Challenges for materials in fusion environment: interactions with tritium and morphology evolution under the WEST first wall conditions

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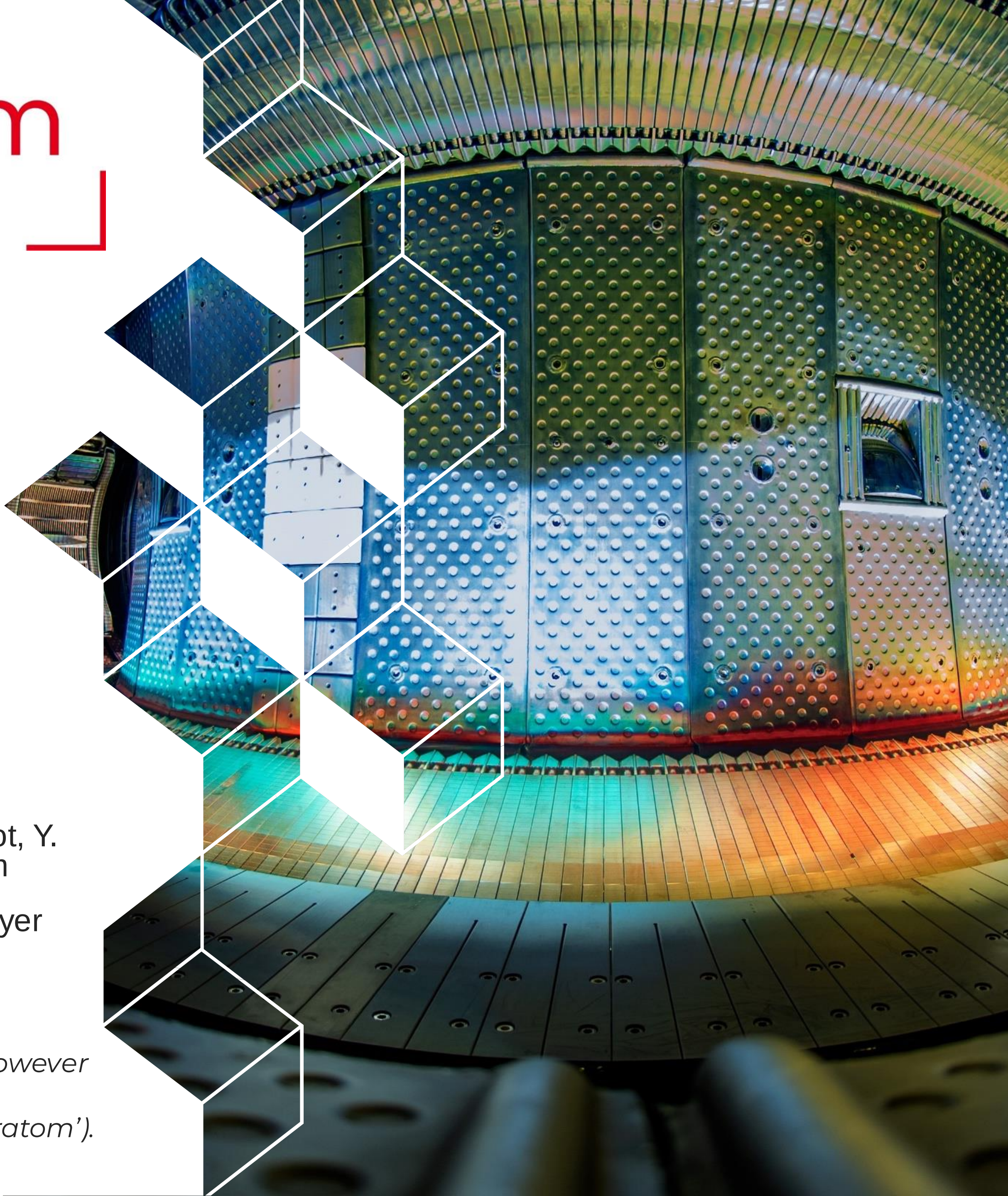

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Outline

1. Reactor technologies and design: required material properties

- Plasma-wall interaction conditions, key functions and properties
- Materials of interest
- The burning issue of tritium behavior

2. Plasma-facing materials in fusion reactors

- Evolution of surface conditions in realistic conditions in the WEST tokamak
- Understanding fundamental mechanisms: impact of He on W microstructure

3. Tritium interaction with materials: the TITANS project

- Enhancement of tritium permeation barriers and tritiated waste management
- Tritium measurement and modelling
- Radiation protection, risk assessment and dosimetry studies following accidental exposure to tritiated dust in support to EU regulators (art. 31)

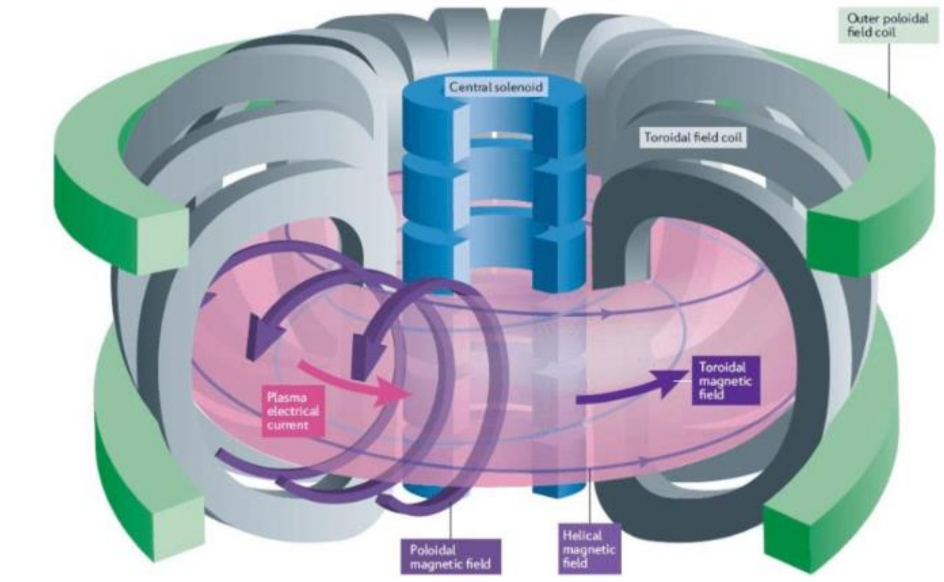
Achieving magnetic confinement in reactors: the tokamak concept

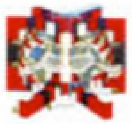
- Confining the hot plasma for nuclear reactions to happen:
  - Inertial confinement
  - Magnetic confinement: **tokamaks** and stellarators

In tokamaks, magnetic confinement is not perfect:

- Particles (and energy) losses
- Intense plasma - wall interaction
  - ➢ *Production of particles (« dust »)*
  - ➢ *Irradiation of plasma-facing materials (PFM)*

Vacuum chamber surrounded by strong magnetic fields



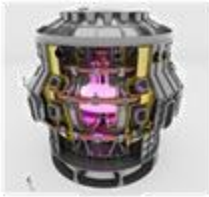


WEST

25 m^3

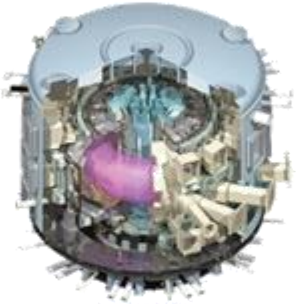
JET

80 m^3



JT-60SA

135 m^3



ITER

800 m^3
(one-third the size of an Olympic swimming pool)

~ 500 MW$_{th}$

DEMO

~ 1000 – 3500 m^3
(half to one and a half times the size of an Olympic swimming pool)

~ 2000-4000 MW$_{th}$

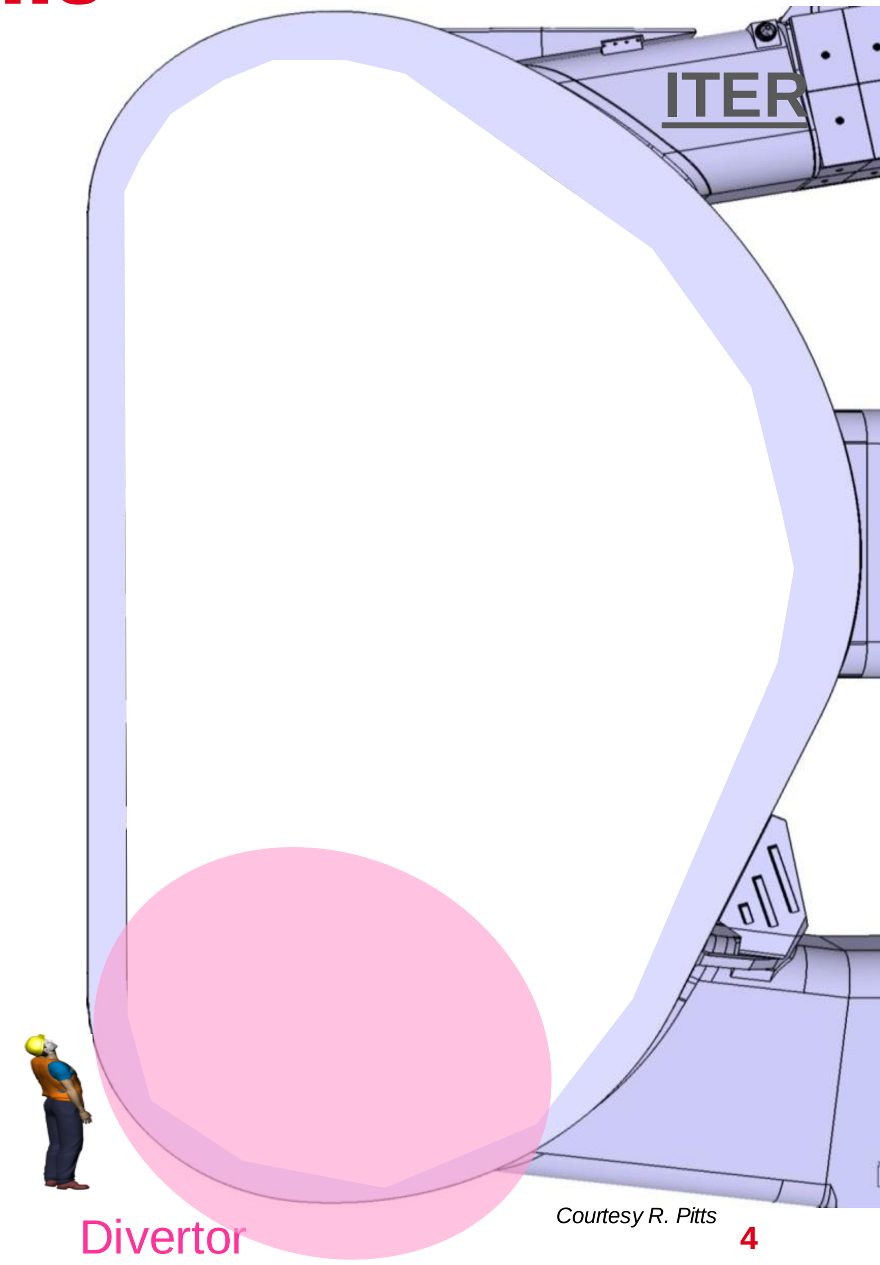
➔ ITER: demonstrate scientific and technical feasibility of fusion as a source of energy + tests of Breeding Blanket (tritium production)

From the magnetic confinement to the first physical barrier in ITER

- **The vacuum vessel:** double actively cooled stainless steel wall
  - 10^{19}-10^{20} m^{-3} plasma densities
  - Minimize impurities: low background pressure (~10^{-5}Pa)
- **First wall components:** the first physical materials facing the plasma
  - Exposed to drastic conditions:
    - High thermal flux (stationnary and transients)

      ITER: 10-20 MW/m^2 up to 60 MJ/m^2 over a few ms
    - Particle irradiation (D,T, He)
    - Neutron irradiation
  - Functions:
    - Extract the heat from plasma
    - Control impurities and particles (He)
    - Produce T

→ **Manage the contact while minimizing the pollution of the plasma and the modification of materials**

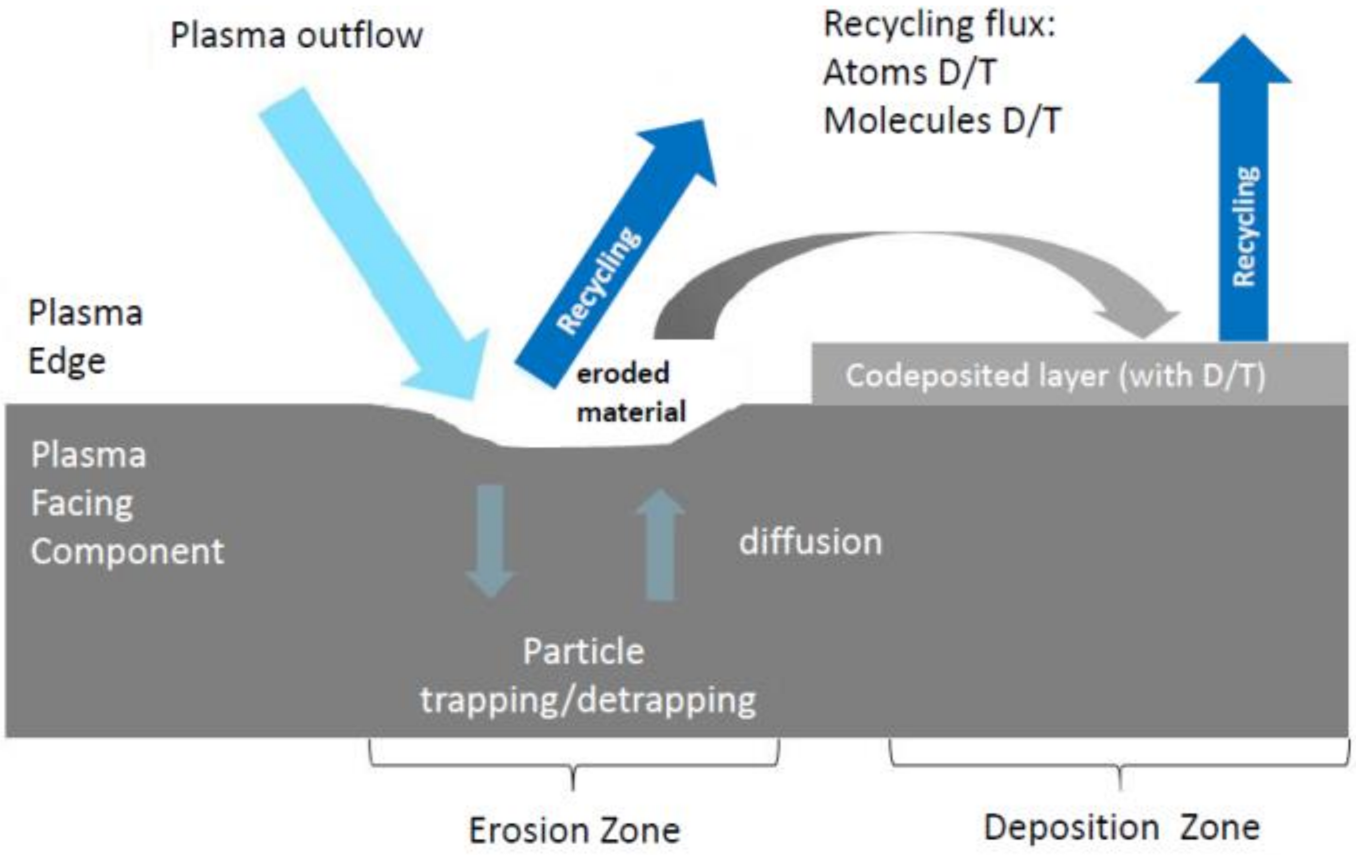


Courtesy R. Pitts

Plasma-Wall interactions in Tokamaks

- Combination of several mechanisms
- Irradiations:
  - D/T
  - He
  - 14 MeV neutrons

+ **Conditioning (boronosation)**
+ **High temperatures (>500°C)**
+ **Drastic events: disruptions, ELMs, runaways electrons, arcs**



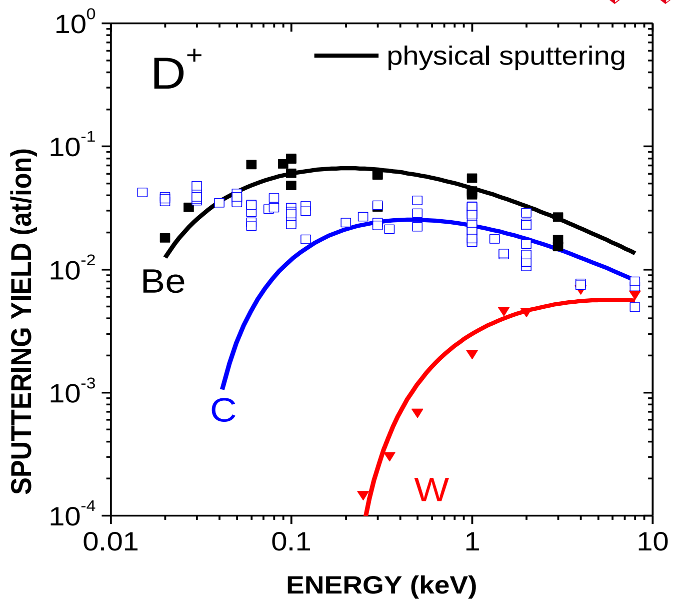
Materials in fusion reactors

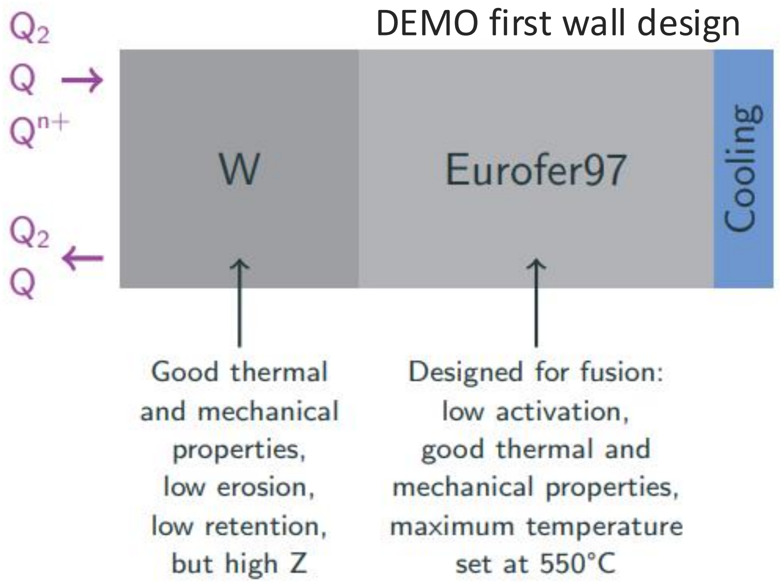
- **Required properties:**
  - No activation or transmutation
  - High electric conductivity
  - Good thermomechanical behavior
  - Low D/T trapping and permeation
  - Low plasma pollution ➔ low erosion and/or plasma pollution

