DE LA RECHERCHE À L'INDUSTRIE

EVOLUTION OF THE W CRISTALLINE STRUCTURE UNDER HE IRRADIATION:

SURFACIC EVOLUTION AND BUBBLE FORMATION

EXPERIMENTAL CHARACTERIZATION

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TUNGSTEN AS A PLASMA-FACING MATERIAL

- W: used in JET, WEST, **ITER**

  ➔ intensive fluxes of He and H isotopes at high temperatures

- Impact of He irradiation at the surface
  - dislocation loops
  - bubbles
  - W-fuzz

  } <530ºC, $E < E_{disp.\ min}$ (538 eV)

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

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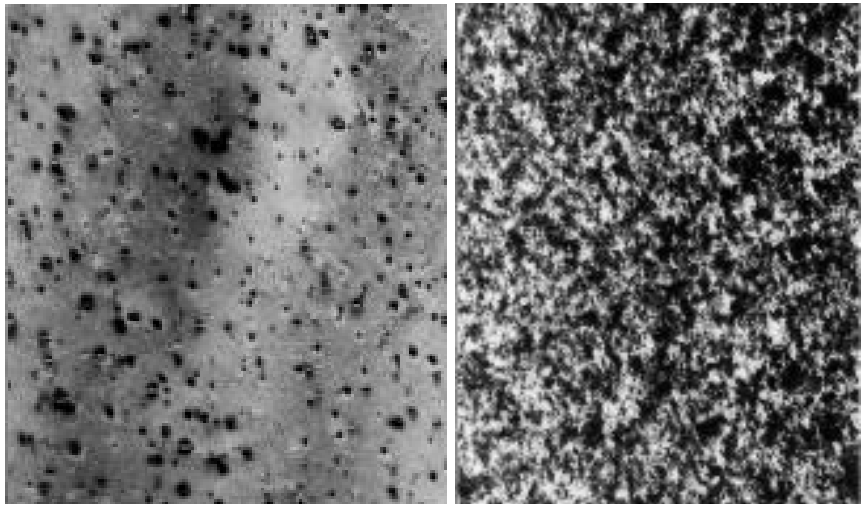
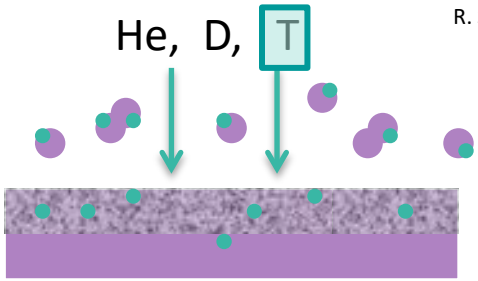


R. Sakamoto

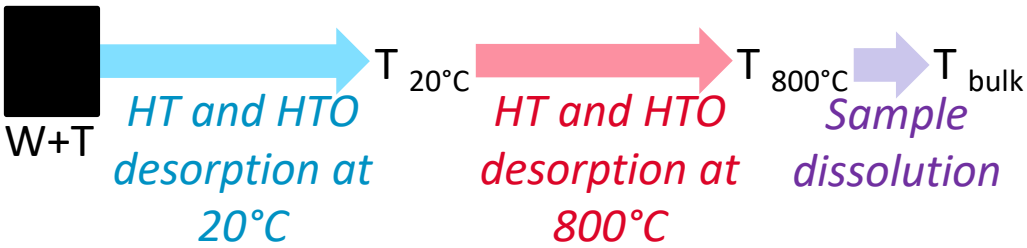
➡ ***He has a strong impact on the material.***

