Deuterium plasma effect on tungsten irradiated with high-energy ions

Khripunov B.I., Koidan V.S., Ryazanov A.I.

IAEA Coordinated Research Project (CRP)
"Plasma-Wall Interaction
with Irradiated Tungsten and Tungsten Alloys in Fusion Devices"

3 rd Research Coordination Meeting
June 28 2017, Vienna, Austria

Participants in the work

NRC Kurchatov Institute,
Moscow, Russia

Center of physical and chemical technologies

Khripunov B.I., Koidan V.S., Gureev V.M., Kornienko S.N., Stolyarova V.G., Muksunov A.M.

Center of fundamental research

Ryazanov A.I., Latushkin S.T., Semenov E.V., Danelyan L.S., Unezhev V.N.

Institute of Nuclear Physics,
Lomonosov University, Moscow, Russia

Kulikauskas V.S., Zatekin V.V.

National Research Nuclear University MEPHI,
Moscow, Russia

Gasparyan Yu.M., Efimov V.S., Pisarev A.A.

Outline

Production of damage in tungsten by high-energy ions

Plasma experiment on irradiated tungsten

W erosion in deuterium plasma

He-irradiations

W damaged by C-ions

W PLANSEE irradiated by protons

Participation in CRP research

Experimental research of deuterium plasma effect on tungsten at **high-level of radiation damage** is performed.

The damage of tungsten produced by **high-energy ions** accelerated to MeV-energies by cyclotron.

The primary defect concentration in irradiated tungsten from **one dpa to a few tens dpa.**

The irradiated tungsten subjected to **steady-state deuterium plasma** and the consequences of plasma-surface interaction on tungsten surface are compared for the damaged material and undamaged one.

Participation in CRP research

Analysis of tungsten microstructure at different stages of the experiments - after high-energy irradiation and during plasma exposures.

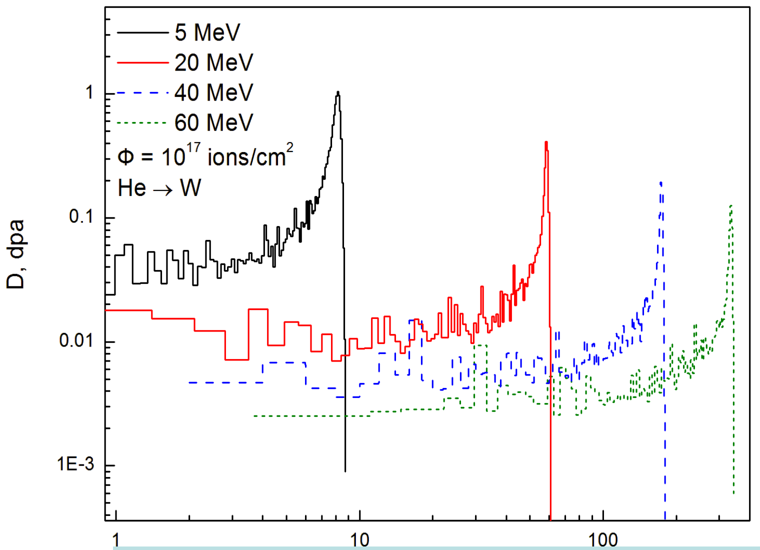
Erosion of the irradiated material in deuterium plasma is evaluated and its relation to irradiation analyzed.

Deuterium retention in irradiated tungsten - analysis of hydrogen isotopes performed by nuclear reaction methods (ERDA, RBS), TDS: penetration depth and the quantity of the retained isotope after exposure of damaged tungsten to plasma fluence 10^{25}-10^{26} m^{-2}.

The role of temperature in production of damage and in plasma impact on irradiated tungsten.

Production of radiation damage in tungsten by high-energy ions

$^4He^{2+} \longrightarrow W$



Primary radiation defects produced by Helium ions accelerated to 5-60 MeV

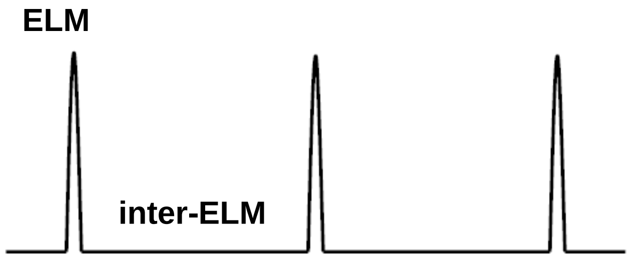
Primary radiation defects in tungsten irradiated by $^4He^{++}$ ions 4 MeV, $\Phi = 10^{23}$ $^4He^{+2}$ $/m^2$, (ρ=19.35 g/cm^3, 183.8 amu)