- **Materials of interest:**
  - Facing the plasma: **tungsten (W)**
  - Adaptative layer: Cu, CuCrZr
  - Structural material: **EUROfer97, stainless steel**

    + active cooling: heat sink (H_2O)

⚠ Impact of interfaces
Evolution of surface condition and bulk microstructure



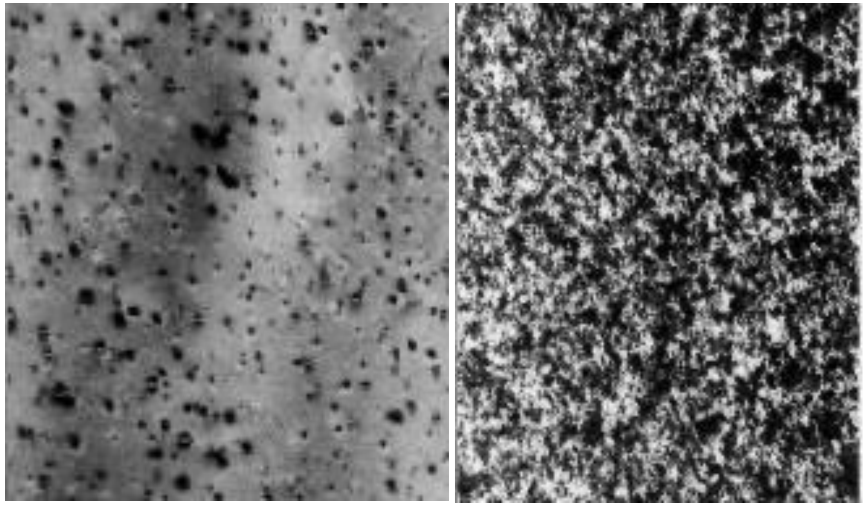


Tungsten as a Plasma-Facing Material

- W: used in JET, AUG, WEST, ITER
  - ➔ intensive fluxes of He and H isotopes at high temperatures
- Impact of He irradiation at the surface:
  - dislocation loops
  - bubbles
  - W-fuzz

(dislocation loops, bubbles: $<530^{o}C$, $E < E_{disp.\ min}$ (538 eV))

W irradiated with 6.5×10^{19} $H.m^{-2}$ | W irradiated with 6.5×10^{19} $He.m^{-2}$



R. Sakamoto

➡ He has a strong impact on the material.

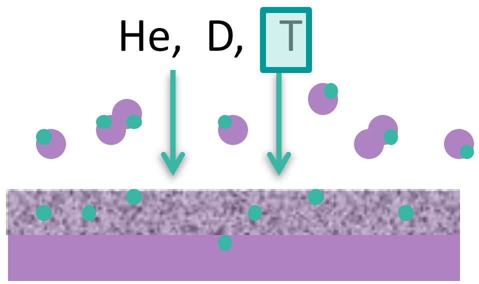
➡ These modifications can affect the trapping of hydrogen (T).

Tritium: a key isotope for fusion devices operation and safety

- **Radioactive hydrogen isotope: ^{3}H (T)**

$$^{3}H \longrightarrow {}^{3}He^{+} + {}_{-1}e^{-} + \nu_e$$

(E_{max} = 18,6 keV - E_{moy} = 5,68 keV, $t_{1/2}$ = 12,5 year)



- H: high mobility in the environment and materials (as gas, water or OBT)
- Very large re-circulation of tritium in the installation (tokamak, tritium plant, …)

➢ **Impacts the power plant efficiency, operability, safety, dismantling and waste management**

All fusion devices will be confronted with T handling and management:

➢ Fuel availability: **^{6}Li + n ⟶ ^{3}H + ^{4}He** (Breeding Blanket)

➢ Safety requirements:

- Address the tritium retention (max 700 g of tritium in ITER Vacuum Vessel)
- Control the permeation
- Limit the tritium releases from tritiated waste

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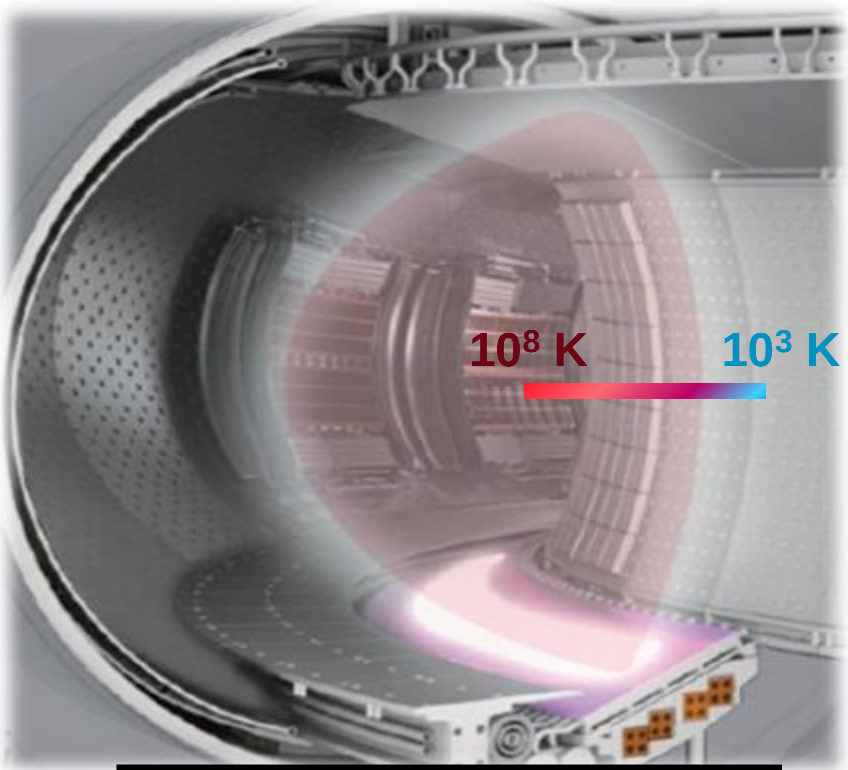
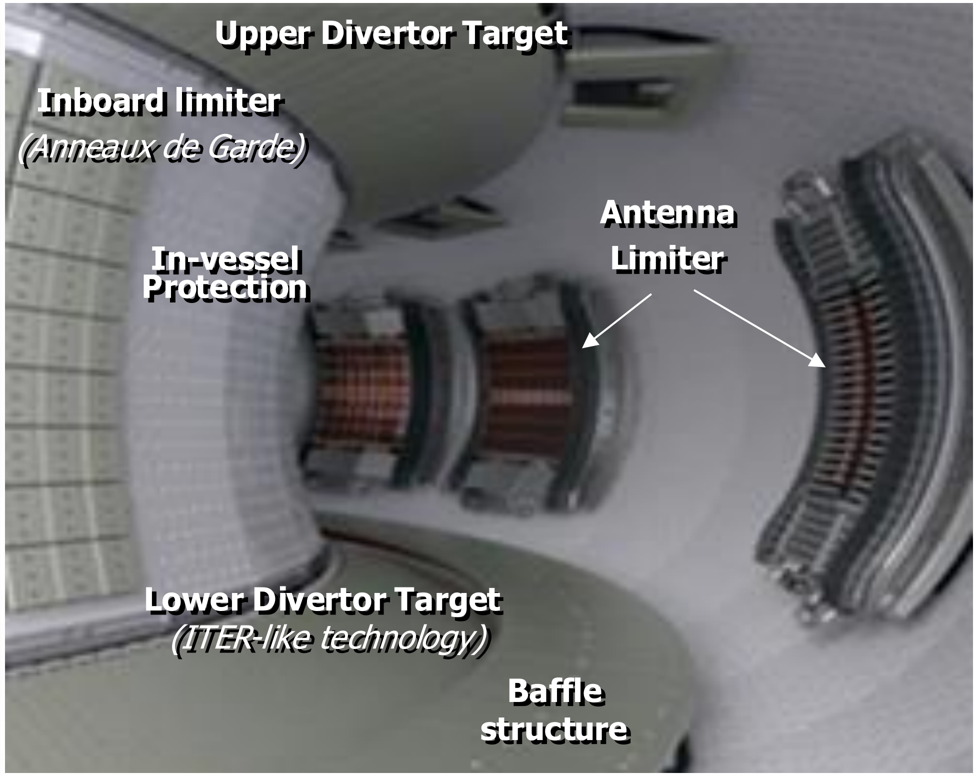
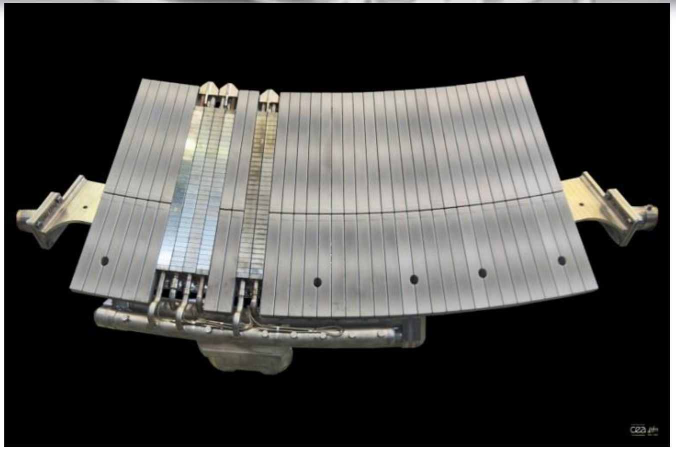
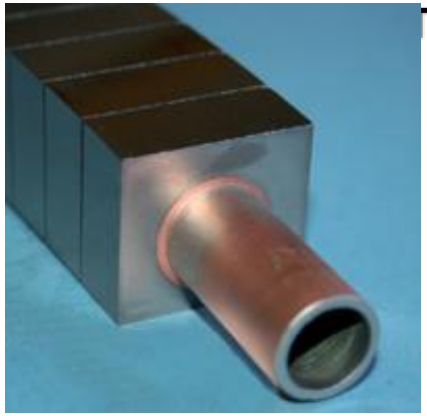
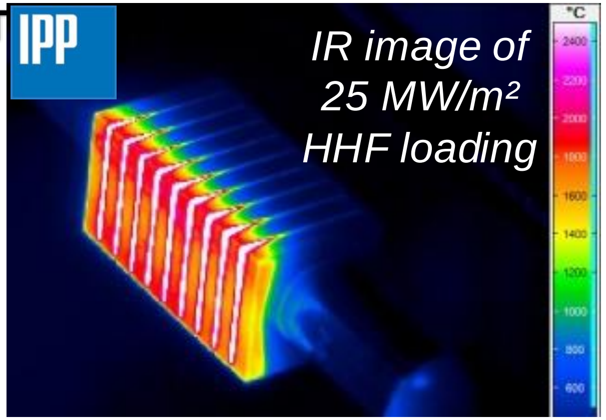
PLASMA FACING COMPONENTS IN WEST







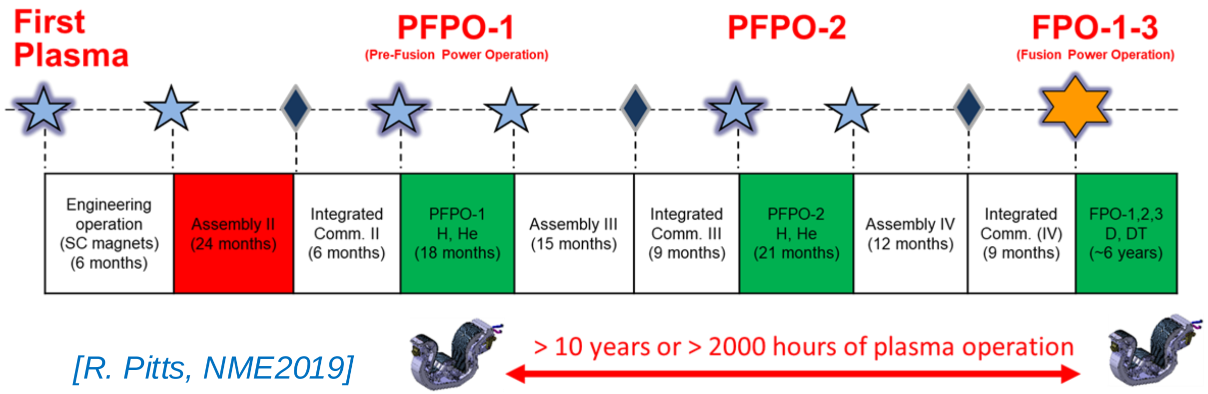




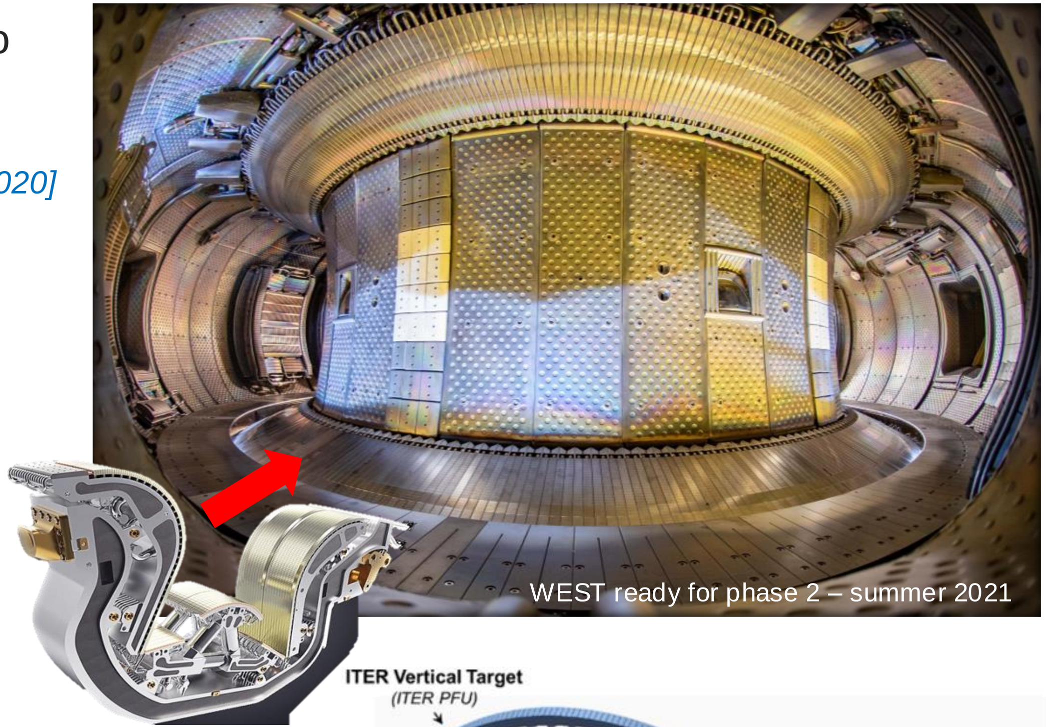
Divertor in next step fusion devices will handle unprecedented particle fluence

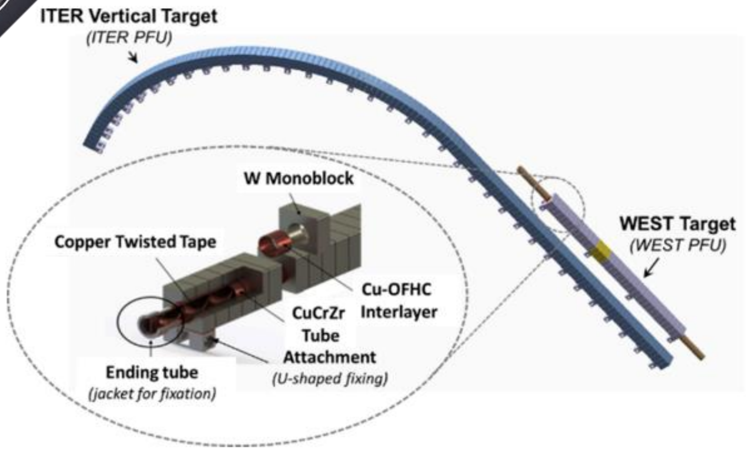
- High priority research area for ITER : divertor lifetime appropriateness to allow operation until well into FPO with the 1st tungsten divertor

[Loarte, ITER R&D needs, 2020]



[R. Pitts, NME2019]





WEST : full W superconducting tokamak targeted at preparing ITER divertor operation

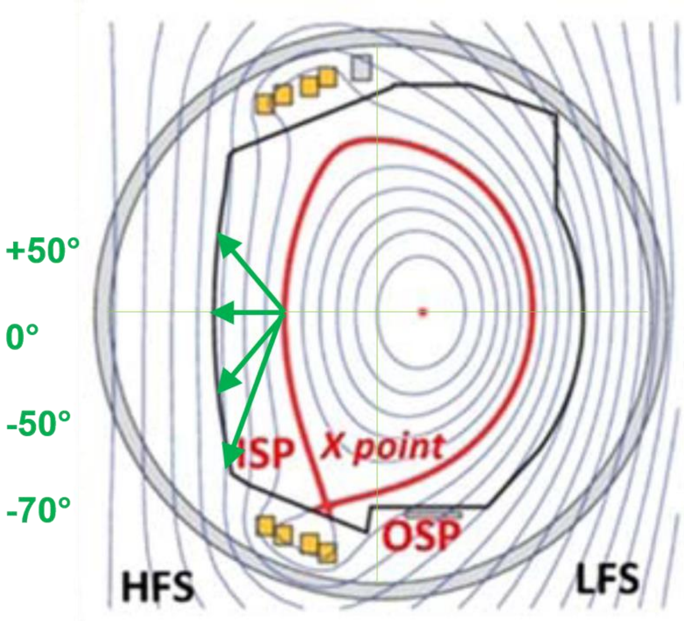
- WEST operates with an ITER grade divertor ➔ long pulse capability
- "High Fluence" phase run at the end of the first experimental campaign of phase 2
- Objective : cumulate ITER relevant particle fluence and assess evolution of ITER grade divertor ↔ plasma operation