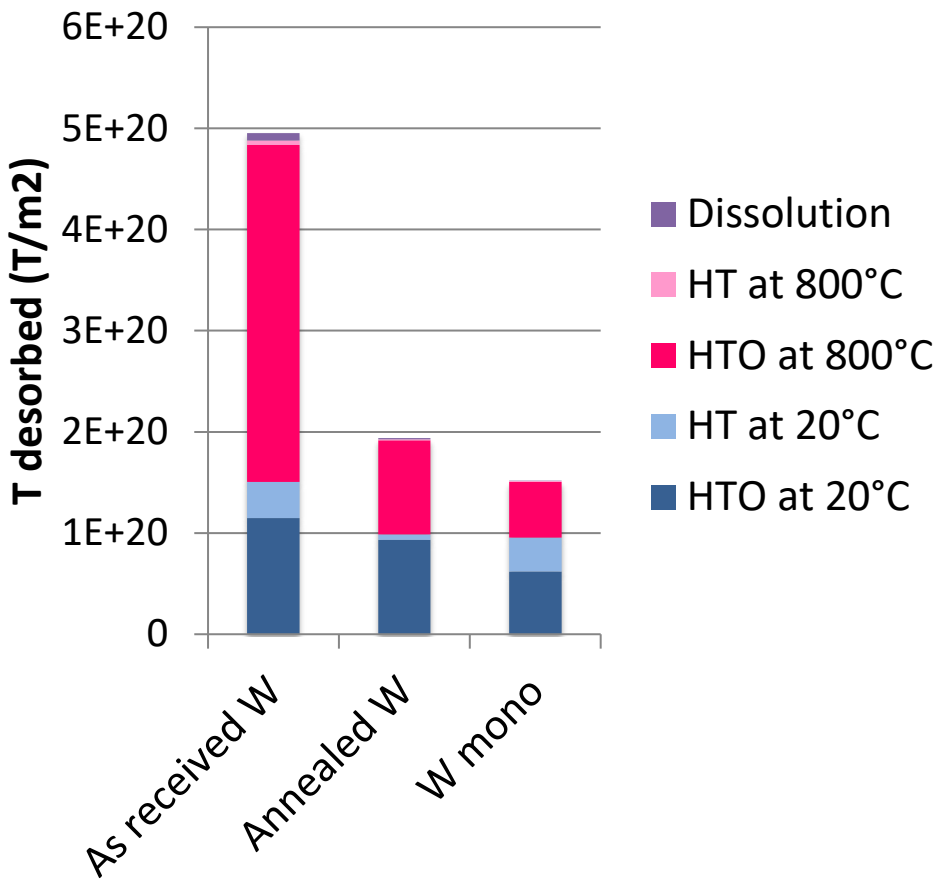


➡ ***These modifications can affect the trapping of hydrogen (T).***

- In tokamaks, multiple plasma-surface interaction complexify the access to fundamental He-W mechanisms

PRISTINE W: MAJOR INCREASE OF T TRAPPING WITH PRE EXISTING DEFECTS





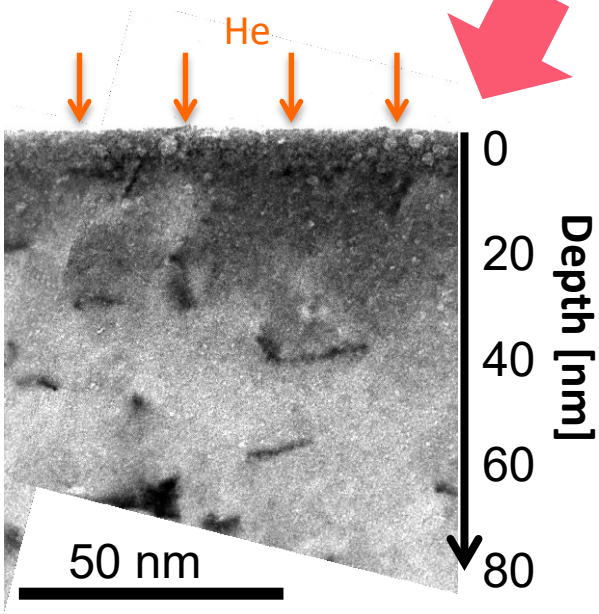
Major increase of T trapping with defects in W structure, desorbing only at high temperature

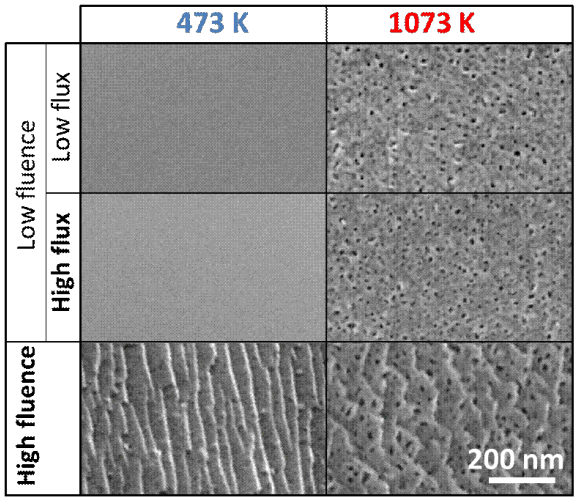
What is the impact of He triggered damages to the W microstructure?