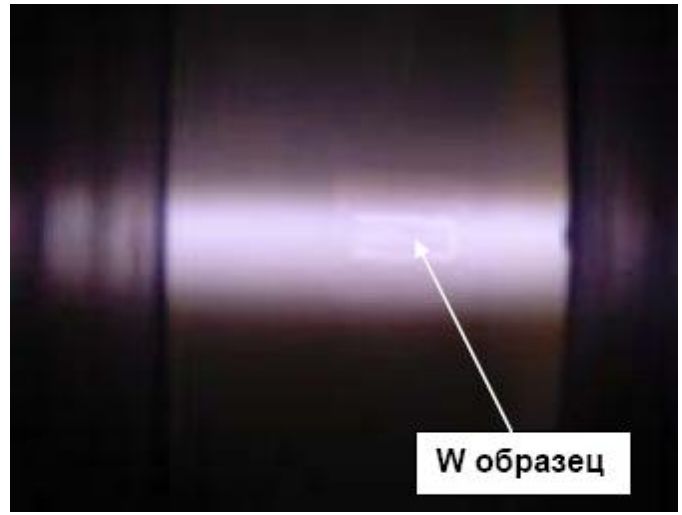
D_{max} = 80 dpa, D_{min} = 2.7 dpa near the surface

<D> = 10 dpa

Plasma exposure of irradiated materials

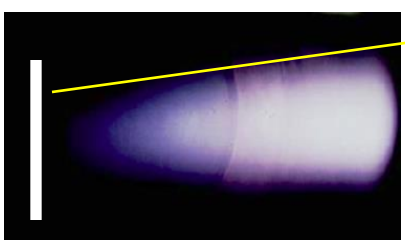
LENTA-M

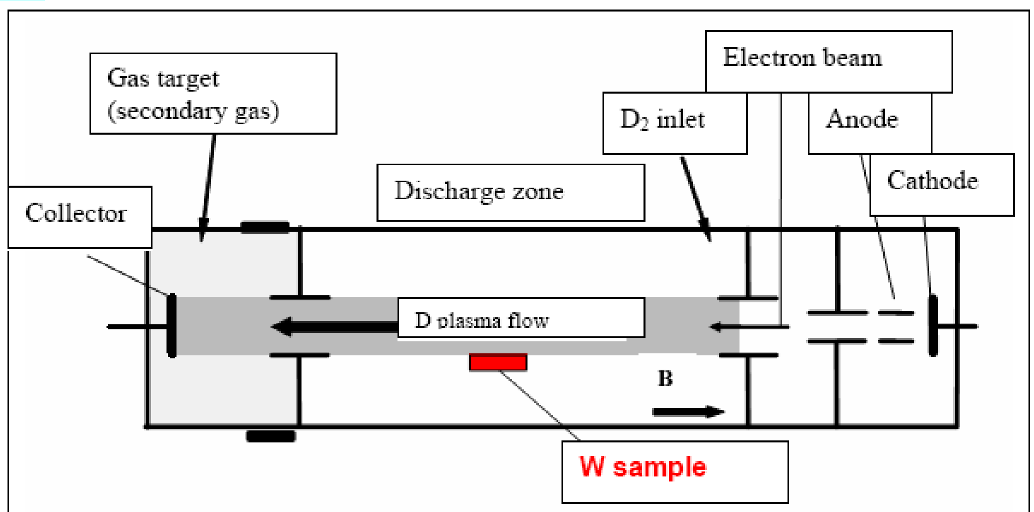




Beam-plasma discharge in axial magnetic field
Steady state operation

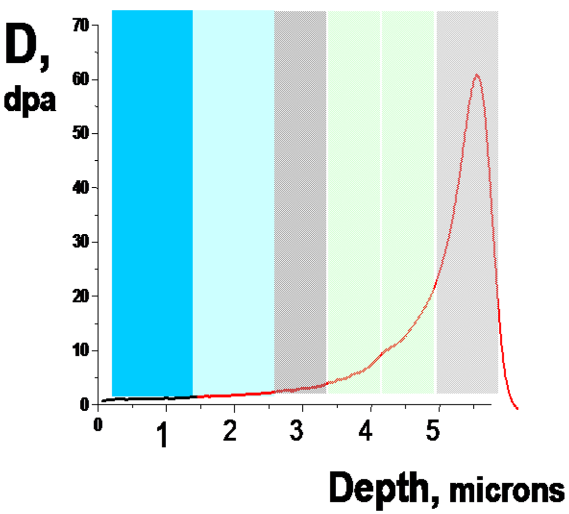
Plasma exposure in tokamak divertor simulated conditions (ion fluence 10^{25}-10^{26} ion/m^2; ion energy 250 eV - erosion condition).