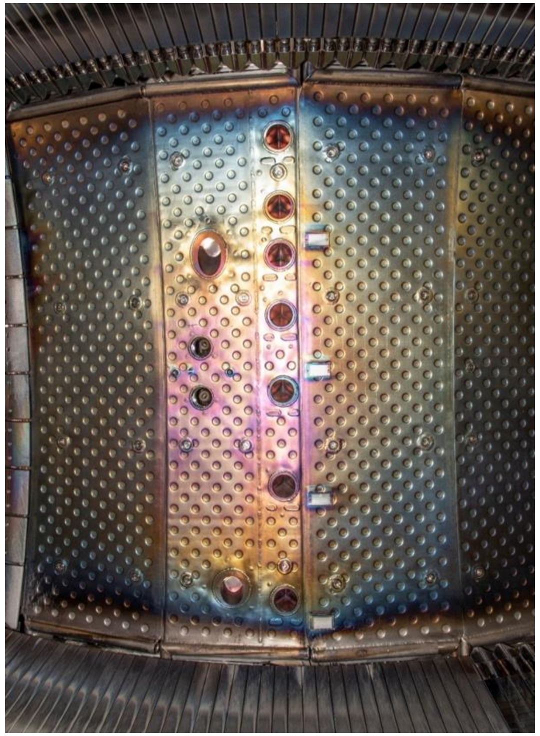
First-wall exposure in WEST: WHIrr sample holders

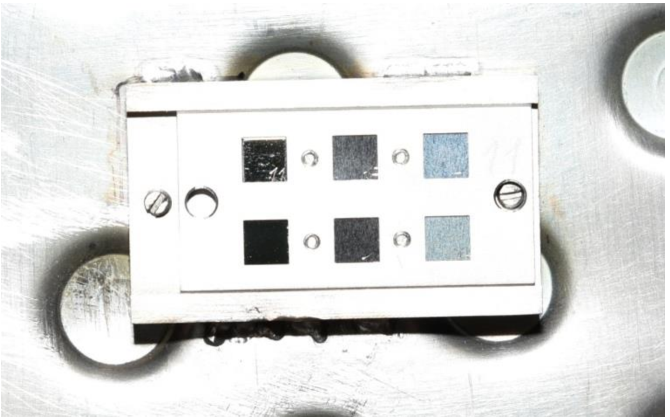
Far in the Scrape Of Layer
- Grazing field line
- Charge exchange area
- Deposition area

➢ The larger the poloidal angle, the further the sample is from the lower divertor.

➢ 4 locations: - HFS: Q3B, Q6A, PJ4
- LFS: PJ2







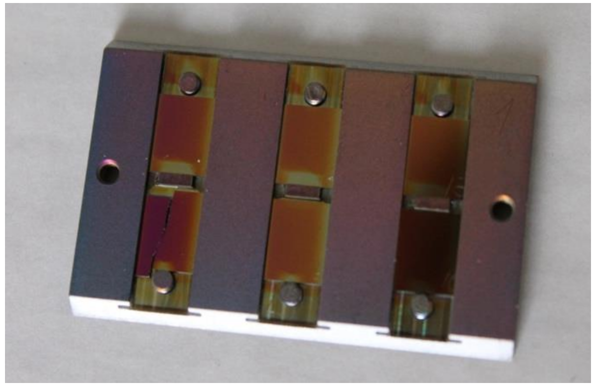
➡ Goal: expose samples at first wall conditions for an easy access to each campaign impact on the surface and stucture of the material (EUROfer, W + various original surface conditions)

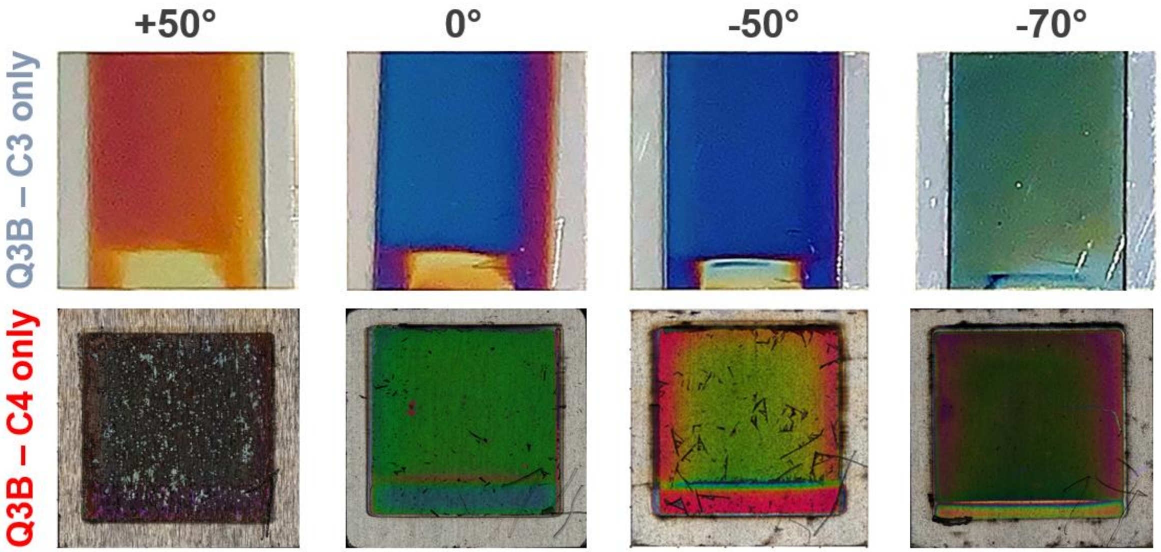
Exposure history throughout WEST phase 1

- Samples exposed during C1, C2, C3, C4 and C5
  - + Cumulative exposure: C3+C4
  - ➢ Focus on C3/C4 comparison to consider the impact on He plasma

- Operational conditions:
  - C3 campaign (D campaign):
    - ➢ 3 boronizations
    - ➢ 2h D plasma
    - ➢ 12 ITER-like PFUs in sector Q3B
  - C4 campaign (D+He campaign):
    - ➢ 13 boronizations
    - ➢ 2h45 D plasma +0.5h He plasma
    - ➢ 14 ITER-like PFUs in sector Q3B

- Major visual changes from C3
  - Shadowing of sample-holders: preferential incident angles for the deposition process
  - Composition and variation of the deposited layer?



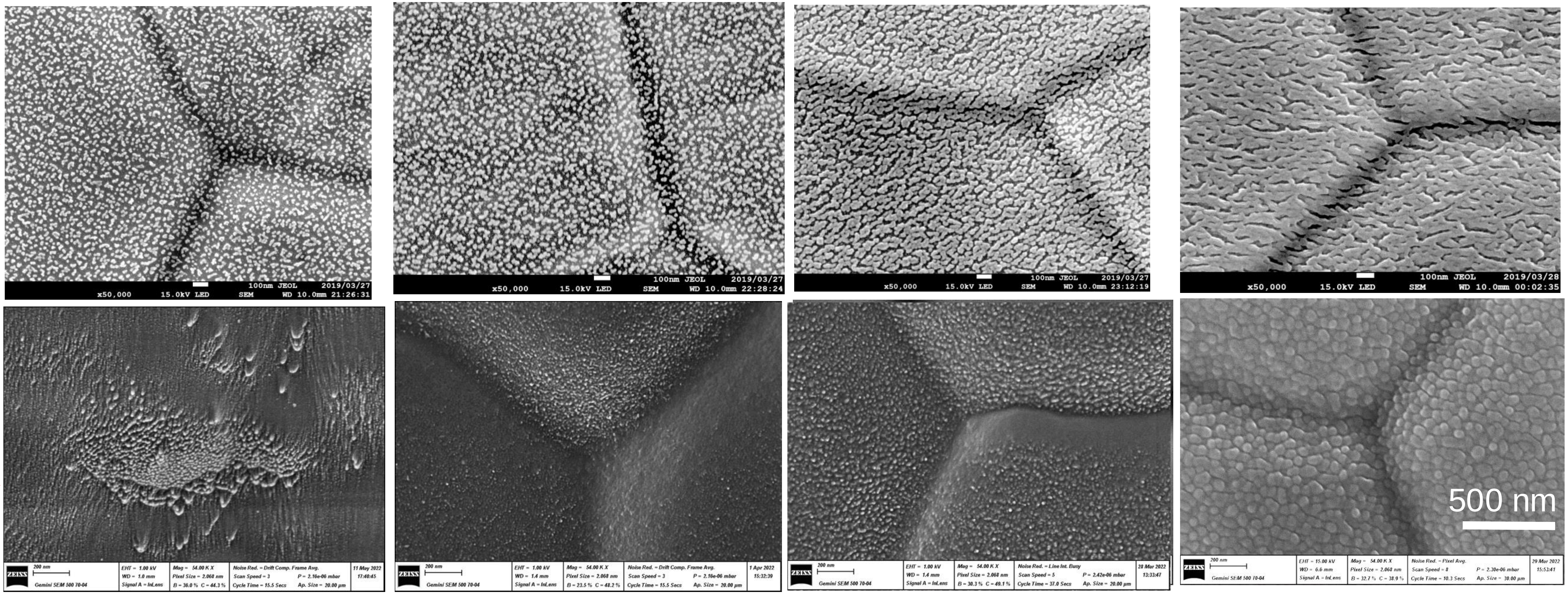


Impact of the campaign history on surface evolution

+50° | 0° | -50° | -70°

Q3B – C3 only

Q3B – C4 only



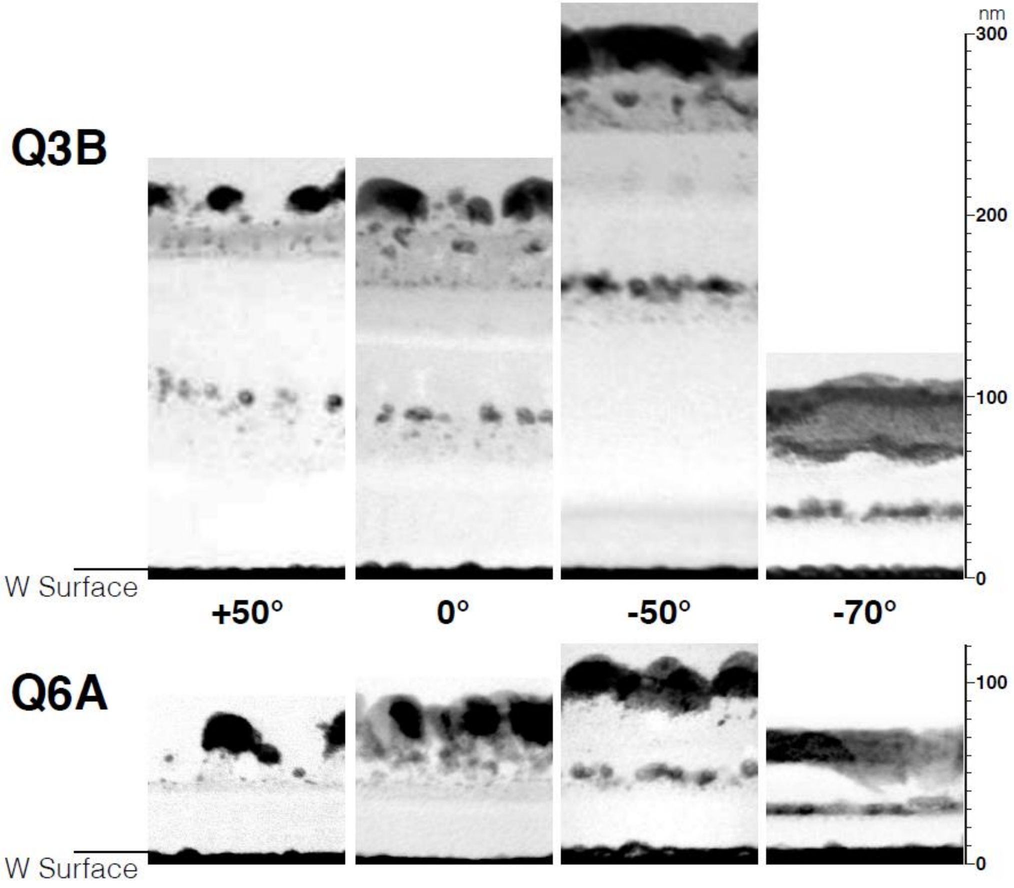
- **C3:** layer of nanoparticles of metal oxide (WO3). The closer the deposit is to the divertor, the larger the particle size and the greater the surface coverage
- **C4**: boron layer except for -70° layer with large W nanoparticles. Low roughness for B layer on recrystallized W and tips along poloidal direction on industrial W (+50°).

C3 exposed W: Three layer of boron deposition interlayed with metal oxide particles

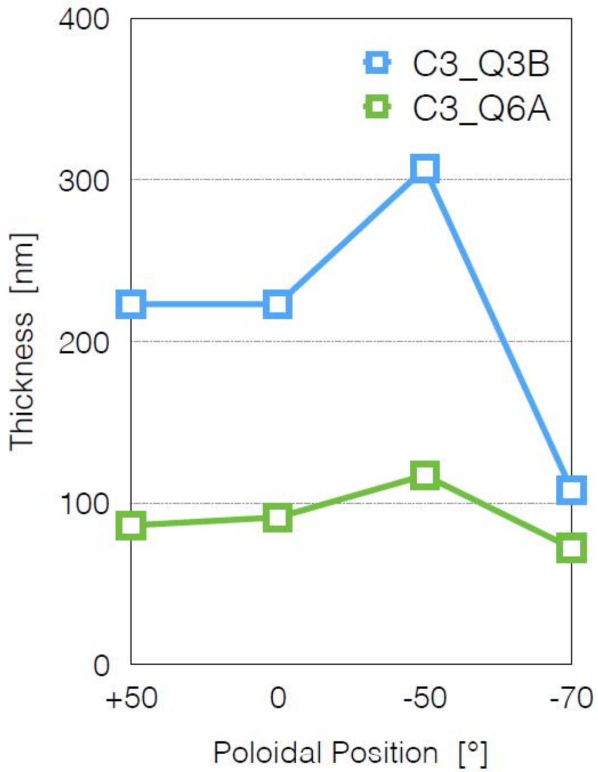
SEM surface observation + TEM cross-section images and EDS quantitative elemental mapping

- Color variation of the deposit is associated with **different thickness of B deposition layer and density of surface metal oxide particles**, but the struture of the deposited layer is similar and **present everywhere**

- 3 B layers
- Deposition thickness is higher in Q3A and at 50° angle
- Metal oxide layer (particles) is observed in the 2 B layer and at the surface
- Lesser oxygen is observed in B rich layers



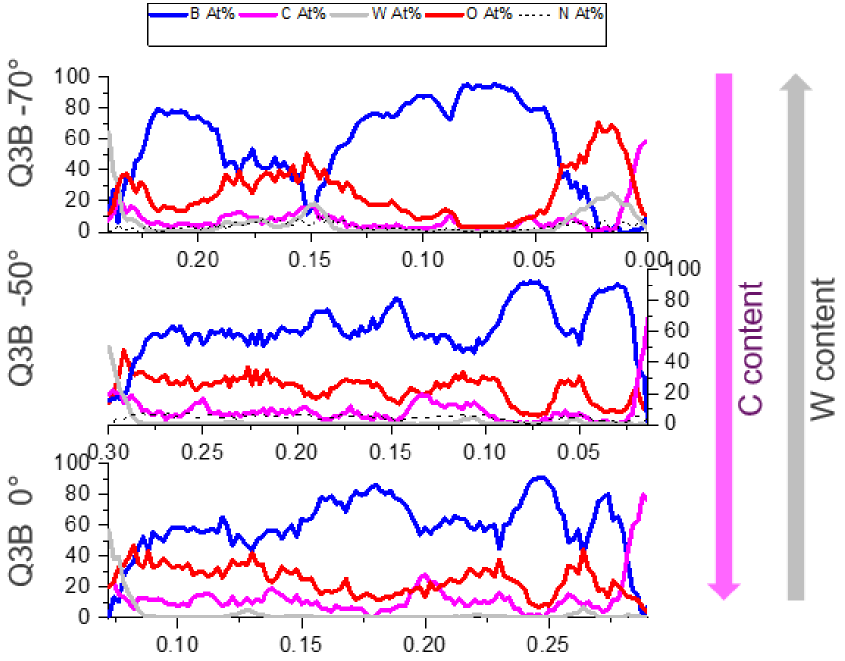
10 % B_2H_6 with 100 bar·L/h for 4 h
⇒ 200 nm thickness

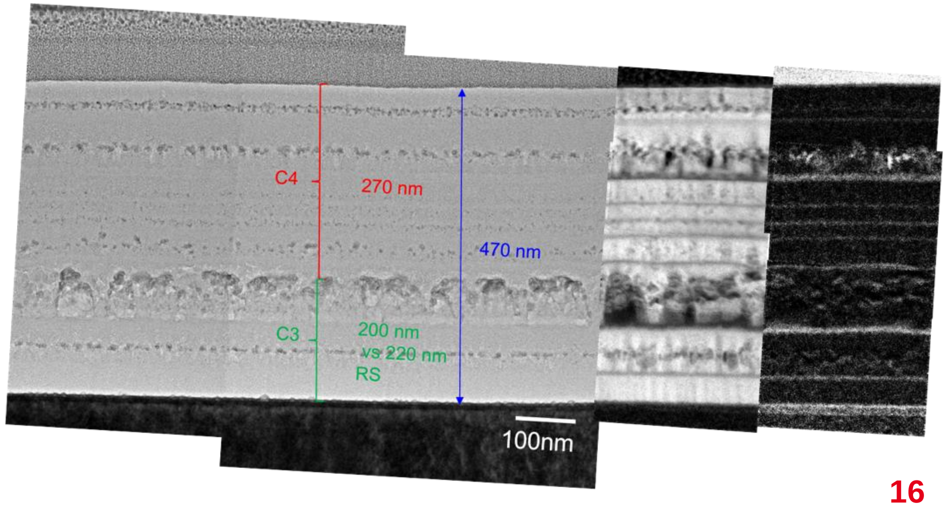


C4 exposed W: a more complex composition of layers

- Different tendency of deposit thickness compared to C3, with a specific surfacic layer at the 70° position (i.e. closer to the divertor) composed of metallic particles