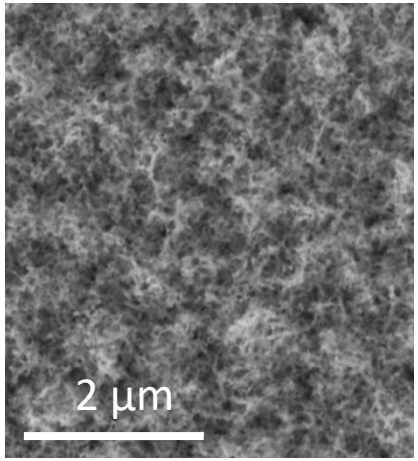
IMPACT ON W: FROM IN SITU CX-HE EXPOSURE (LHD) TO HIGHER HE FLUX IN LINEAR PLASMAS (PSI-2, PISCES-A)

All exposures: temperature-controlled sample holders

	LHD	PSI-2	PISCES-A
Exposure	CX He (up to 1 keV)	75 eV He^+	70 eV He^+ (W fuzz)
Temperature (°C)	500-800	250- 800	850
Flux ($m^{-2}.s^{-1}$)	$1x10^{21}$ to $1x10^{22}$	$2.5x10^{20}$ to $2.5x10^{22}$	$9.26x10^{21}$
Fluence (m^{-2})	$3x10^{22}$ to $1x10^{23}$	$3x10^{23}$ to $1x10^{26}$	$1x10^{26}$







IN SITU HE-W INTERACTIONS ARE COMPLEX AND THEIR IMPACT HARSHER THAN EXPECTED

All exposures: temperature-controlled sample holders

	LHD	PSI-2	PISCES-A
Exposure	CX He (up to 1 keV)	75 eV He^+	70 eV He^+ (W fuzz)
Temperature (°C)	500-800	250- 800	850
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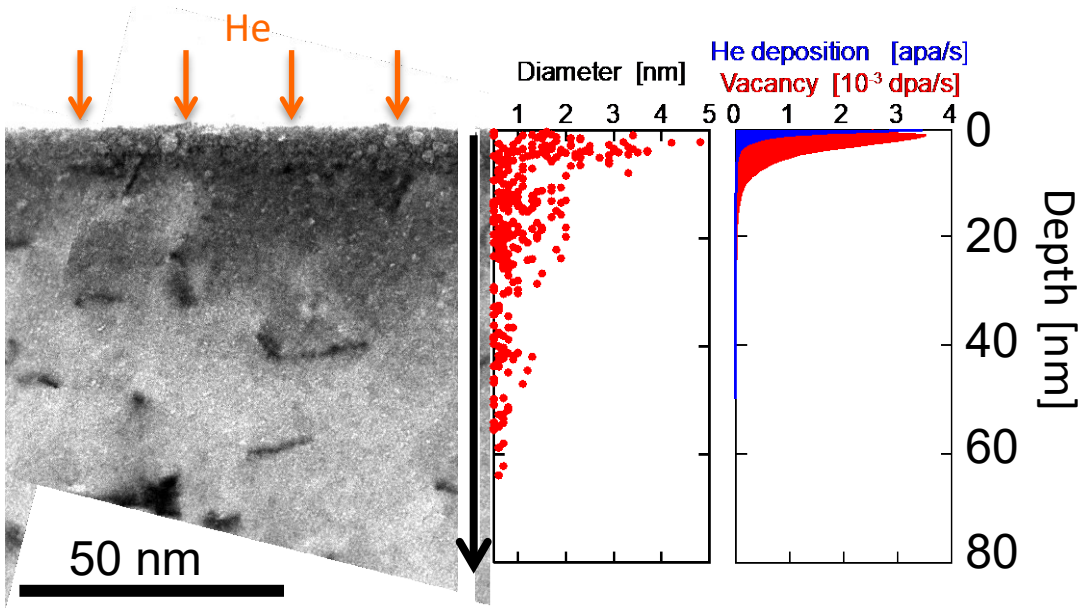
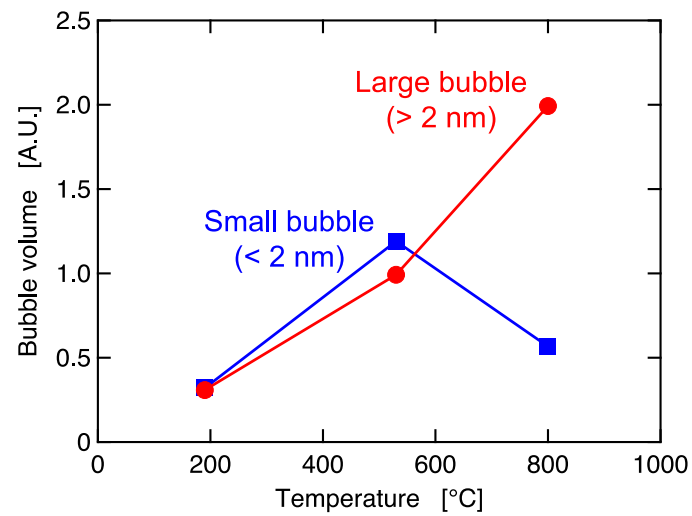
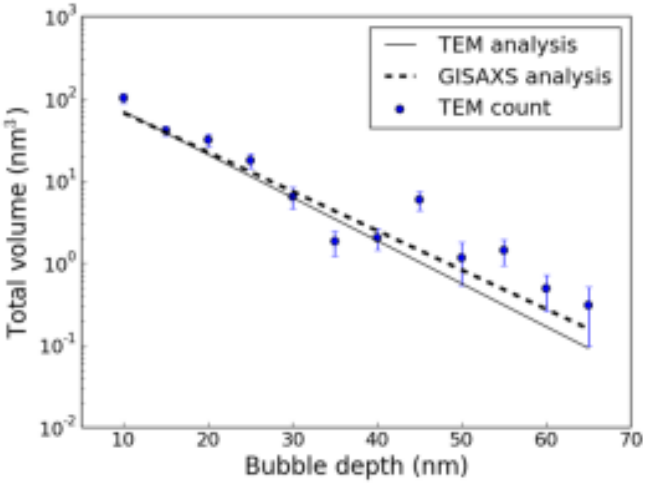