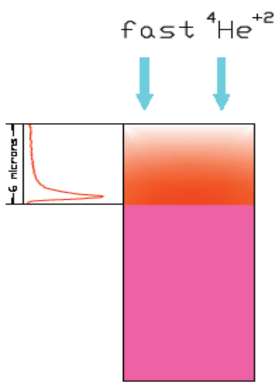


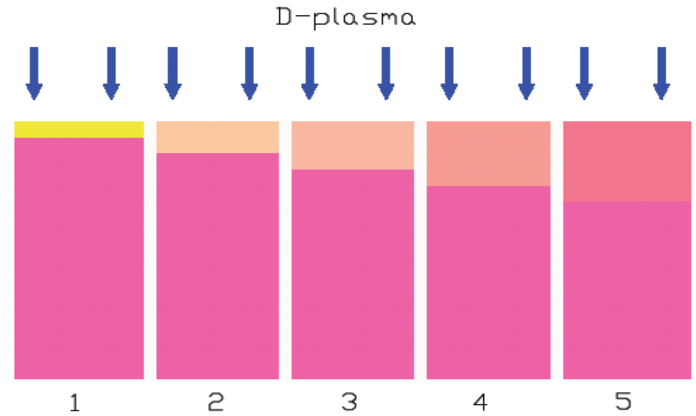


Experimental procedure
D-plasma on damaged tungsten

- ***Multiple exposures to D-plasma after damage by fast ions***

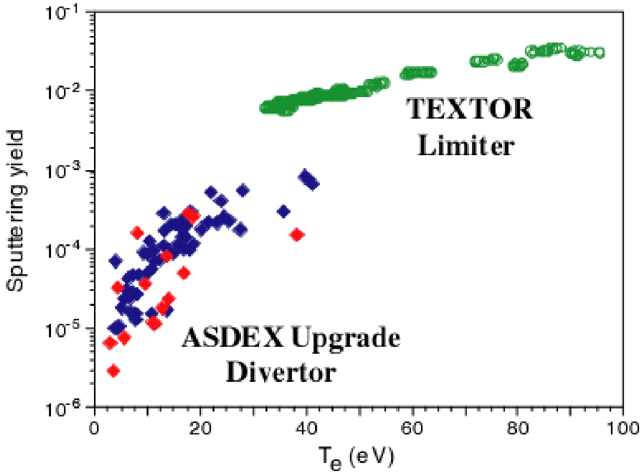




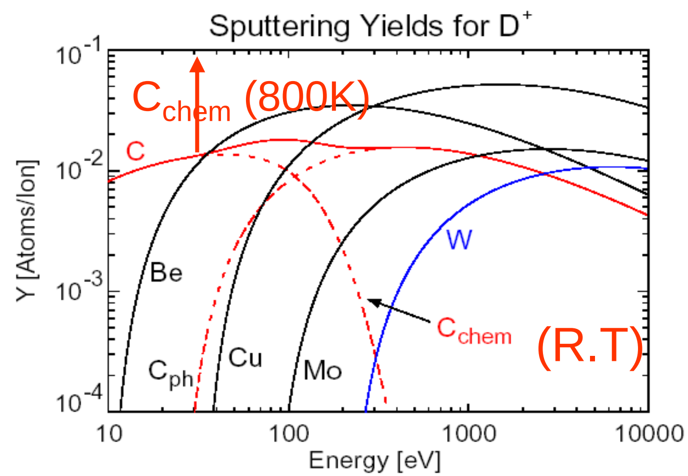


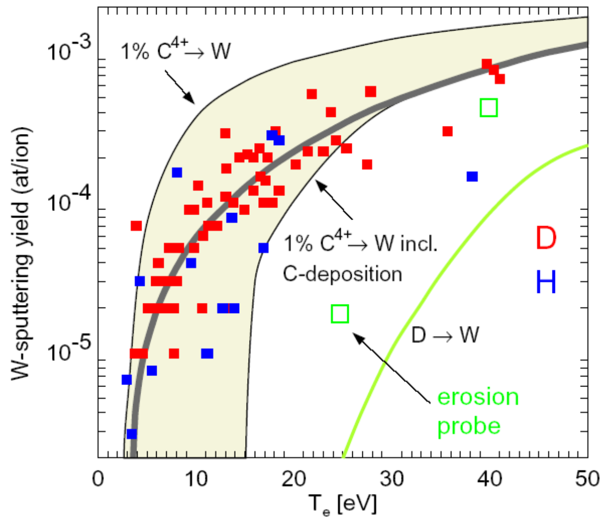
- **Working gas** **deuterium**
- **Plasma density** **$2 \cdot 10^{12}$ cm^{-3}**
- **Plasma temperature** **6 eV**
- **ion current** **j = 10-20 mA/cm^2**
- **ion energy** **250 eV**
- **exposure time** **1- 3 hours**
- **sample temperature** **40-100 C**
- **erosion in plasma – step-by-step**
- **ion fluence in one exposure step** **~10^{21} ion/cm^2**
- **Total ion fluence** **$2 \cdot 10^{22}$ ion/cm^2**