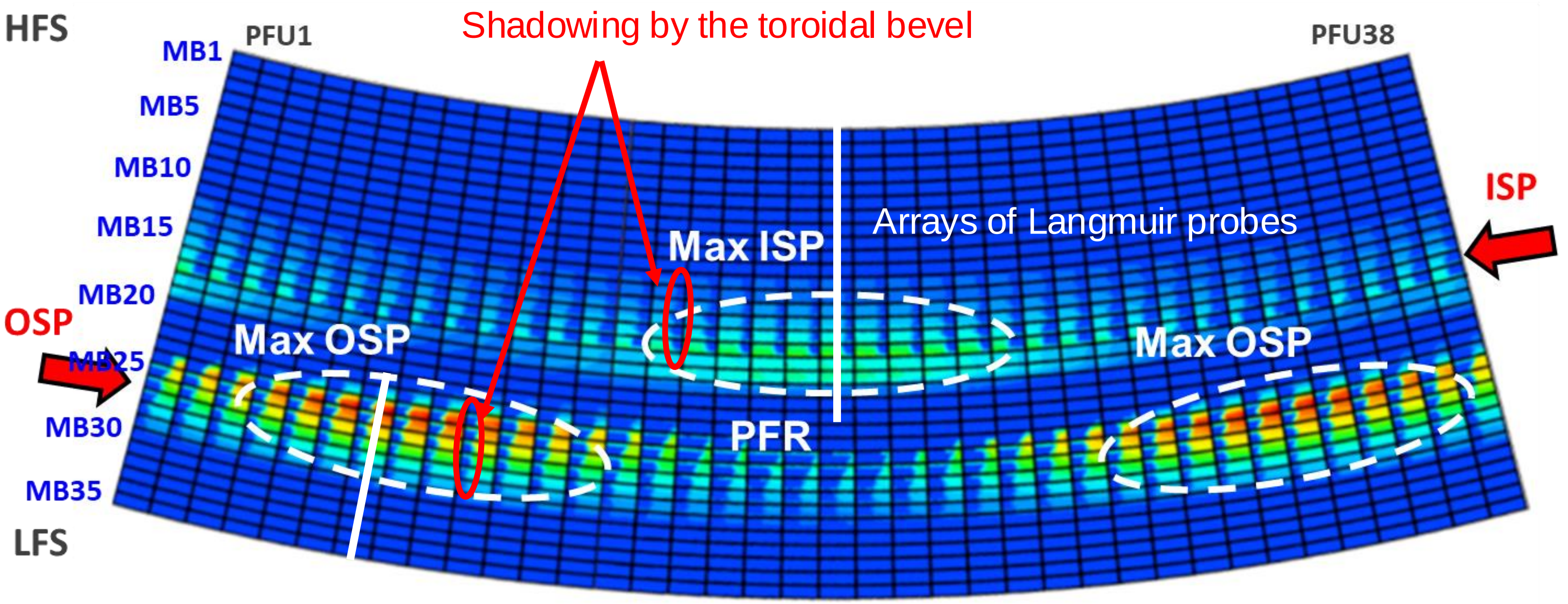
- **Comparison between the 2 campaigns:**
  - Strong presence of B on the first wall after both C3 and C4
  - Deposition layer:
    - Similar structure and elements
    - Variation of boron and metal oxide particles
  - Profile of deposition layer
    - After C4 at -70° only (near divertor) metal oxide layer is thickest
    - Metal oxide layer (W nanoparticles) are observed (2 for C3 and 5 for C4) not directly linked with boronization history



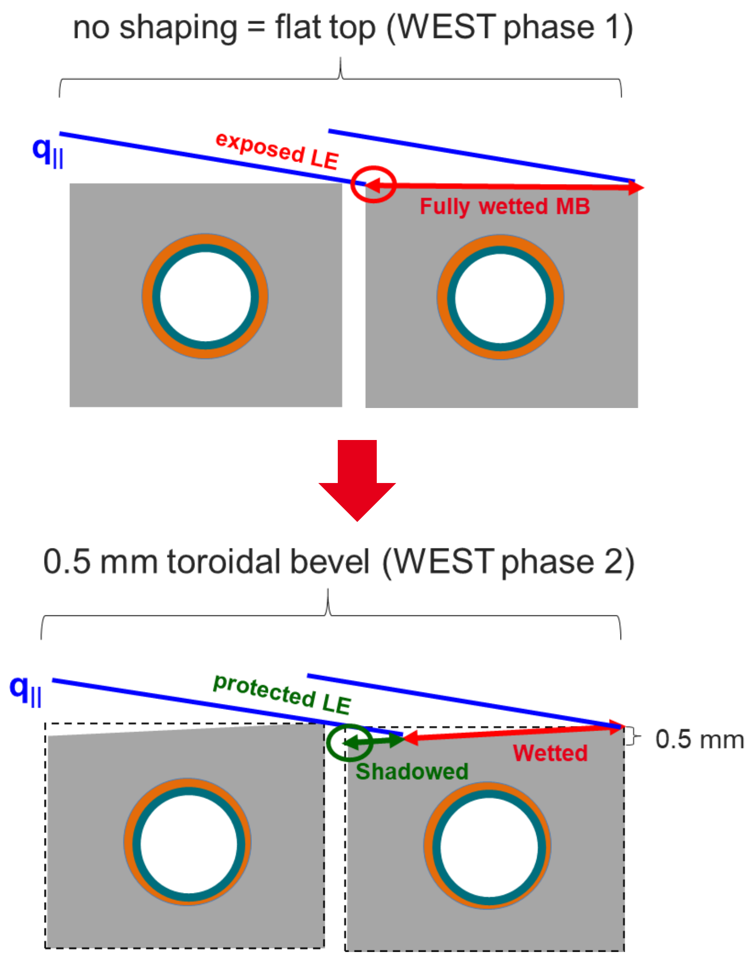


Modulated heat and particle loads on the WEST divertor

- WEST divertor heat/particle load pattern modulated by ripple
- Toroidal bevel to protect leading edge (ITER) : local monoblock shadowing

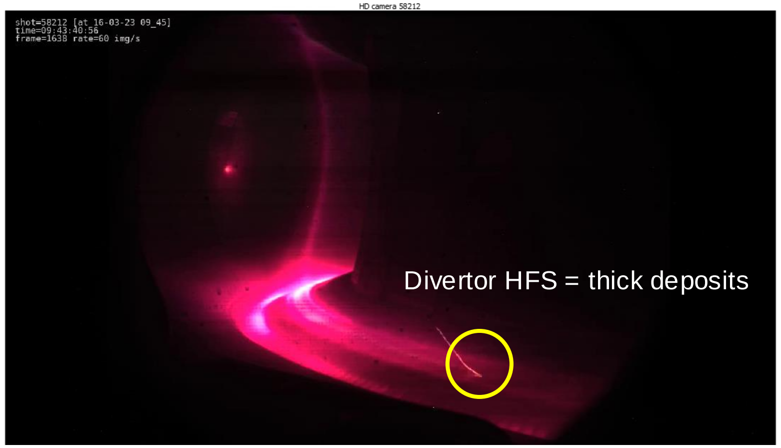


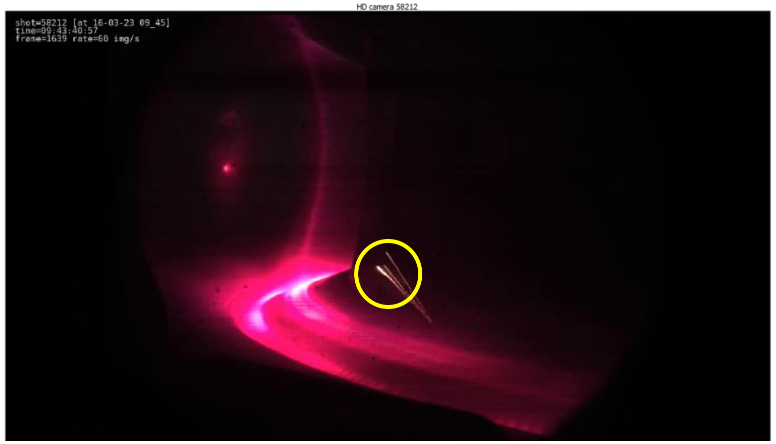
Simulated heat load deposition (PFCflux code)

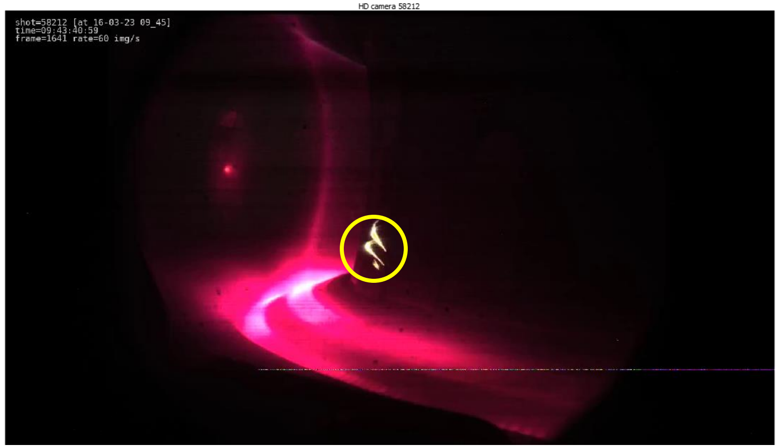


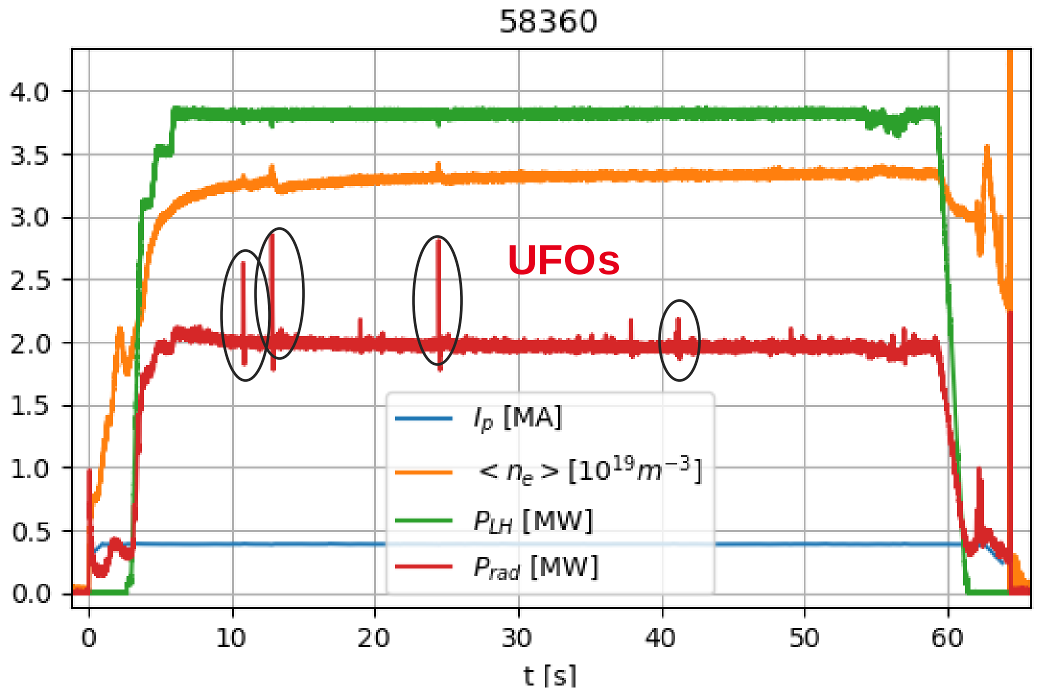
- High fluence campaign conditions:
  - ~ 380 repetitive shots run for 1 month, cumulating ~3 hours of plasma / 30 GJ of energy
  - ITER relevant fluence reached (~2 PFPO shots) : ~5 10^{26} D/m^2

UFO hampered the High Fluence campaign







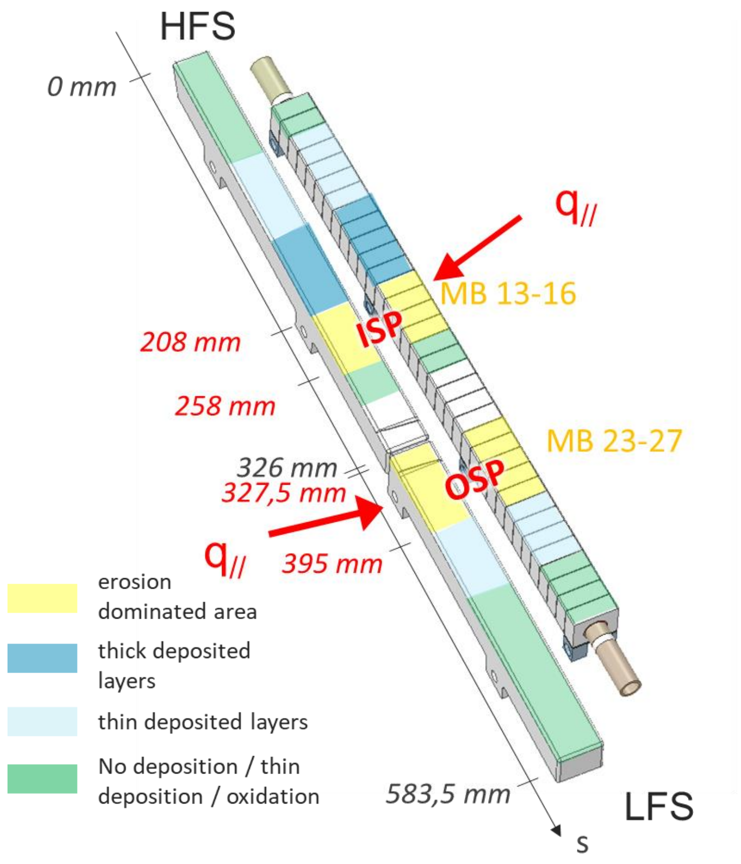


- UFO analysis : peak > 200 kW on P_{rad} from bolometry (+ distinction from MHD crash) ➔ database of ~ 700 UFO
- 3 classes of UFO defined :
  - small impact (~80%) : plasma survives w/o subsequent issues
  - medium impact (~17%) : drives plasma into "cold branch" regime prone to MHD ➔ disruption > 200 ms, up to several seconds later
  - large impact (<3%): leads to disruption within ~200 ms
- UFO detected with IR originate mostly from HFS (thick deposits area)

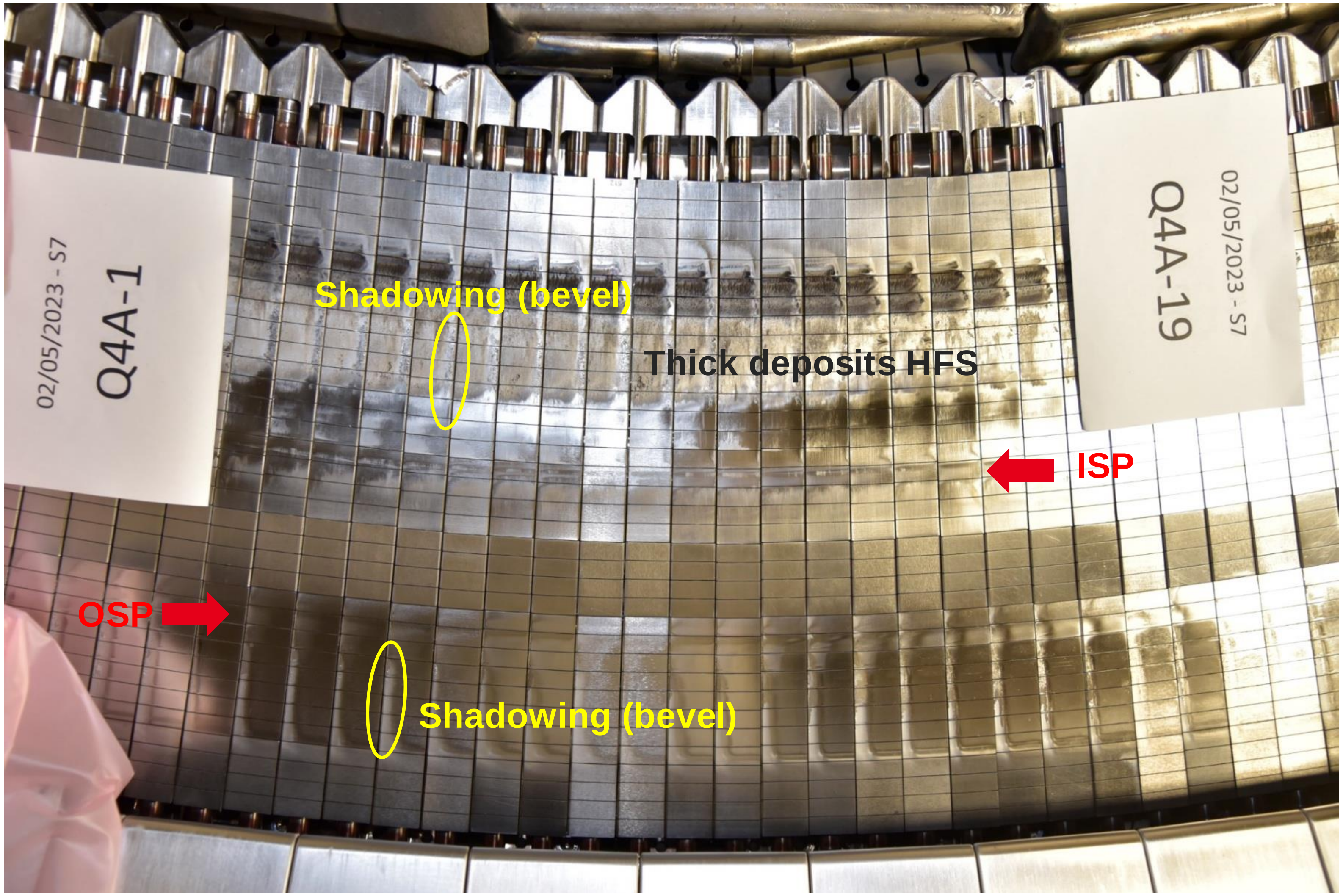
Complex erosion / deposition divertor pattern