ACCESSING HE-W MECHANISMS: THE NEED FOR A FUNDAMENTAL DYNAMIC NANOSCIENCE STUDY

Access the dynamics of fundamental He-W interactions:

- **Low Energy Electron Microscopy** (LEEM) for surface evolution
- X ray Diffraction (XRD) and **Grazing Incident Small Angle X-ray Scattering** (GISAXS) for bubble formation and evolution



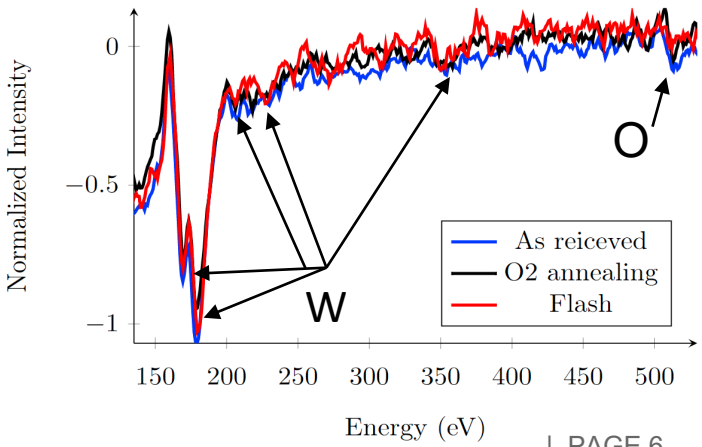
M. Thompson *et al.*, *J. Nucl. Mater.*, vol. 473 (2016) 6–12.

First time in situ GISAXS and He exposure at the ERSF BM 32

+ Temperature-controlled setups

+ Coupled with post-mortem characterizations: FIB+TEM, AFM, SIMS

- Monocristalline samples: W(100), W(110), W(111)
- Preparation protocol:
  - Ideal surface orientation (<0.1° orientation error)
  - **Cleaning and surface roughness minimization** (Auger electron spectroscopy)
    - 15 min Oxygen annealing 1200K (P = 3.0x10-7 torr)
    - 40 s high temperature flash (2200K) under vacuum
  - **Au film deposition to prevent native oxide formation**