Tungsten erosion in deuterium plasma

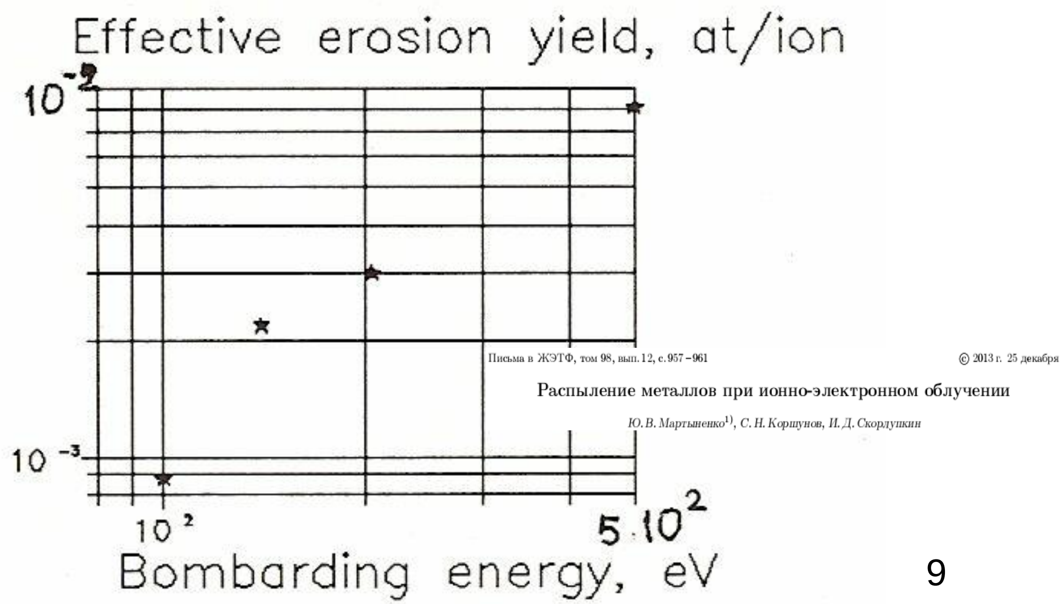


Progress in ITER Physics Basis
(Nucl.Fus.V.47, Nr.6,2007) V. Philipps et al., PPCF 42





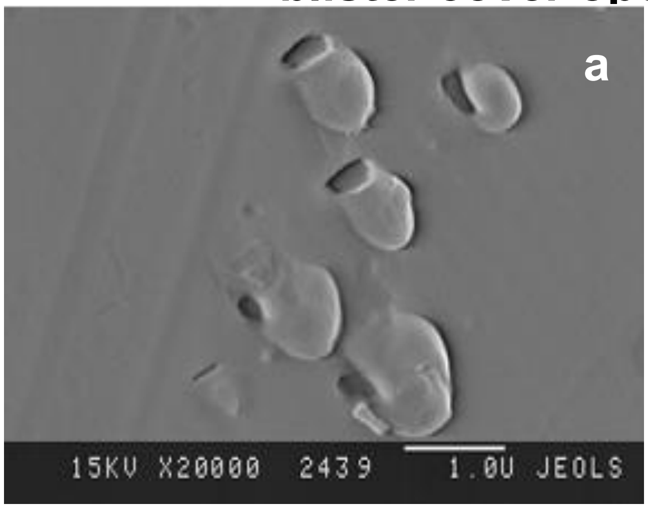
Kaufmann, SOFT 2006, Warsaw

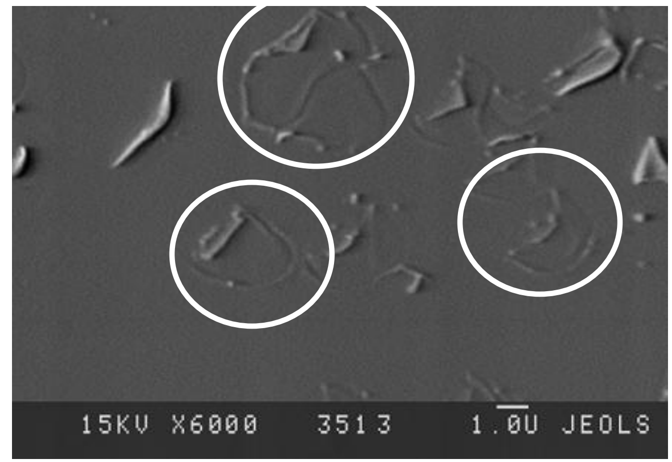


Fusion Technology, SOFT 18, Karlsruhe (SPRUT-4)