- Divertor : “usual” complex erosion / deposition pattern, as observed in phase 1
- New features : impact of toroidal bevel

Phase 1 erosion / deposition pattern

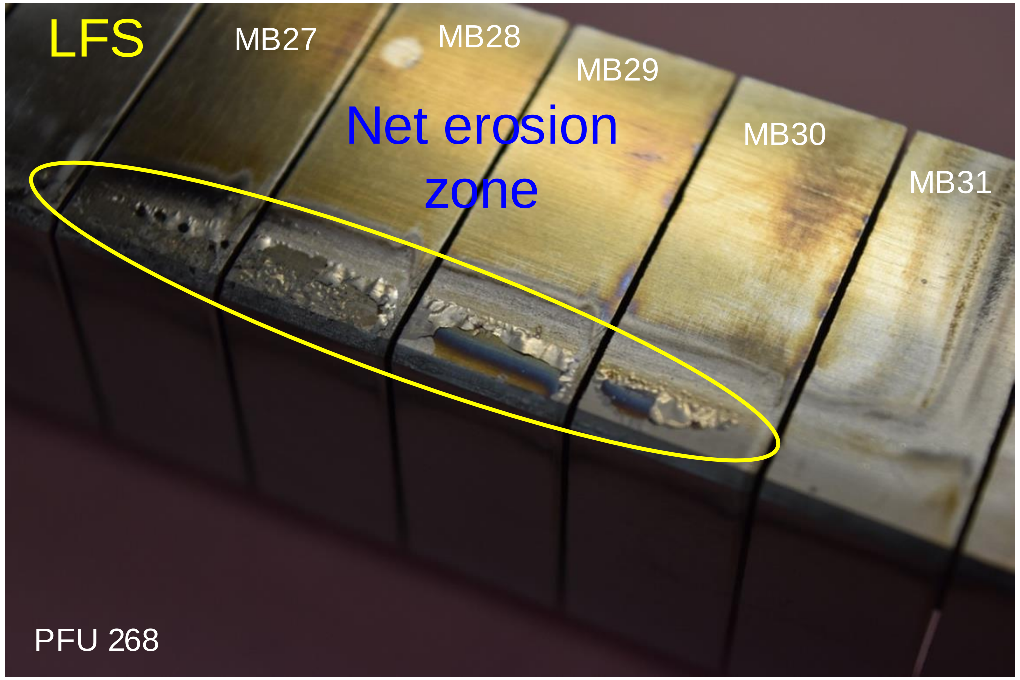


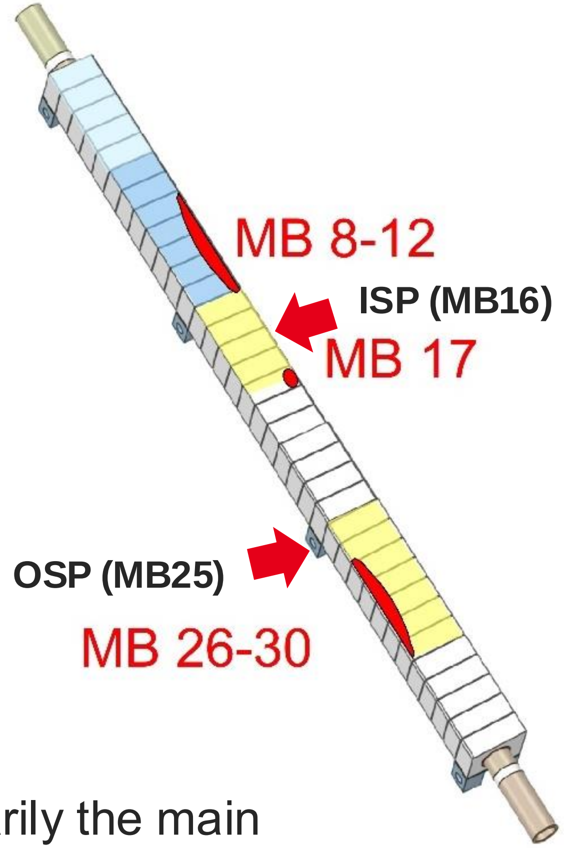
M. Diez, NME 2023



Deposits in shadowed area of beveled monoblocks

- New : “thin foil like” deposits in area shadowed by the toroidal bevels (and in gaps ?), both on HFS/LFS
- These deposits tend to delaminate easily (exposure to air ?) ≠ thick adherent deposits on HFS





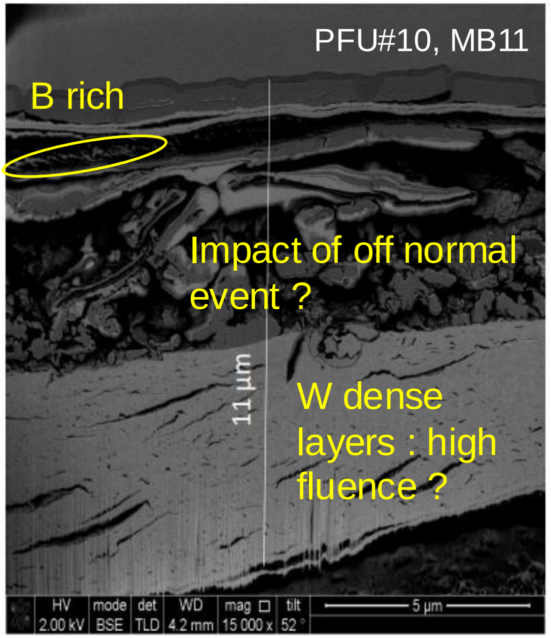
- Note that these “bevel deposits” are not necessarily the main cause for UFOs : UFOs detected by IR originate mostly from HFS, while “bevel deposits” are present on both HFS/LFS

Complex deposited layer structure

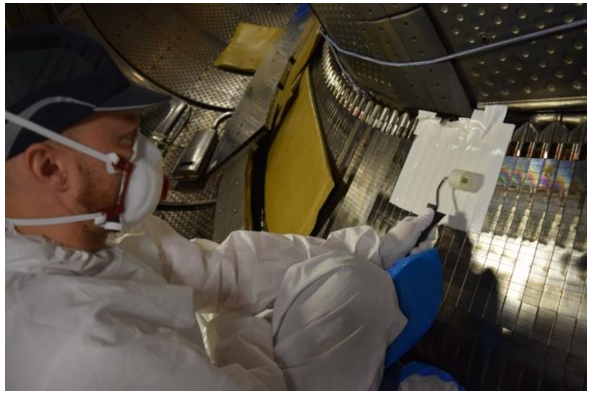
- HFS thick deposited layers collected on PFU exposed to C5-C7
- Up to 50 μm deposited layers
- Complex structure : mix of high Z / low Z layers, delamination, impact of off normal events (molten material) ?
- High fluence : mainly W dense layers ?

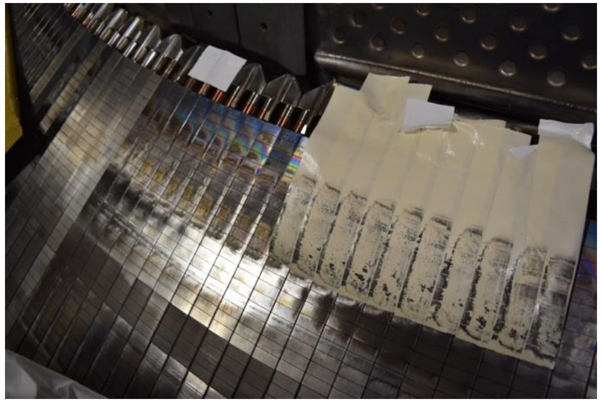
- Enhanced dust collection after C7 (quantity and dust size > 100 microns)

C5 from C7 (high fluence)



- Partial divertor cleaning performed after C7 (HFS deposits) : adhesive tape used
- R&D ongoing to improve the divertor cleaning method (will be required again after the spring 2024 campaign)

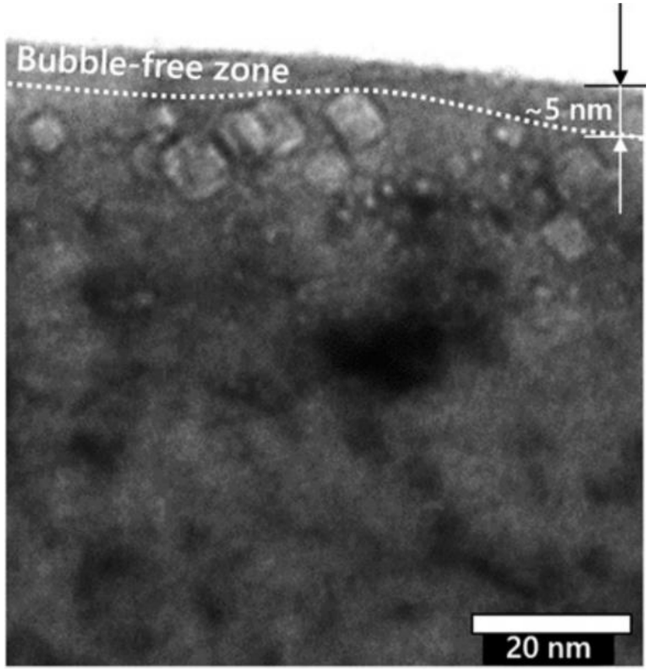




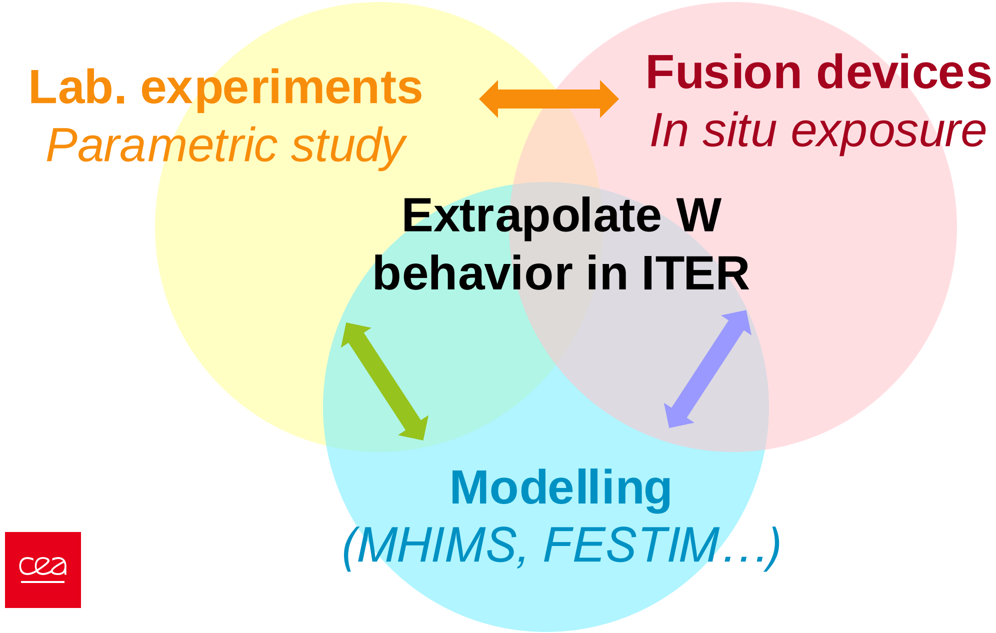
Understanding fundamental mechanisms at stake: the insight of nanoscience techniques

- He bubbles form in W under tokamak-relevant conditions:
  - ➢ Post-mortem characterization via Transmission Electron Microscopy (FIB-TEM)
  - ➢ Competing simultaneous phenomena
  - ➢ Crucial impact temperature

  ➔ **Initial stages and kinetics are out of reach**



[1] M. Ialovega *et al.*, Nucl. Fusion **62**, 126022 (2022).



➡ **Simplify the system to allow experimental characterization of the fundamental mechanisms for He irradiation of W**

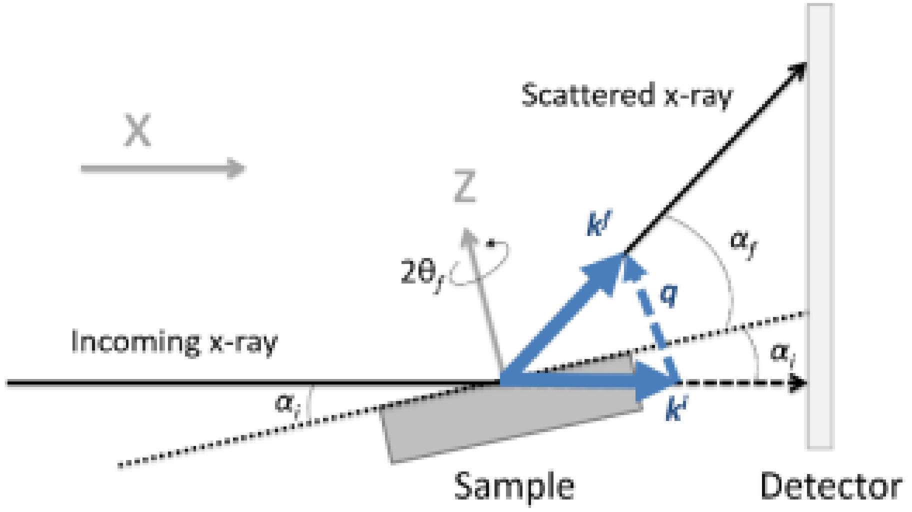
Coupling Grazing Incidence Small X-ray Scattering and He implantation in « ideal » W

- Grazing-incidence Small Angle X-ray Scattering (GISAXS):

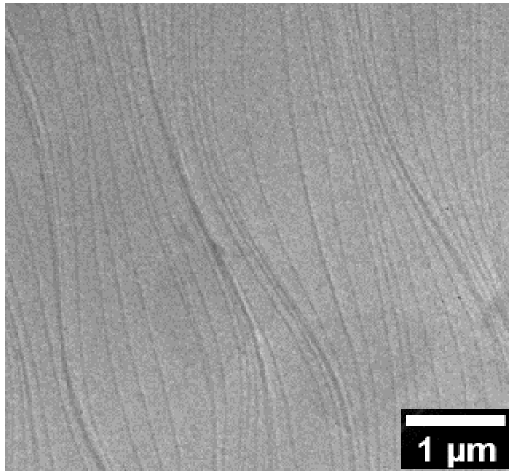
  non destructive technique using a **photons probe** to study nanostructure materials, combining the **length scales of small-angle scattering** and **surface sensitivity of grazing incidence diffraction**.

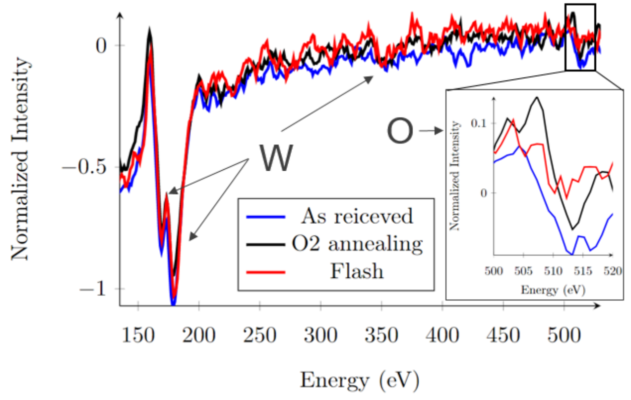
  ➡ Ideal complement for TEM: determines average particle properties on a larger scale

  ➡ Simultaneous He irradiation and GISAXS measurement at BM 32 at the European Synchrotron Radiation Facility (ESRF).