DIRECT OBSERVATION OF SURFACE RECONSTRUCTION UNDER LEEM

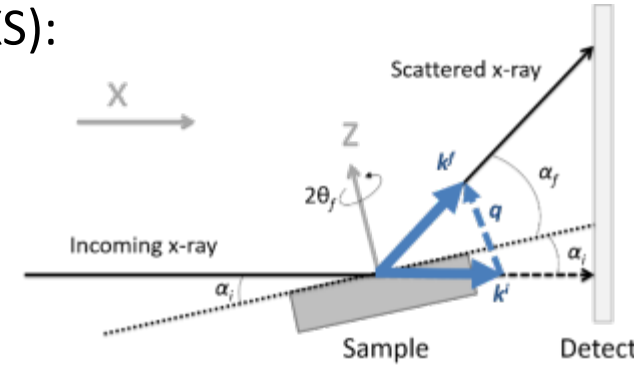
- **W(100) exposed to 2 keV He^+ exposure**
  - Strong surface modification
  - Original ideal surface state is recovered during annealing up to 1573 K

➡ Temperature is a key parameter

➡ Surface recovery can undergo transient stages inaccessible with post-mortem studies

KINETIC STUDY OF HE BUBBLE FORMATION AND EVOLUTION IN TUNGSTEN BY IN-SITU GISAXS

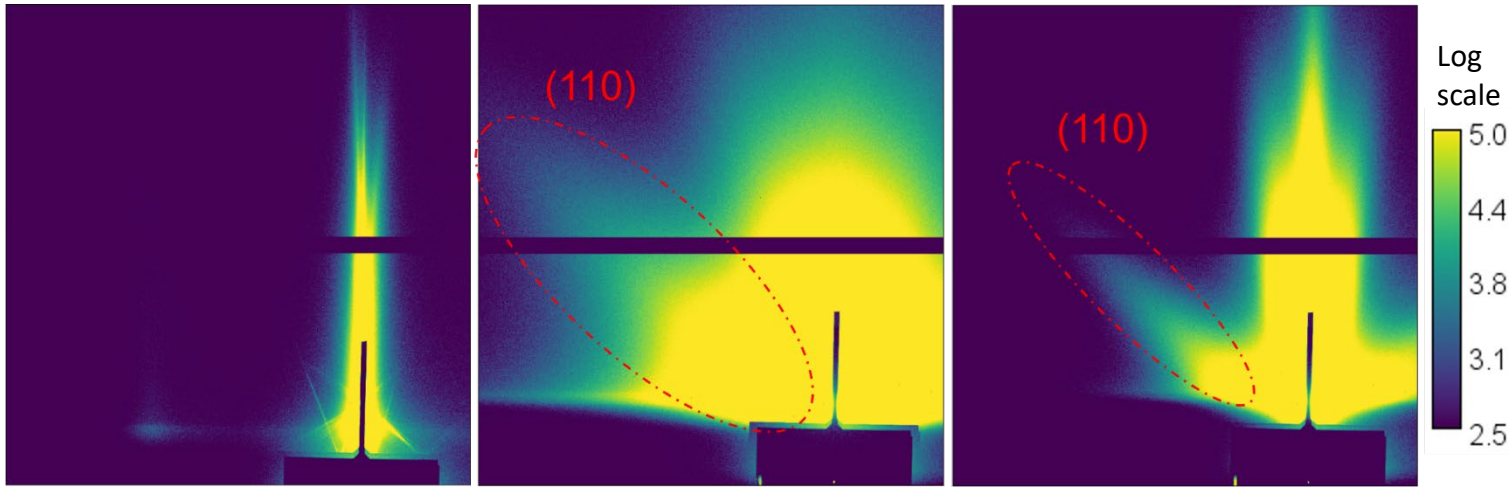
- Grazing-incidence Small Angle X-ray Scattering (GISAXS):
  - non destructive technique using a **photons probe** to study nanostructure materials, combining the **length scales of small-angle scattering** and **surface sensitivity of grazing incidence diffractio**n.
  - ➢ Determines average particle properties on a larger scale



- ESRF campaign 1: E_{He}=2 keV (2.4×10^{17} He.m^{-2}s^{-1}, 1×10^{22} He.m^{-2}), θ=1273 K