W erosion enhanced by blistering

blister cover opening

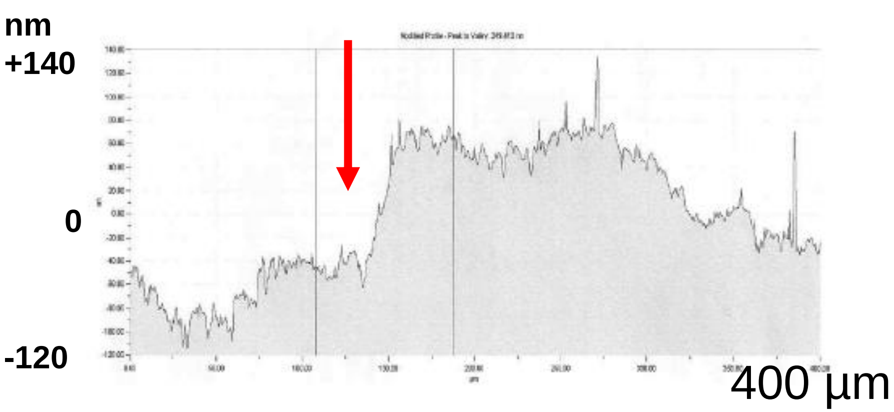


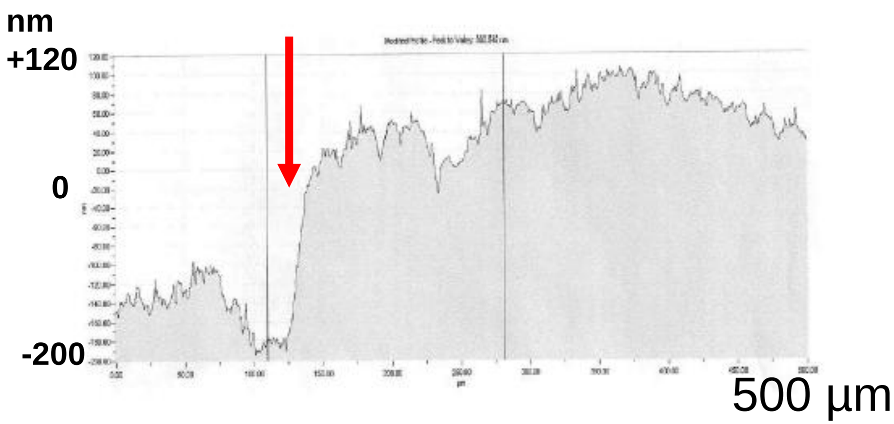


Erosion of surface layer on irradiated tungsten by blister damage in deuterium plasma

Blister damage enhances tungsten surface erosion. Mechanism is illustrated: local overheating of the blister cover by plasma followed by sputtering and total destruction.

Swelling of Helium-irradiated tungsten





Swelling step

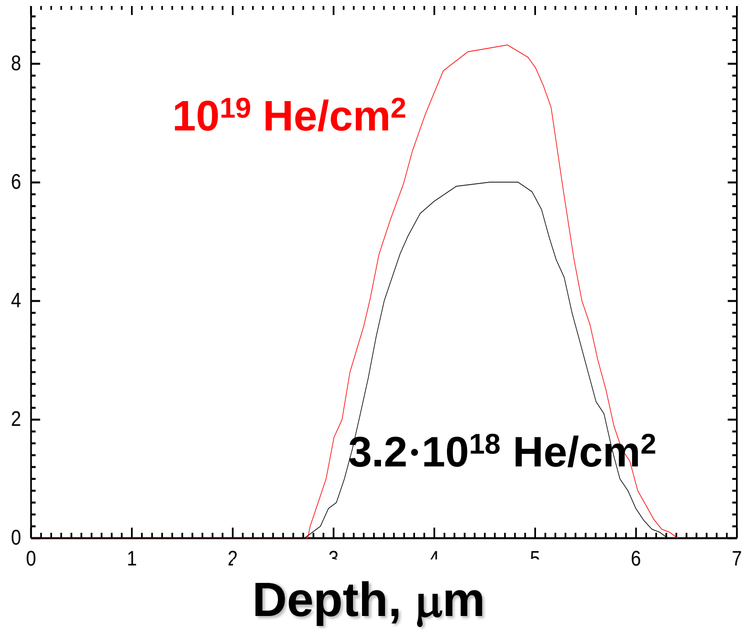
Profile around the irradiation area border