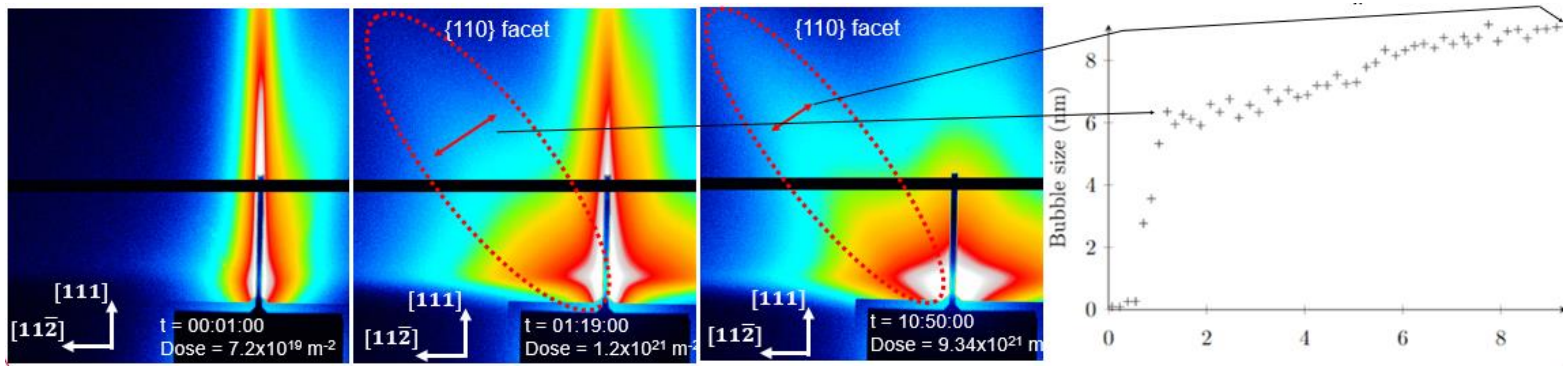
- Cleaning and surface roughness minimization:
  - Single crystalline W
  - 15 min Oxygen annealing 1200 K
  - 40 s high temperature flash (2200 K) under vacuum



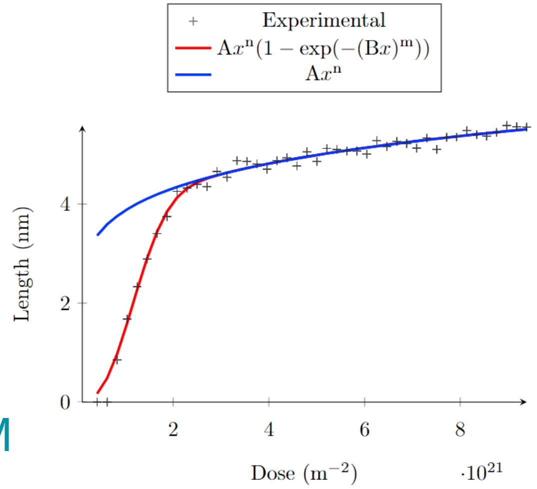


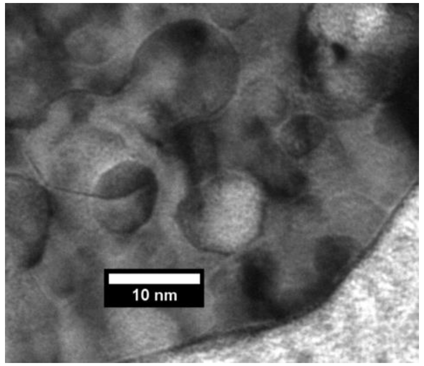
Identification of migration coalescence mechanism for He bubbles

- Analysis of GISAXS data allow tracking of the bubble growth

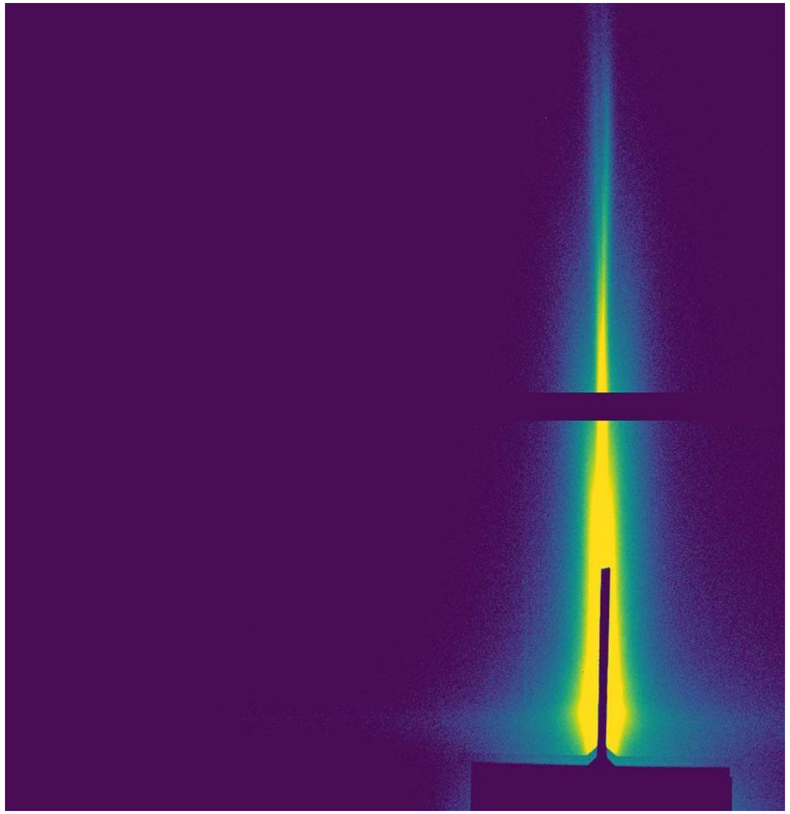


- In the literature, several growth mechanisms: static mechanism (Oswald ripening) and dynamic mechanism (Migration and coalescence)



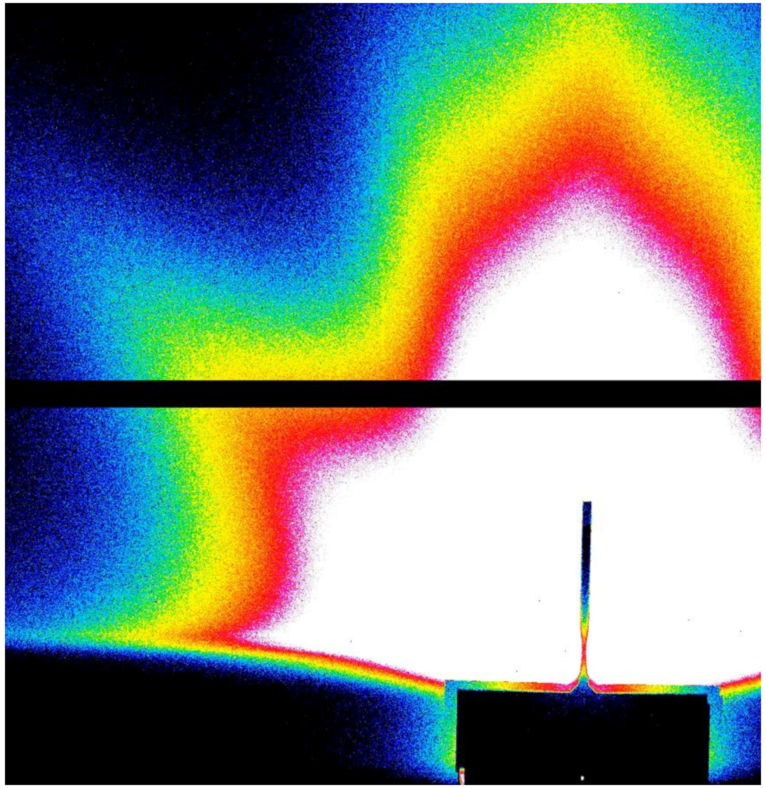


+ Coalesced bubbles seen by post-implantation FIB-TEM



He (2 keV) at 600°C, flux = 2,40x10^{17} m^{-2}s^{-1}, fluence = 1,00x10^{22} m^{-2}

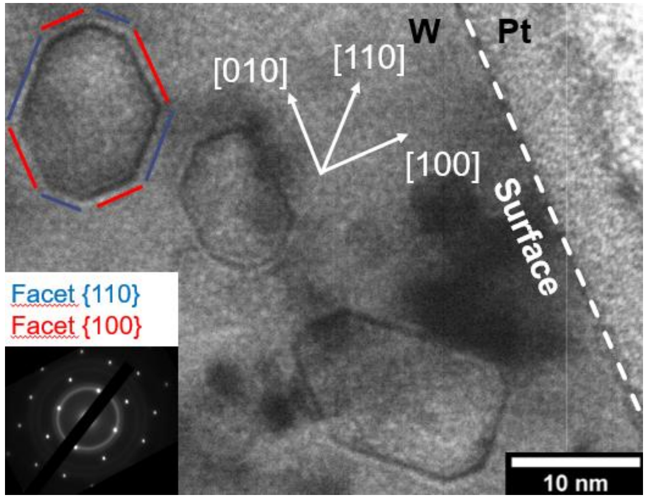
Enhanced preferential facetting at high temperatures

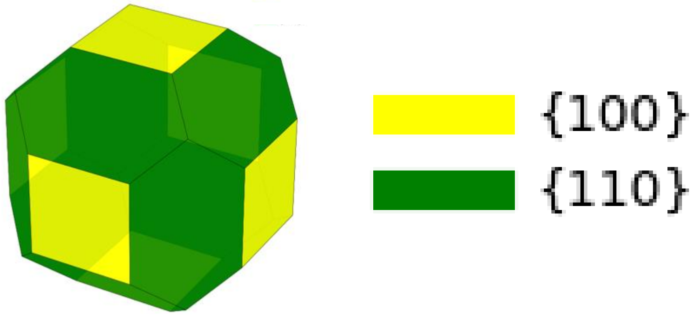


Ultra high vacuum annealing up to 1500°C

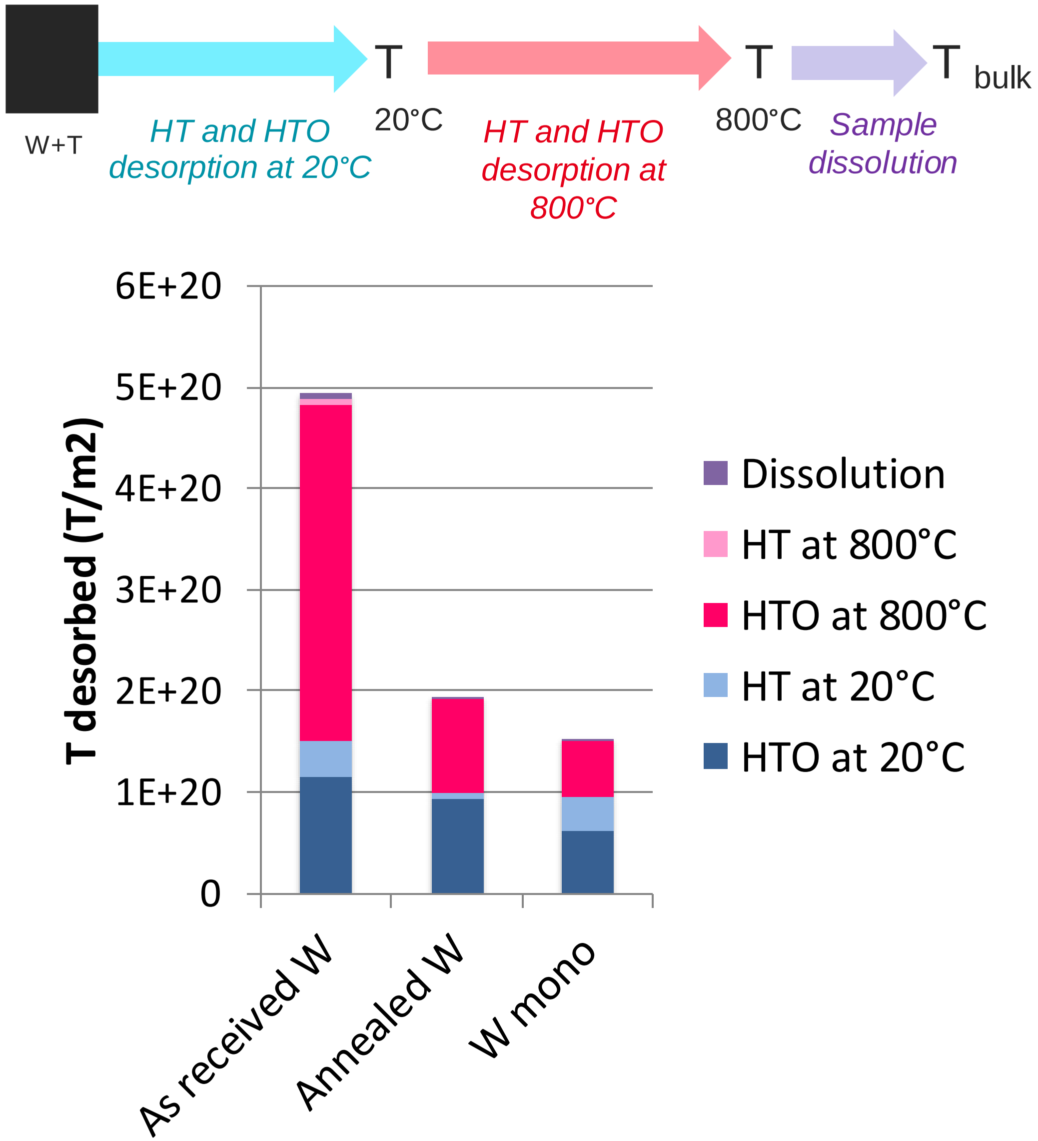
- Preferential faceting appears at high temperatures during or after He irradiation
- Enhanced during annealing up to 1500°C
  - Good agreement with TEM

➡ Minimization of surface energy (Wulf theorem)





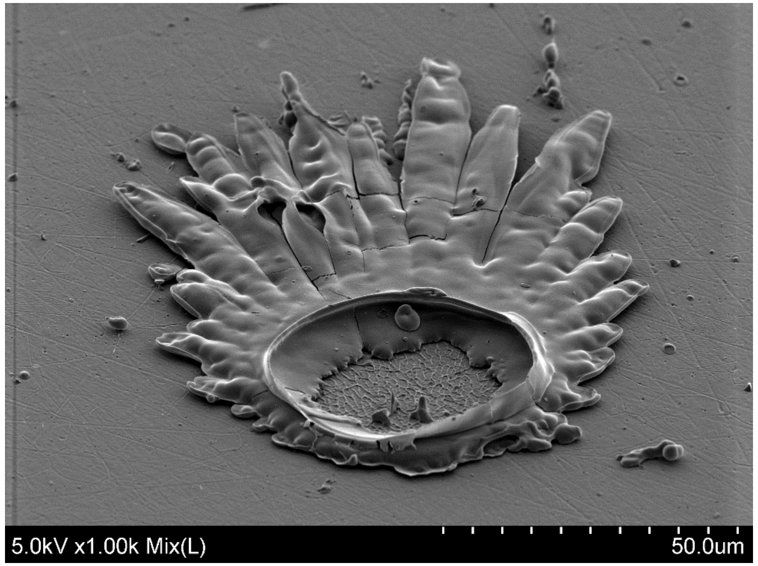
PRISTINE W: Major increase of T trapping with PRE EXISTING defects



➡ Major increase of T trapping with defects in W structure, desorbing only at high temperature

What is the impact of He triggered damages to the W microstructure?

Plasma-facing materials in fusion devices: take-home messages



- Plasma-facing materials (W) are submitted to extreme conditions in tokamaks
  - Strong surface evolution observed after in situ exposure: complex deposit and erosion patterns
    - **Crucial for T inventory, trapping and permeation**
  - Multi-scale analysis needed to guarantee the materials integrity and properties conservation
  - Simultaneous phenomena integrated over a whole campaign complexifies identification of respective impacts

- Coupling to laboratory studies is crucial to understand fundamental mechanisms at stake
  - Simplified systems to isolate respective contributions
  - Expansion of the experimental range at reach
    - **Impact of pre existing defects, neutron irradiation, higher fluences…**

+ Modelling efforts on irradiation effects (neutrons) and multi-isotope simulations underway

Outline

1. Reactor technologies and design: required material properties

- Plasma-wall interaction conditions, key functions and properties
- Materials of interest
- The burning issue of tritium behavior

2. Plasma-facing materials in fusion reactors

- Evolution of surface conditions in realistic conditions in the WEST tokamak
- Understanding fundamental mechanisms: impact of He on W microstructure

3. Tritium interaction with materials: the TITANS project

- Enhancement of tritium permeation barriers and tritiated waste management
- Tritium measurement and modelling
- Radiation protection, risk assessment and dosimetry studies following accidental exposure to tritiated dust in support to EU regulators (art. 31)

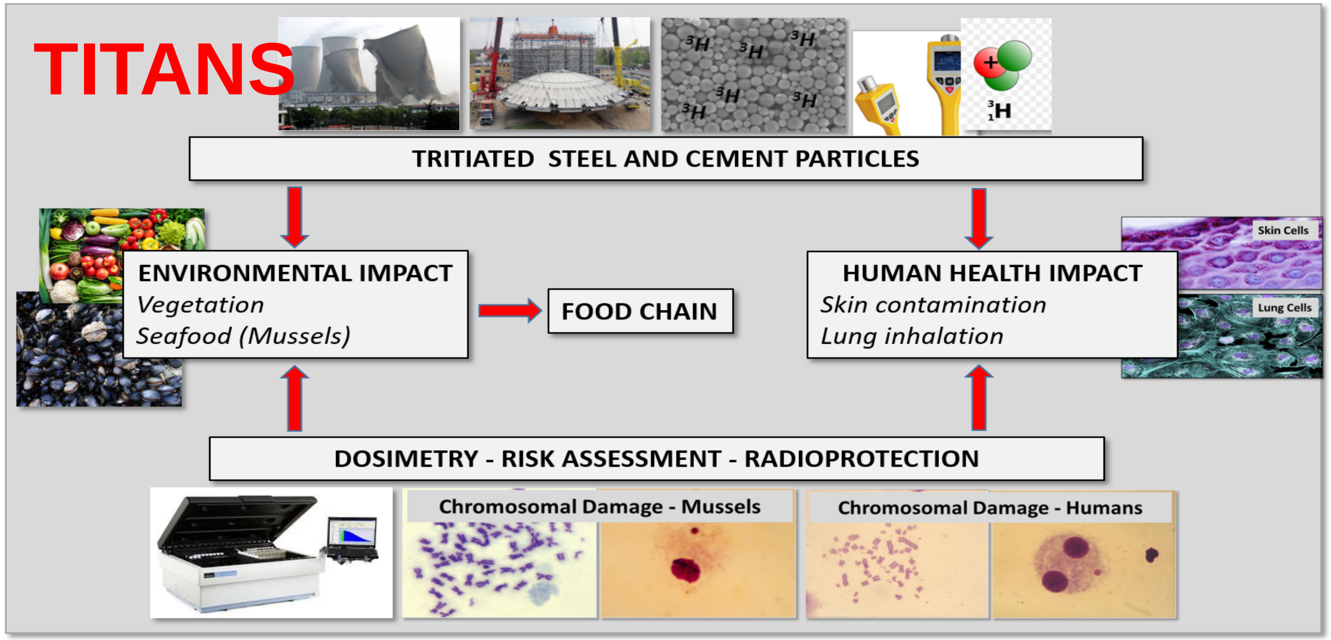
TITANS: Tritium Impact and Transfer in Advanced Nuclear reactorS

- 21 partners, 3 years – EU Horizon Europe 2021-2027

- **Goal:** fusion/fission cross cutting multidisciplinary project to provide suitable innovative answers to the major tritium challenges
  - **Release mitigation**
  - **Minimization of sources**

  } Throughout the whole T cycle

+ Improve knowledge on the health effects of T ➔ Support to radiation protection authorities



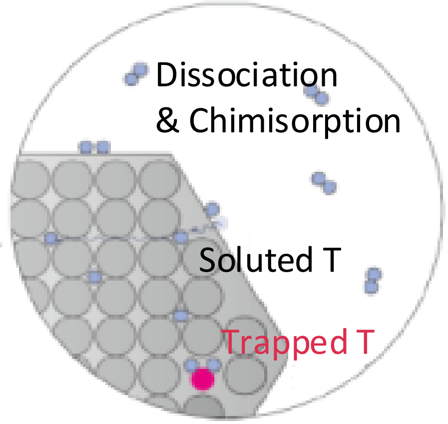
➔Handle, control & protect

TITANS: HANDLE

1. **WP1: Enhancement of tritium permeation barriers and tritiated waste management (KIT)**
   - Upgrade of tritium permeation barrier (treatment of surfaces)
   - Binder matrix to immobilize tritiated metallic dust and minimize the tritium release
   - Compare methods and procedures of decommissioning tritiated components/systems
   - Design of a mobile water detritiation facility

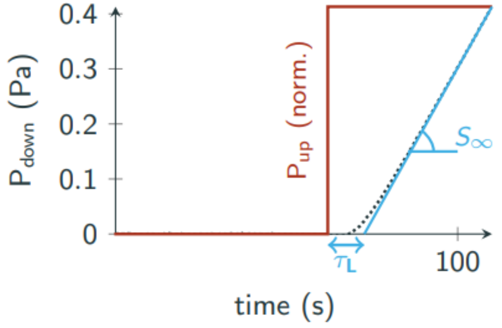
Permeation experimental methods

- H/D/T exposure: H_2/D_2 OR T_2 gas loading
  > no damage creation + trap saturation



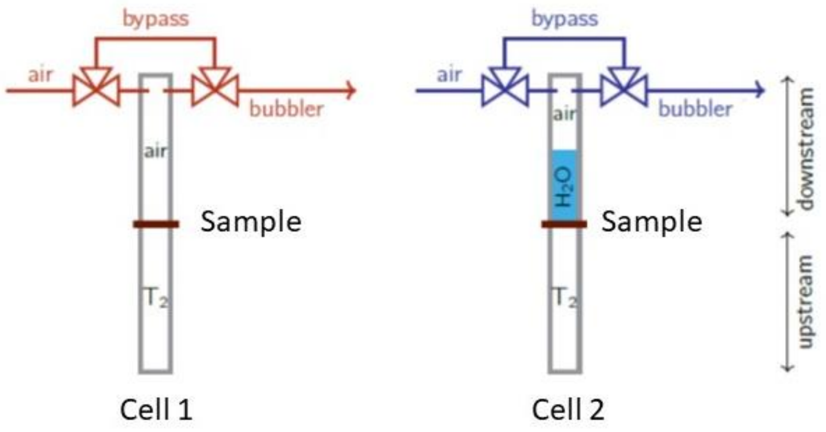
- Trapping parameters: TDS, T desorption (t, temperature)
  + NRA (depth profiling)

- Transport parameters: measure the permeation timelag and permeation flux
  - H_2/D_2 permeation in Hypertomate:
    - ➢ diffusivity, solubility and permeability at temperatures from 100 to 550°C



  - T_2 permeation in WAPITI
    - ➢ diffusivity, solubility and permeability at RT with/without **water**

      ➔ Longer permeation time but complementary with Hypertomate conditions



Each permeation cell connected to a dedicated bubble.
To obtain direct comparison, upstream conditions and membranes identical.