➡ He nano-bubbles formation from very low fluence

➡ Preferential scattering of X-ray shows (100) and (110) facetted He bubbles

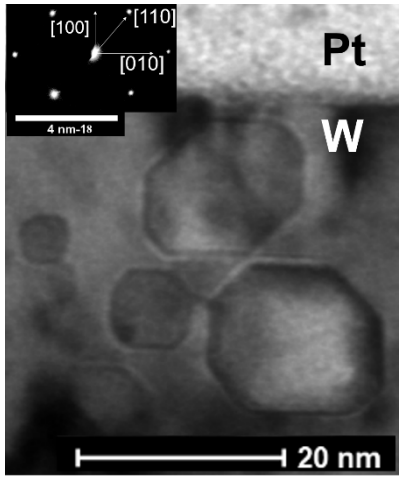


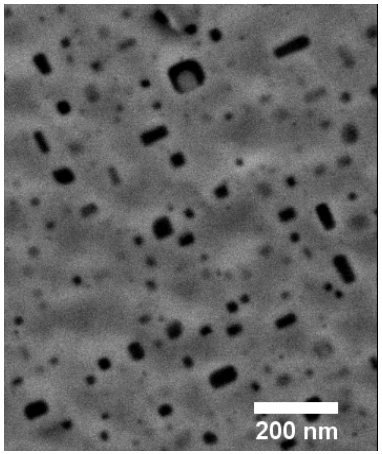
W(100) before, after He implantation, and after annealing up to 1773 K

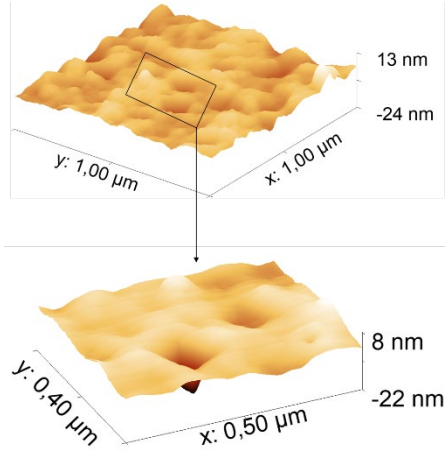
POST MORTEM ANALYSIS: ADDITIONAL CLUES FOR THE GISAXS DATA MODELING

- GISAXS diffraction spectra: integrated contribution (surface+bubbles)
  - IsGISAXS modeling to specify bubble size, distribution and density

- Post-mortem characterization tools:
  - Transmission Electron Microscopy (**TEM**):
    - Bubbles distributed in the first 50 nm
    - (100) and (110) facets are visible
    - Radius varies from 2 to 10 nm
  - Secondary Electron Microscopy (**SEM**) + Atomic Force Microscopy (**AFM**):
    - Holes linked with bubble bursting
    - Squared shape on (100) surface



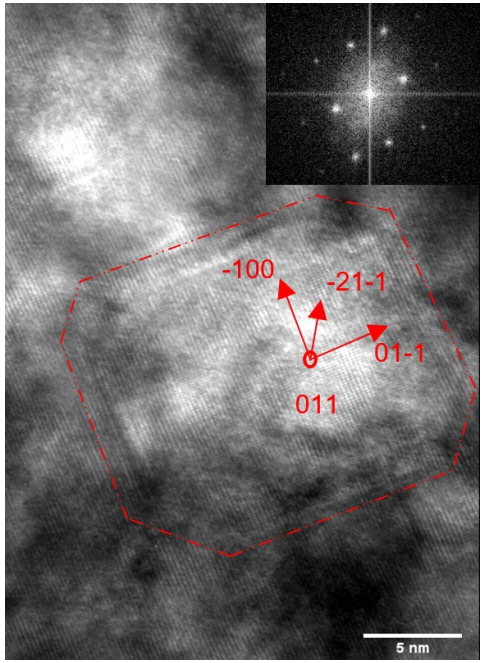




What about He content?

CONCLUSIONS AND PERSPECTIVES

- Impact of pre existing W structure: crucial for T inventory
  - Defects, dislocations, vacancies are present in “real life” tokamak W
    - **Importance of manufacturing process and/or sample preparation**
- Complexity of PWI He irradiation conditions: competition of the impacts of the creation of defects and He bubbles
    - **Fundamental study needed to decouple the various contributions to the morphology changes and understands He-W fundamental interactions**
- First dynamic He-W interaction study based on LEEM and GISAXS
  - **Temperature** is a key parameter
  - **Facetted bubbles** with (100) and (110) planes are formed during He implantation and coalesce during annealing
  - Bubble bursting creates **square shaped holes** on the surface
- ESRF campaign 2: E_{He} = 300 eV (Oct 2022)
- Evaluation of He inventory



Link with modeling

THANK YOU FOR YOUR ATTENTION

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