Δh = **0.1-0.2 µm** for **5-6 µm** of damaged layer depth

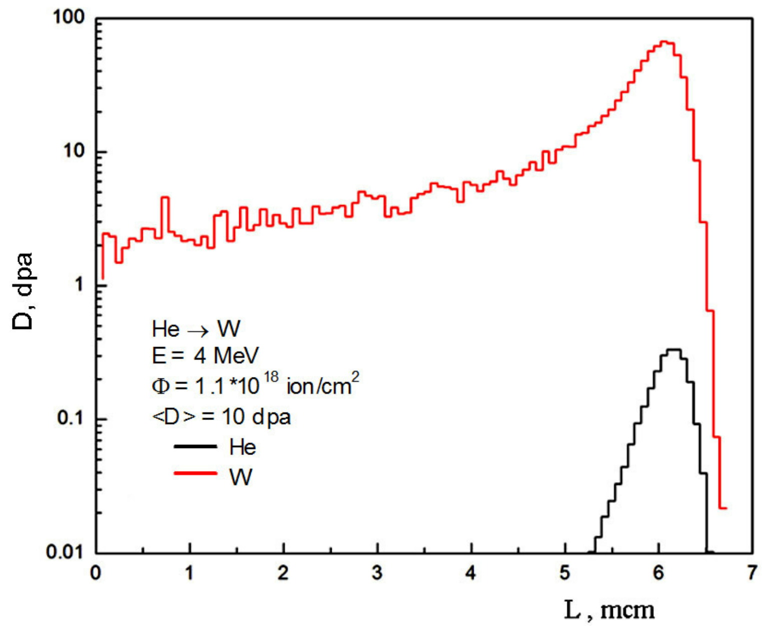
2-3 % as average value

Helium in irradiated tungsten

Helium concentration, at %
RBS analysis



$^4He^{2+} \longrightarrow$ W

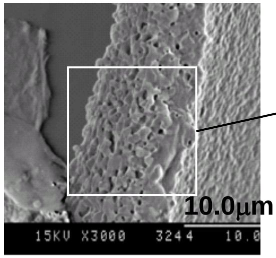


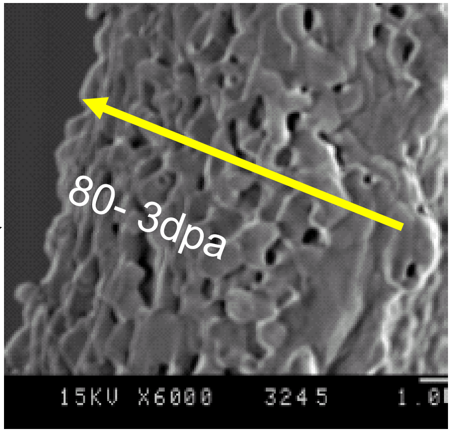
- Major of helium is concentrated in the layer 3-6 micron deep
- This corresponds to calculated distributions
- Maximal helium concentration in tungsten is about 8 % at.

- Nt =$1.1\cdot10^{18}$ He/cm²
- Nt=$7.5\cdot10^{17}$ He/cm²

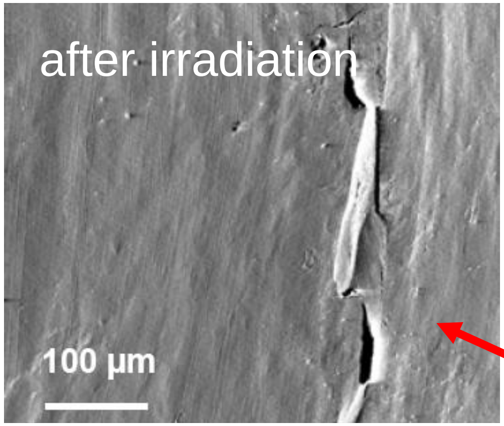
He-irradiated tungsten exposure to deuterium plasma

structure of damaged layer



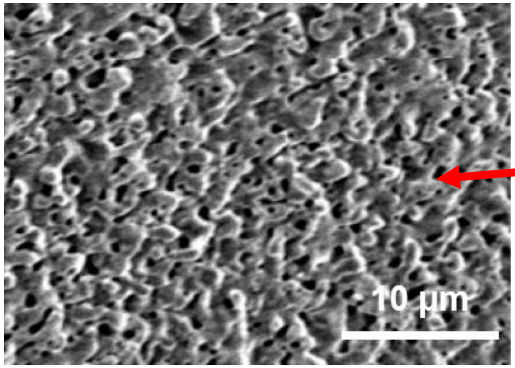


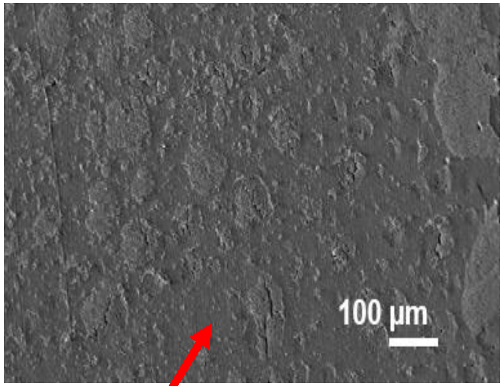
Surface at different stages of exposure series