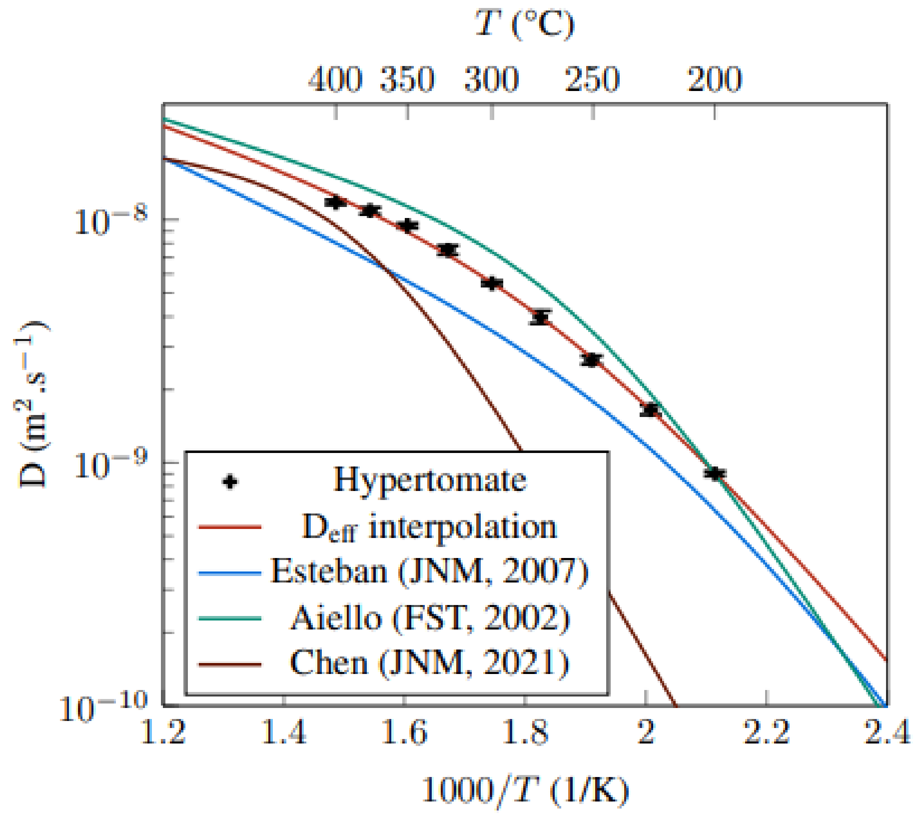
[E. Bernard JNM 2015]
[F. Montupet-Leblond NME 2021]

Hydrogen isotopes transport & trapping in Eurofer97

- Hydrogen gas-driven permeation experiments were conducted on Eurofer97

  - Good agreement with existing studies

  - Diffusivity is not purely interstitial
    - ➢ **influence of trapping sites on permeation in the 200°C to 400°C temperature range**



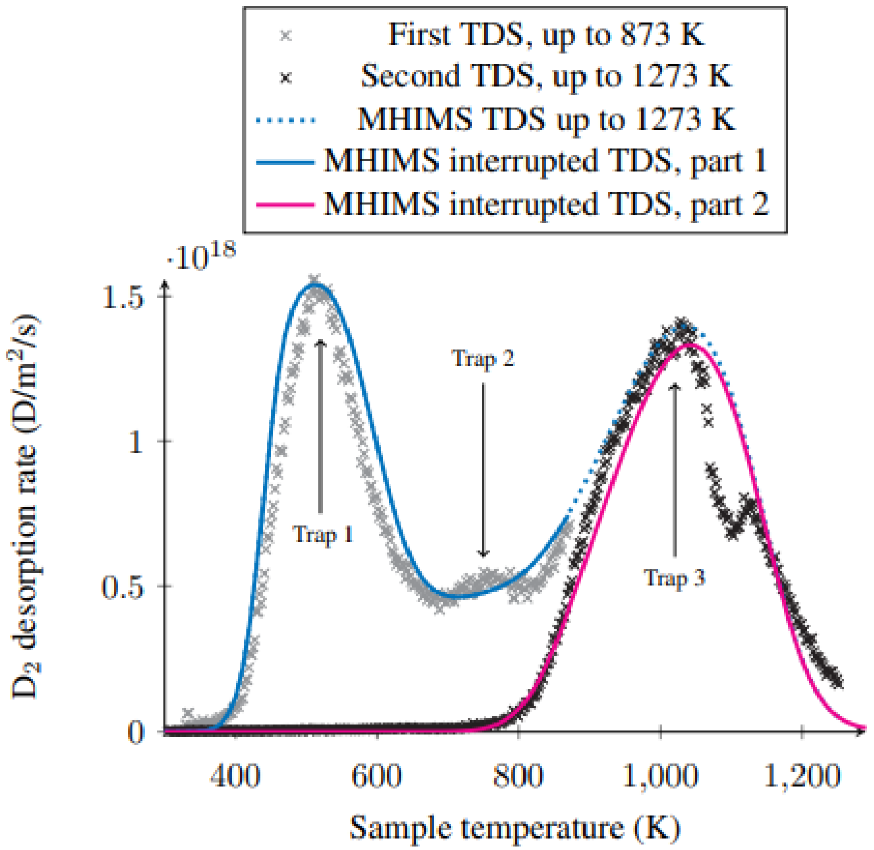
[F. Montupet-Leblond Nuc. Fus. 2022]

Hydrogen isotopes transport & trapping in Eurofer97

- Additional TDS experiments to investigate trapping sites present:
  - 3 trapping sites are needed to adequately model the observed behavior

⚠ more than one trapping site in Eurofer97 invalidates the hypotheses required for the effective diffusivity to be valid.

➔ Underestimation of retention and of the time need for tritium to reach the cooling system



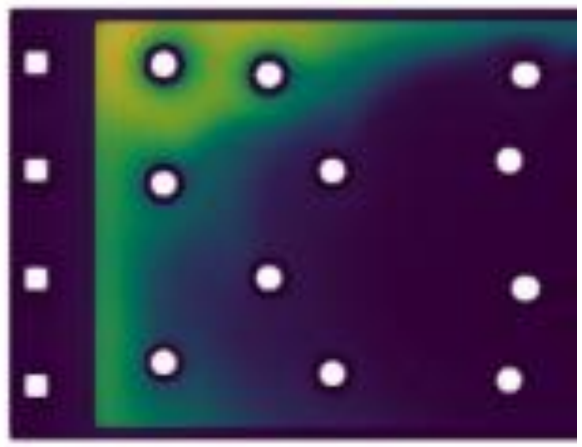
	$E_{dt,i}$ (eV)	n_i (m^{-3})
Trap 1	0.51	$6.01 \cdot 10^{25}$
Trap 2	1.26	$6.44 \cdot 10^{22}$
Trap 3	1.65	$3.88 \cdot 10^{23}$

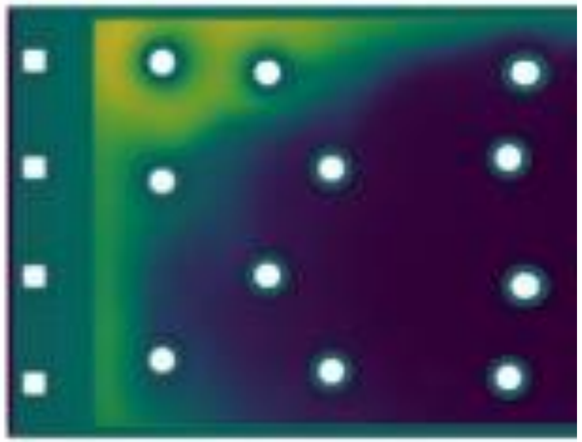
Hydrogen isotopes transport & trapping in Eurofer97

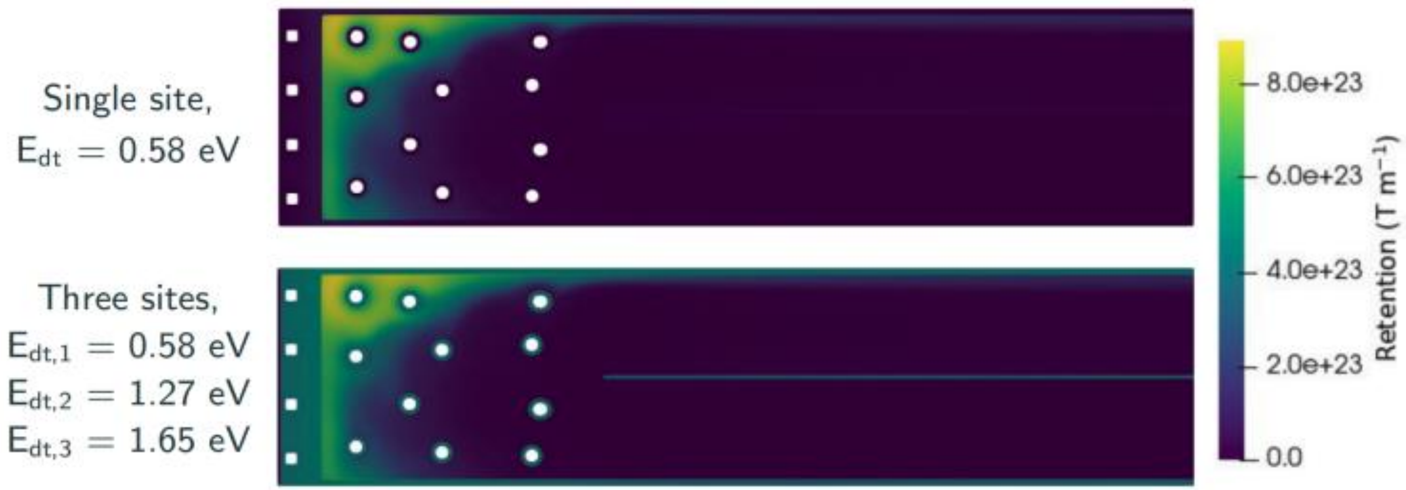
- Simulation of the T retention fields in a 2D section of a WCLL Breeding blanket with FESTIM:
  - **Adding the 2 high detrapping energy traps leads to a 18-fold increase of the retention:**
    - 1-trap model: $1.72 \cdot 10^{20}$ $T.m^{-1}$ (0.86 mg/m of WCLL)
    - 3-traps model: $3.12 \cdot 10^{21}$ $T.m^{-1}$(15.5 mg/m of WCLL)

  + permeation through the pipe is done in 29 s with the 1-trap model vs 3.8 hours with 3-traps model

  ➔ Considering only the low detrapping energy traps significantly underestimates retention







[J. Dark Nuc. Fus. 2021]

TITANS: HANDLE

1. **WP1: Enhancement of tritium permeation barriers and tritiated waste management (KIT)**
   - Upgrade of tritium permeation barrier (treatment of surfaces)
   - Binder matrix to immobilize tritiated metallic dust and minimize the tritium release
   - Compare methods and procedures of decommissioning tritiated components/systems
   - Design of a mobile water detritiation facility

Decommissioning and treatment of tritiated components

- SCK CEN Tritium laboratory:
  - Commissionned in 1975
  - 30 years operation
  - Max inventory: 37 TBq

- Low T release limit: intensive decontamination labor
  - **Significative impact of the approach**

	"Idealistic"	"Pragmatic"
Comp. nucl. Waste	4.0 m³	5.7 m³
Free rel. metals	79 % (weight)	27 % (parts)
Free rel. other mat.	75 % (weight)	65 % (parts)
Man hours (h)	4000 h	1300 h
Time span (years)	2.75 y	1 y

- Characterisation of tritium contaminated metal:
  - Large range of activity measured: 6 to180 kBq/dm²
  - Historical data: ~ 4 GBq/kg

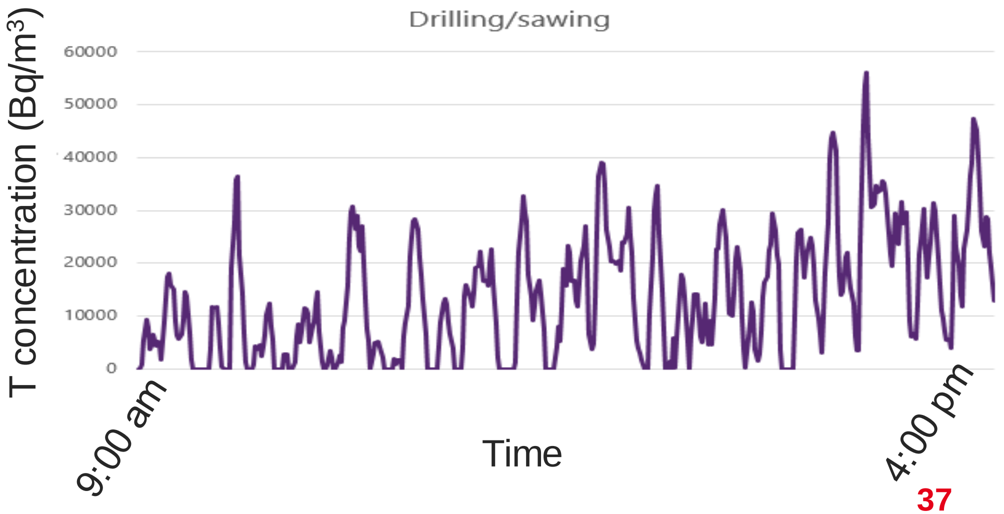
➔20 times lower than measured

Study of ^{3}H release during various cold cutting techniques

- Pneumatic cutter: up to 240 kBq/m³
- Sawing : up to 70 kBq/m³
- Milling machine: up to 50 kBq/m³
- Drilling: up to 40 kBq/m³
- Background-signal 20 ± 10 kBq/m³

\+ Advantages:
- no contaminated oil (dry)
- less tritium emission

− Disadvantages:
- − Dry friction heating causes material hardening
  ➔ time consuming + wear of cutting materials

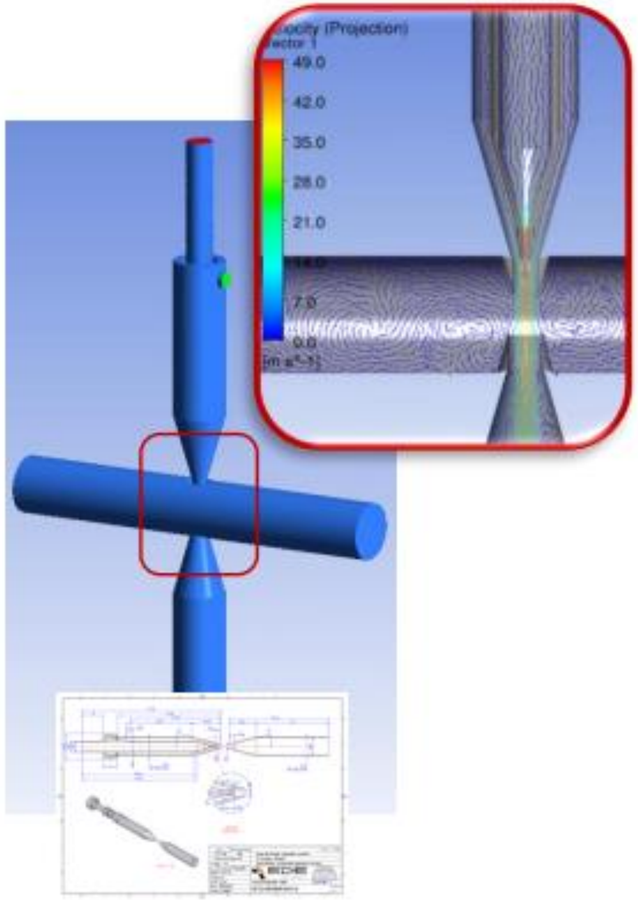


⚠ **Mobilizable dust created**

TITANS: HANDLE, CONTROL

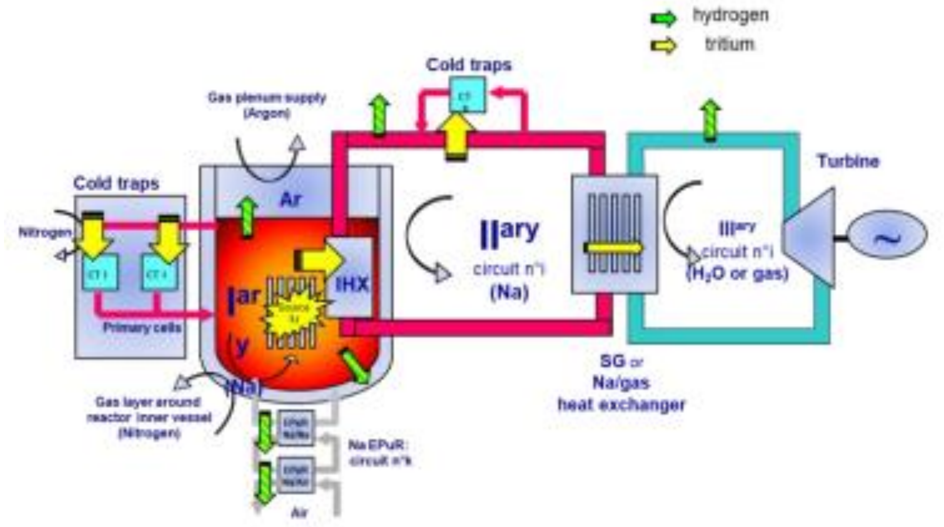
1. **WP1: Enhancement of tritium permeation barriers and tritiated waste management (KIT)**

