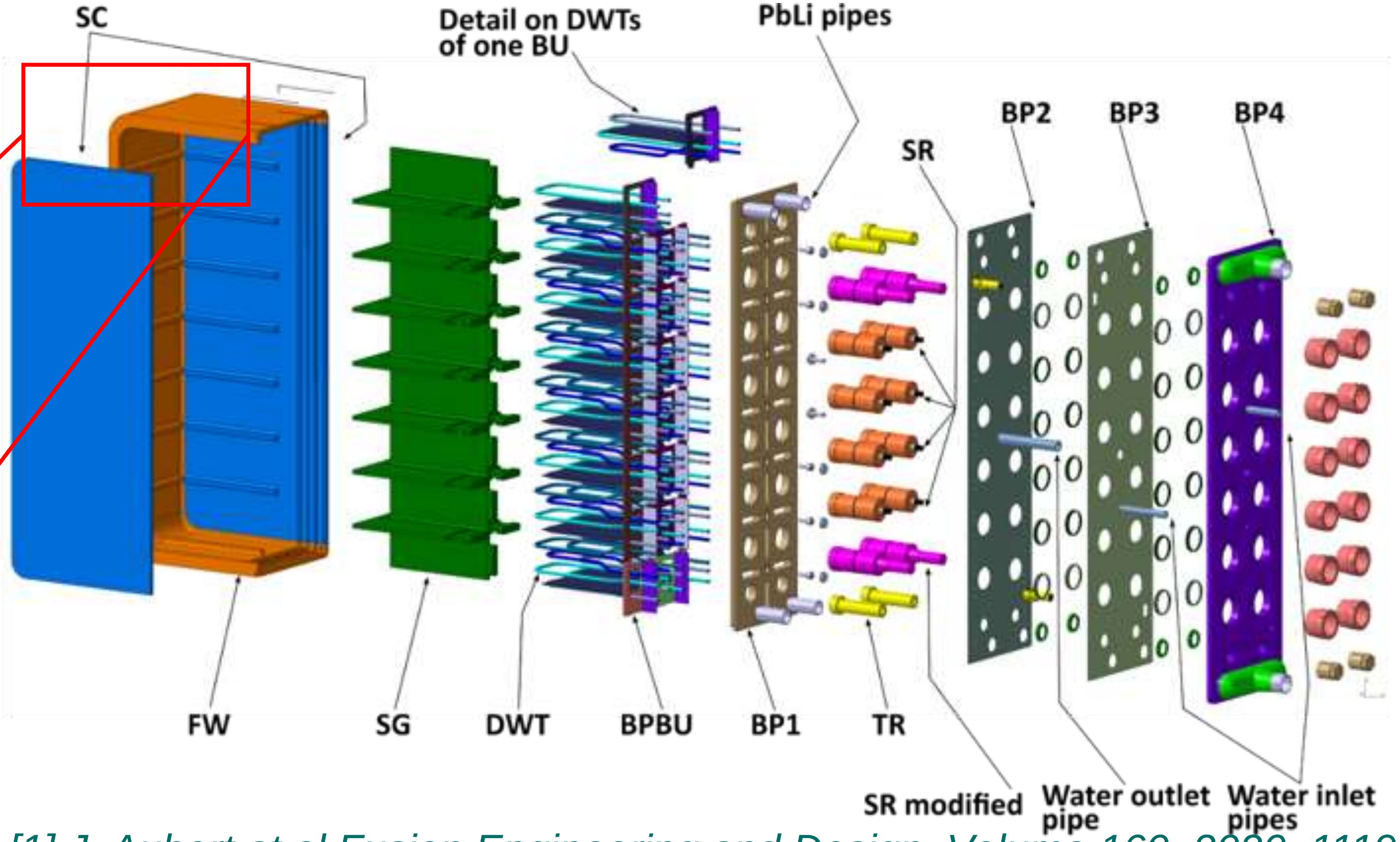
- **The work on W will mainly be continued into next year**

- **Some tasks will be completed however and I‘d like to shift the focus onto EUROFER**
  - Why is H, D, T in EUROFER important?
    - After all its not a plasma facing component

# Why is H, D, T in EUROFER important?

- ITER test blanke module [1]





*[1] J. Aubert at al Fusion Engineering and Design, Volume 160, 2020, 111921*

- ➢ Made of EUROFER
- ➢ In contact with PbLi with dissolved T

- ➢ Made of EUROFER with ~mm thick W armor layer
- ➢ Loaded by D, T, CX

- ➢ **Most of material between plasma and coolant is EUROFER**

# Why is H, D, T in EUROFER important?

## ❖ Preliminary estimates on T-loss to EUROFER [1,2]

- ➢ How much T can we loose to the wall and still be T-self-sufficient?
- ➢ Simple balance model [3,1]:

| $\Gamma^{In}$ | T-core fueling by pellets | $\left({}^{1}/_{s}\right)$ |
|---|---|---|
| $\Gamma^{Wall}$ | T-wall flux | $\left({}^{1}/_{s}\right)$ |
| $\Gamma^{Burn}$ | T-burn rate | $\left({}^{1}/_{s}\right)$ |
| $N^{Surplus}$ | **TOTAL** T-"excess" source | (#) |
| $N^{Trapped}$ | **TOTAL** T-trapping rate | (#) |
| TBR | Tritium breeding ratio | 1.05 |
| R | Recycling coefficient | 0.999 |
| $p_{Burn}$ | fraction of tritium burned | 0.05 |
| $\eta_{Pellet}$ | Pellet fueling efficiency | 30% |
| $\eta_{Rec}$ | Recycling fueling efficiency | 1% |

$$\Gamma^{In} = \Gamma^{Burn} + (1-R)\Gamma^{Wall}$$

$$\Gamma^{Burn} = p_{Burn}\left(\eta_{Pellet}\,\Gamma^{In} + R\,\eta_{Rec}\,\Gamma^{Wall}\right)$$

$$N^{Surplus} = (TBR-1)\,\Gamma^{Burn}\Delta t$$

$$\mathrm{N}^{Trapped} = \int p_{Wall-Loss}\,\Gamma^{Wall}\,dt = \Gamma^{Wall}\int p_{Wall-Loss}\,dt$$

T-self sufficiency: $N^{Surplus} \gg \mathrm{N}^{Trapped}$

$$\langle p_{Wall-Loss}\rangle = \frac{\int p_{Wall-Loss}}{\Delta t} = \frac{\int \Gamma^{Trapped}}{\Gamma^{Wall}\Delta t} \ll (TBR-1)\,\frac{p_{Burn}(\eta_{Pellet}-R(\eta_{Pellet}-\eta_{Rec}))}{1-p_{Burn}\eta_{Pellet}} \sim \mathbf{10^{-4}}[1,2]$$

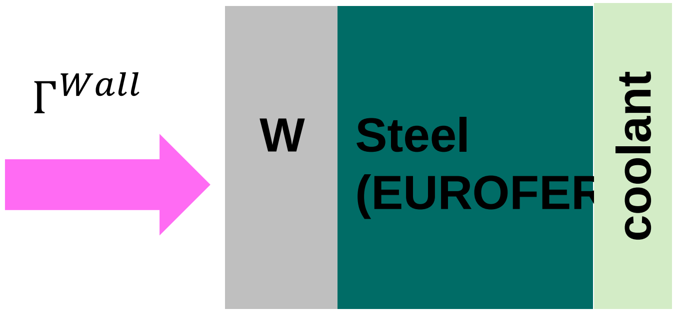
**$\int p_{Wall-Loss}$ can be calculated from diffusion trapping code**

*[1] R. Arredondo et al Nuclear Materials and Energy 32 (2022) 101228*  *[3] R.P. Doerner et al Nuclear Materials and Energy 18 (2019) 56*

*[2] R. Arredondo et al Nuclear Materials and Energy 28 (2021) 101039*

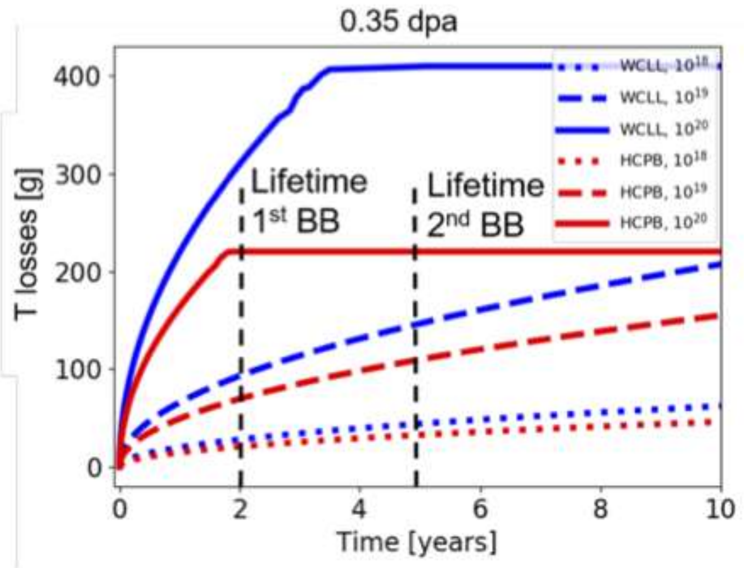
# Why is H, D, T in EUROFER important?