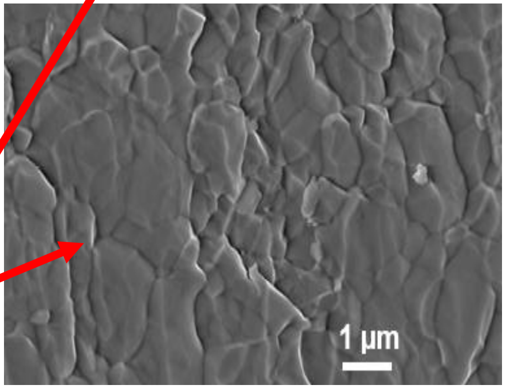


$\Phi = 3 \times 10^{18}$ He++/cm^2, 3.5 MeV

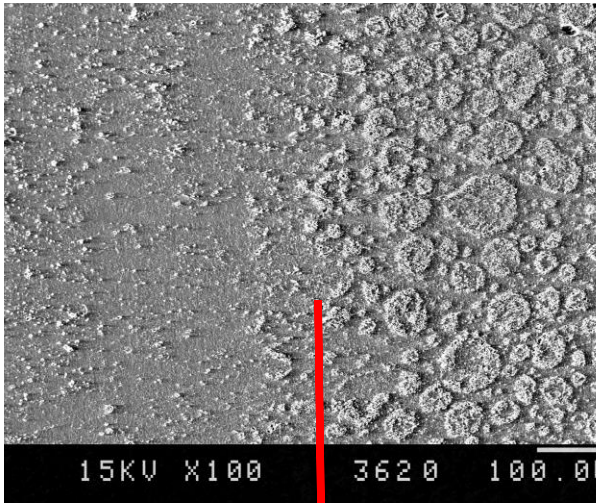
Exp. Nr	D-fluence, 10^{21} D/cm^2	Erosion depth, µm	Y, at/ion	D, dpa
1	0,9	0,13	$1 \cdot 10^{-3}$	6
2	1,8	0,63	$2.3 \cdot 10^{-3}$	7.5
3	2,7	1,7	$3 \cdot 10^{-3}$	10.5
4	2,4	1,1	$2.4 \cdot 10^{-3}$	15
5	1,6	0,8	$2.8 \cdot 10^{-3}$	19.5
6	1,0	1,0	$5.9 \cdot 10^{-3}$	54
Σ	10,4	5,4		



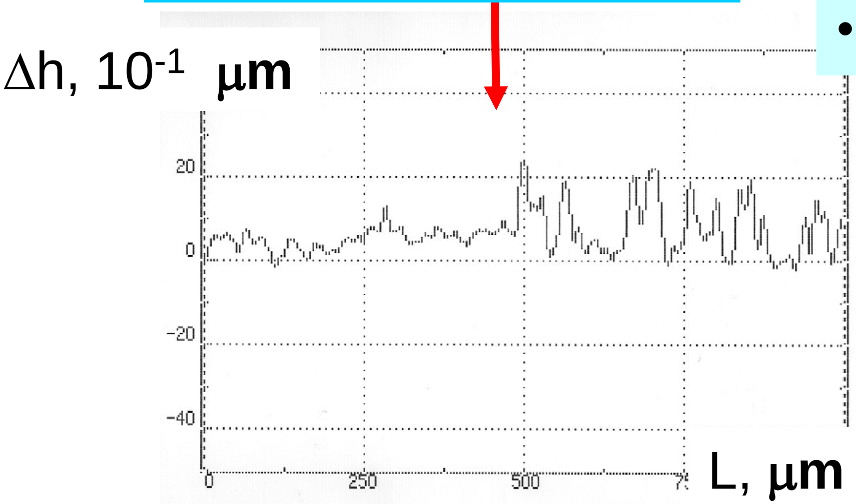




Surface erosion of He-irradiated tungsten in deuterium plasma



Boundary of irradiated area



- **Surface profile at the damaged area boundary**
- **Deuterium ion fluence $2 \cdot 10^{22}$ D^+/cm^2**
- **Erosion depth ~ 5 μm**

Development of the structure at the fast ion stopping range

- **Column elements hight Δh ~2 μm**

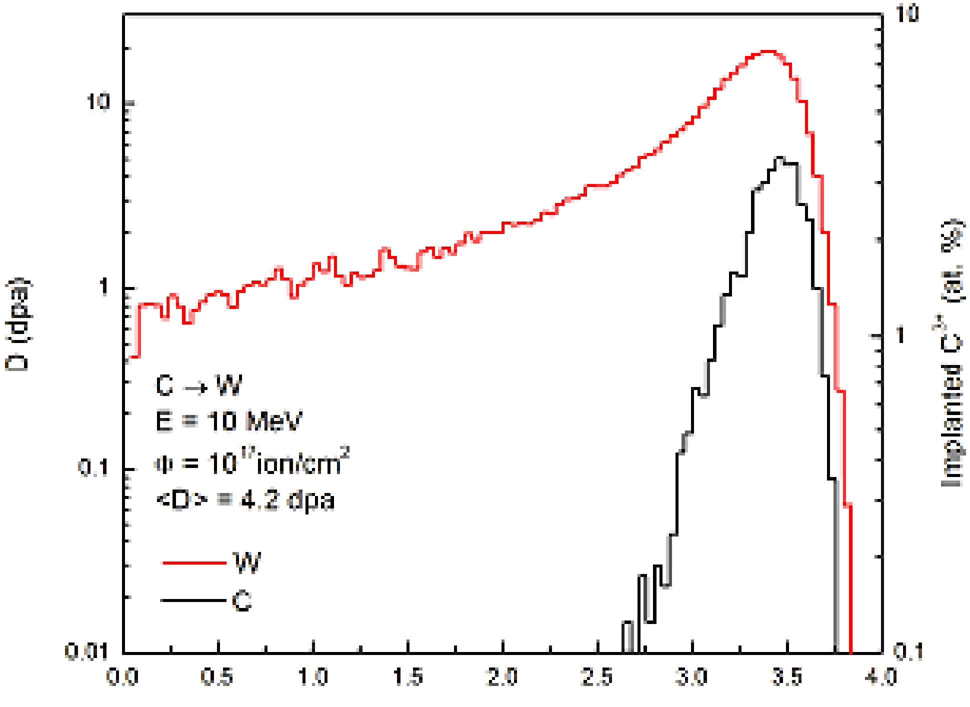
Tungsten erosion yield in deuterium plasma