2. **WP2: Tritium measurement and modelling (CIEMAT)**
   - Tritium measurement in solid, dust and aerosol
     - Autoradiography
     - Nuclear reaction analysis
     - Nuclear Magnetic resonance
     - Tritium inventory in aerosol
   - Tritium measurement in liquid metal
   - Tritium transport code from system to detail level in fission and fusion devices

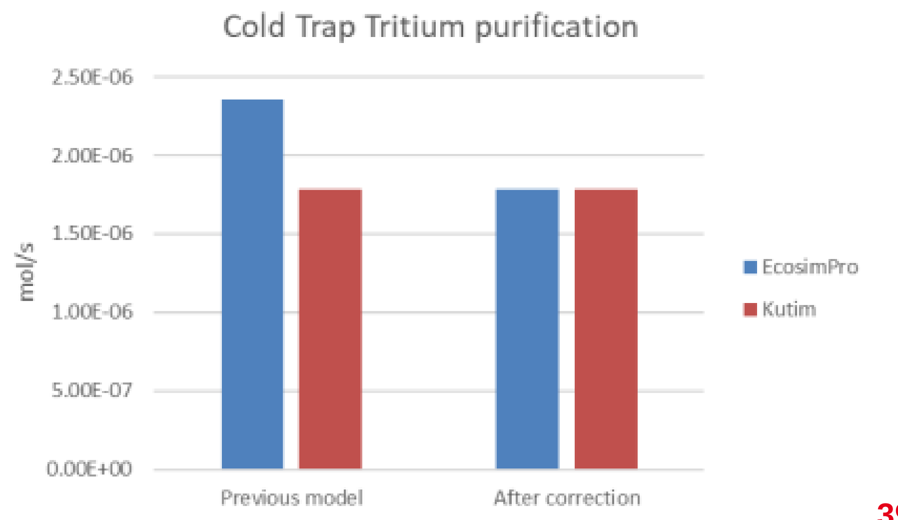


Benchmark study and validation of fusionfission system level codes: KUTIM-EcosimPro

- Benchmarking of 2 system codes:
  - **EcosimPro Tritium Transport Libraries** (fusion)
  - **KUTIM** (fission)
    - Influence of temperature
    - Impact of the H source term (secondary circuit)
    - Impact of Na flowrate in cold traps
    - \+ Consequences on overall permeation transfers



- Transfer fluxes in cold traps
  - Different approaches applying temperature to calculate Na density
    - Na density equation calculated with corrected temperature
  - Different modelling approaches to simulate the cold trap component in the process material balance



Benchmark study and validation of fusion/fission system level codes: KUTIM vs EcosimPro

➔ Permeation:

- EcosimPro: permeability is the product of solubility and diffusivity

$$P_H = D_H \cdot K_{SH}^{met} = P_o\, e^{\left(-\frac{E_p}{RT}\right)}$$

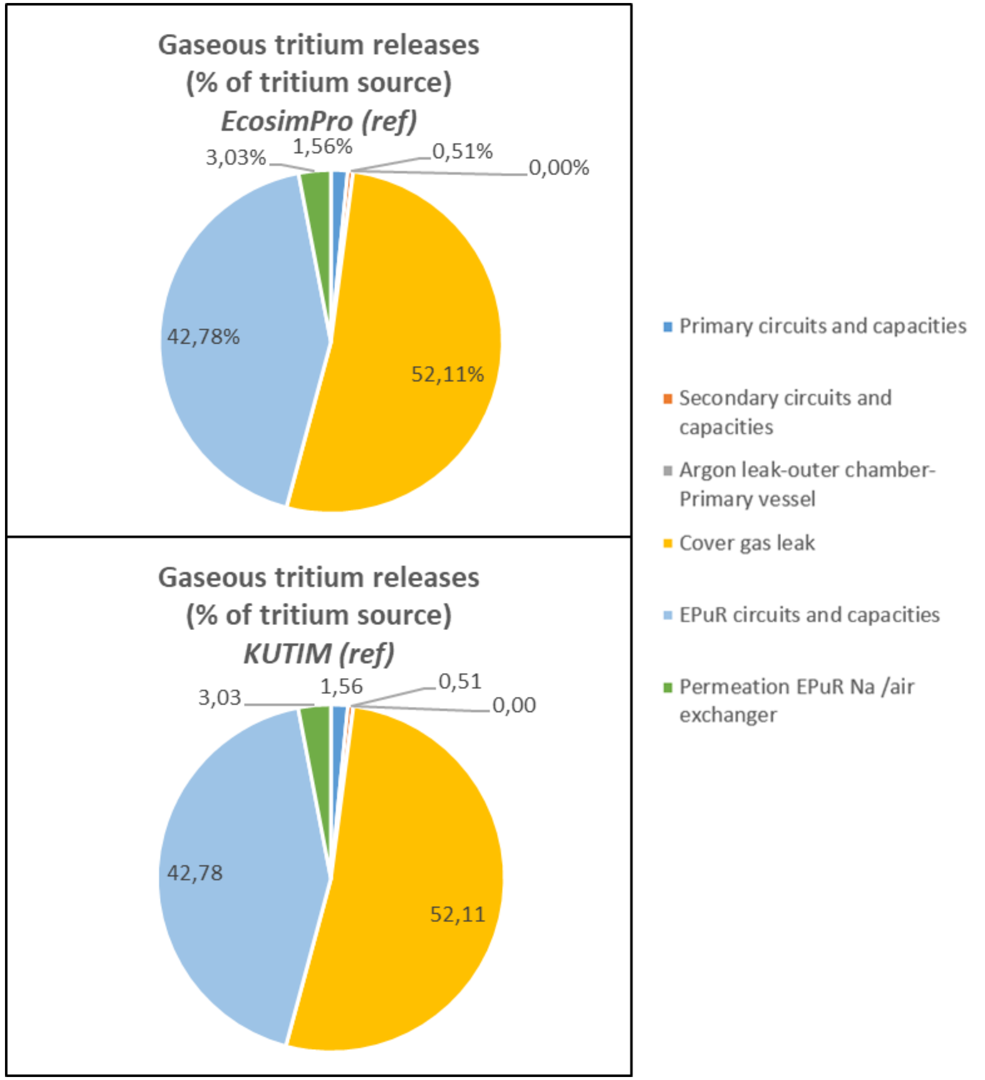
- KUTIM: permeation is based on “permeability coefficient” Pe_X ($kg_{Na}.m^{-1}.s^{-1}$)

$$Pe_H(T) = D_H \cdot \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot \rho^{Na} = e^{\left(-\frac{a}{T}-b\right)}$$

➔ 0.05 % difference for the global gaseous release analysis

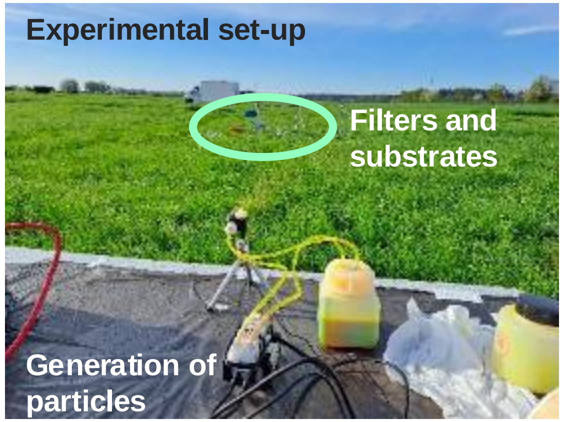
➔ Sensitivity analysis (temperature, H source, flow rate to cold Trap)

➔ Implement validation scenario for liquid sodium loop (Superfennec training loop at CEA)



TITANS: HANDLE, CONTROL & PROTECT

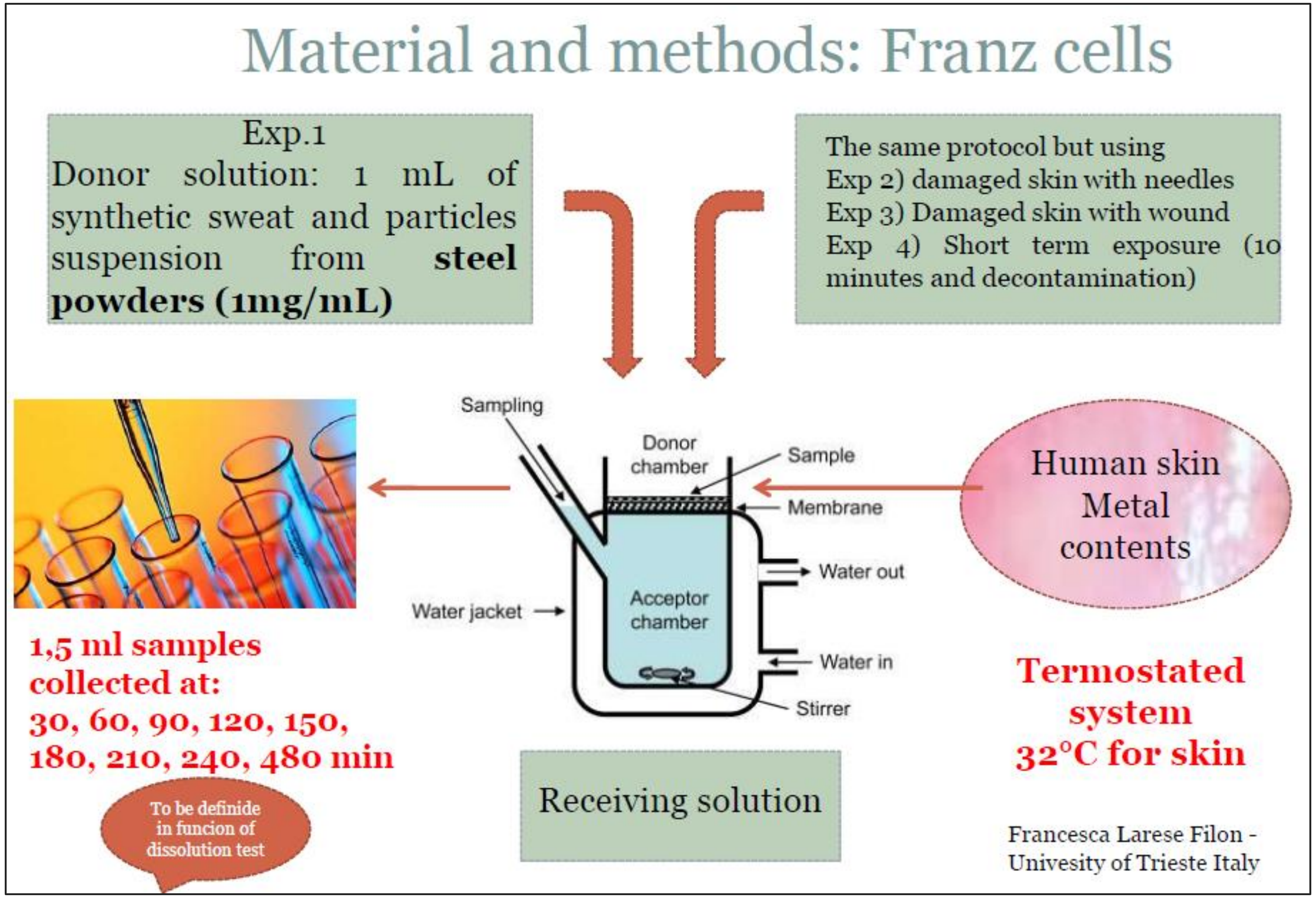
1. **WP1: Enhancement of tritium permeation barriers and tritiated waste management (KIT)**



2. **WP2: Tritium measurement and modelling (CIEMAT)**

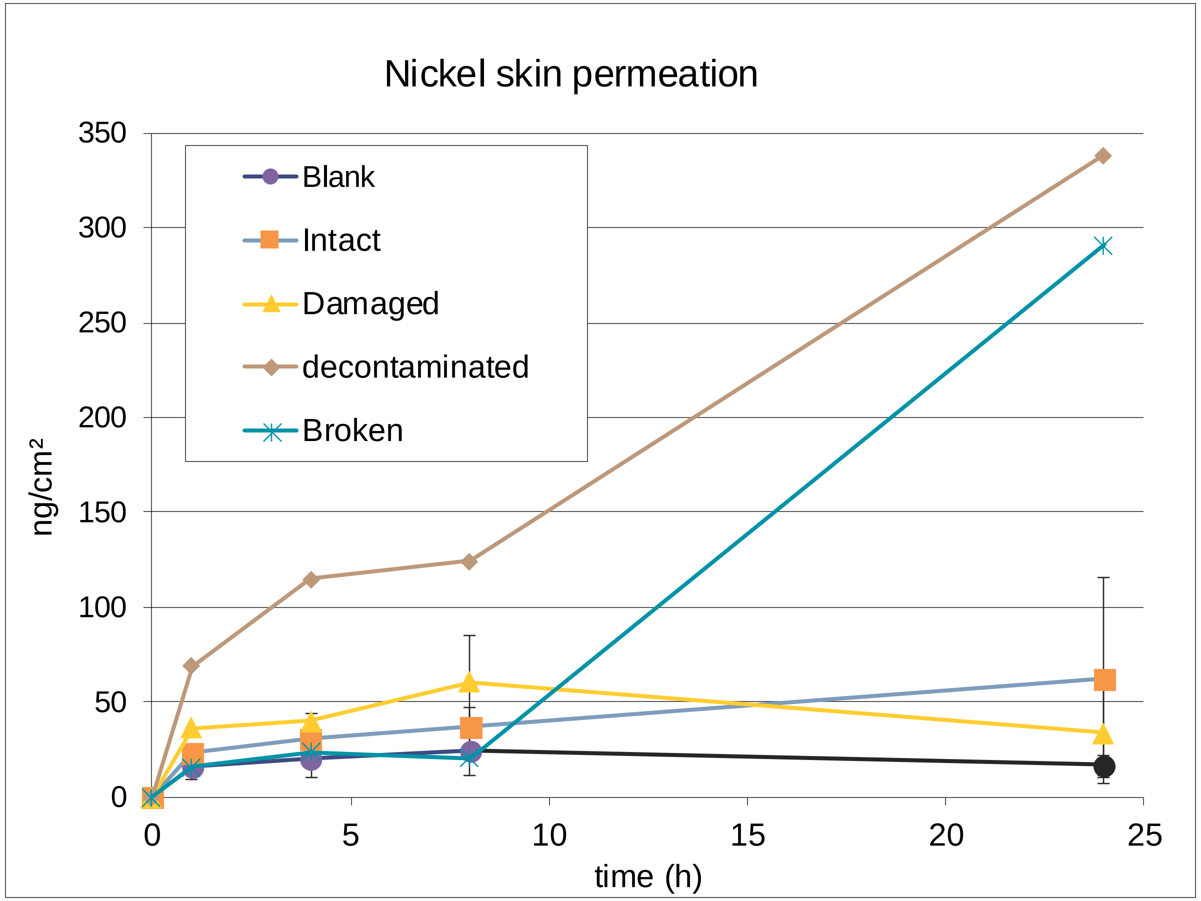
3. **WP3: Radiation protection, risk assessment and dosimetry studies following accidental exposure to tritiated dust (CEA)**
   - Dispersion and deposition of aerosols on vegetation
   - Establish a dose-effect relationship (essential to radiation risk assessment) in the case of:
     - Contamination of skin
     - Contamination of human lung macrophages
     - Contamination of a population of mussels

Study of tritium particles biokinetic by the skin route: a fast track to T bio accumulation?



Evaluation of tritium and metals' permeation through intact and damaged human skin following exposure to tritiated particles (*OECD Guidelines and Regul Toxicol Pharmacol. 2020 Nov, 117:104752*)

Skin decontamination can increase steel particle element permeation through the skin



- Only decontaminated and broken skin present an increase of metal permeation, with different profiles:
  - For **broken skins**: permeation after 8 h
  - **Decontaminated skins using soap:** caused by surfactant action of soaps on stratum corneum integrity?

TITANS project:
take-home messages

❖ Develop and test innovative technologies to measure T in materials and mitigate T release in the environment

- **Learn from decommissioning ac**tivities and prepare waste management
- Develop T measurements techniques
- Develop and upgrade experimental benches for T testing
- Validate and **benchmark modelling tools**

❖ Provide inputs to ICRP biokinetic models and dose coefficients for radioprotection guidelines

- Understand potential dispersion routes
- **Evaluate T contamination routes** (skin permeation, food chain integration)
- Estimate geno and cyto-toxic impact

➢ **TITANS built on strong interaction between fusion/fission experts**

- All the major tritium EU experts/institutions involved
- All results, workshop, news accessible: https://titans-project.eu/

➔ **newsletter available!**

Thanks for your attention

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