- **Preliminary estimates on T-loss to EUROFER [1,2]**
  - How much T can we loose to the wall and still be T-self-sufficient?
  - **DEMO main chamber first wall (1400 $m^2$): 0.8 mm W on 1.2 mm Steel [1]**



- Two different blanket cooling concepts WCLL (673K) vs. HCPB (793K)
- Intrinsic & neutron generated traps in W & steel layer
- Vary $\Gamma^{Wall}$ from $10^{18}$ $10^{20}$ ($m^{-2}$ $s^{-1}$)

  → Compute loading of wall with 50:50 D/T mix



- At high $\Gamma^{Wall}$ trapping front reaches coolant
  → Retention becomes constant
- At low $\Gamma^{Wall}$ trapping front does NOT reach coolant
- T-losses into the wall are significant

*[1] R. Arredondo et al Nuclear Materials and Energy 32 (2022) 101228*

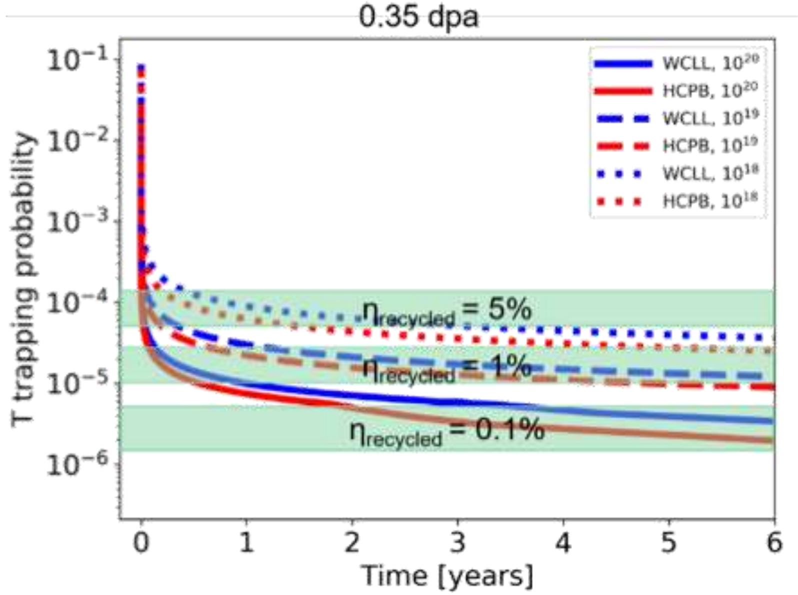
*[2] R. Arredondo et al Nuclear Materials and Energy 28 (2021) 101039*

# Why is H, D, T in EUROFER important?

- **Preliminary estimates on T-loss to EUROFER [1,2]**
  - How much T can we loose to the wall and still be T-self-sufficient?
  - **DEMO main chamber first wall (1400 m$^2$): 0.8 mm W on 1.2 mm Steel [1]**

$$\langle p_{Wall-Loss}\rangle \ll (TBR-1)\,\frac{p_{Burn}(\eta_{Pellet}-R(\eta_{Pellet}-\eta_{Rec}))}{1-p_{Burn}\eta_{Pellet}}$$

| | | |
|---|---|---|
| TBR | Tritium breeding ratio | 1.05 |
| R | Recycling coefficient | 0.999 |
| $p_{Burn}$ | fraction of tritium burned | 0.05 |
| $\eta_{Pellet}$ | Pellet fueling efficiency | 30% |
| $\eta_{Rec}$ | Recycling fueling efficiency | 0.1-5% |



- **It takes up to 2-3 fpy to become T self sufficient!**
- **More than the blanket life time…**

- As trapping filling front penetrates deeper the gradients flatten and thus the flux into the wall & trapping rate drops
- Years are FPY (1 FPY ~3 years real time)

*[1] R. Arredondo et al Nuclear Materials and Energy 32 (2022) 101228*

*[2] R. Arredondo et al Nuclear Materials and Energy 28 (2021) 101039*

# Why is H, D, T in EUROFER important?

- **Preliminary estimates on T-loss to EUROFER [1,2]**
  - **Major unknowns for displacement damaged EUROFER**

- CX-fluxes and energies
- Solubility of T in PbLi and EUROFER
- **Trap site concentration η**
- **De-trapping energies $E_D$**
- **Surface boundary condtions**

**WP-PWIE SP-C can contribute**

$$\eta = \eta(DPA, T, C_{He}, C_{SOL}, t)$$

$\boldsymbol{DPA}$ = **Displacements per Atom**
$T$ = Temperature
$C_{He}$ = Concentration of He
$C_{H,D,T}$ = Concentration of H-isotopes
t = time

[1] R. Arredondo et al Nuclear Materials and Energy 32 (2022) 101228
[2] R. Arredondo et al Nuclear Materials and Energy 28 (2021) 101039

# Possible Contributions of WP-PWIE SP-C

- **Major unknowns**
  - **Trap site concentration η**
  - **De-trapping energies $E_D$**
  - **Surface boundary condtions**

$$\eta = \eta(DPA, T, C_{He}, C_{SOL}, t)$$

$\boldsymbol{DPA}$ = **Displacements per Atom**
$T$ = Temperature
$C_{He}$ = Concentration of He
$C_{H,D,T}$ = Concentration of H-isotopes
t = time

- **For displacement damaged EUROFER**
  - Annealing of displacement damage
  - Annealing of He containing displacement damage
  - Simultaneous damaging and loading
  - De-trapping energies in displacement damage generated defects (w/wo He)
  - Permeation (different ransport regimes)
  - D:T co-permeation D:H co-deposition
  - Permeation across W:EUROFER interface
  - ...