$$Y_{D\ ion \to W} \sim (2\text{-}3) \cdot 10^{-3}\ \text{at/ion}$$

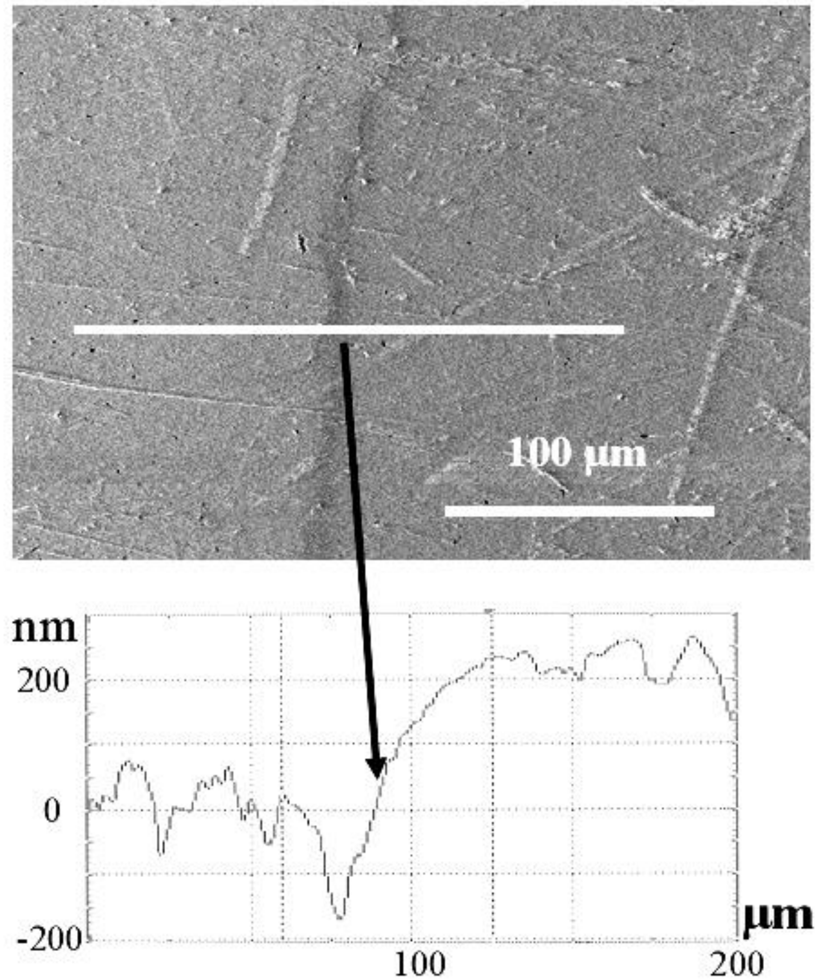
C-irradiation of tungsten - swelling

$^{12}C^{3+} \longrightarrow W$

dpa



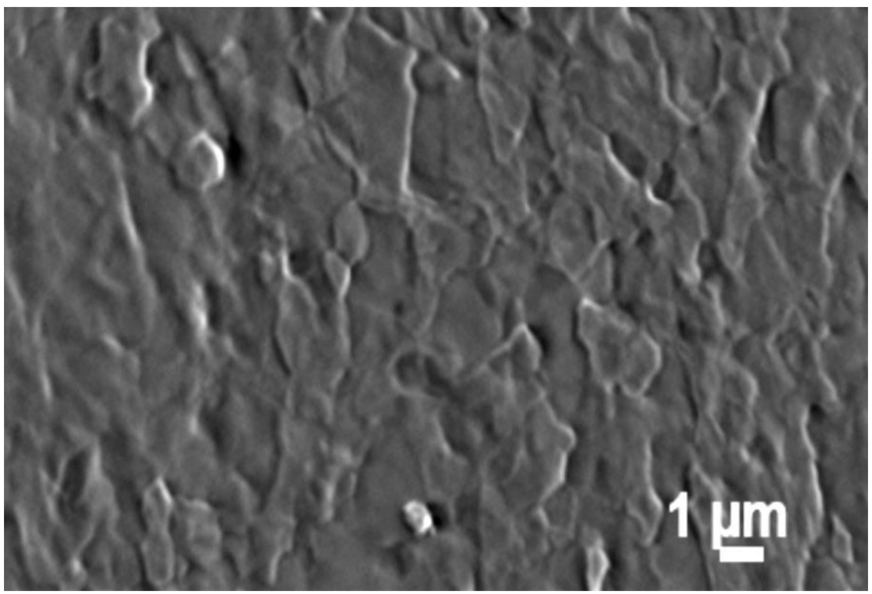
L, µm

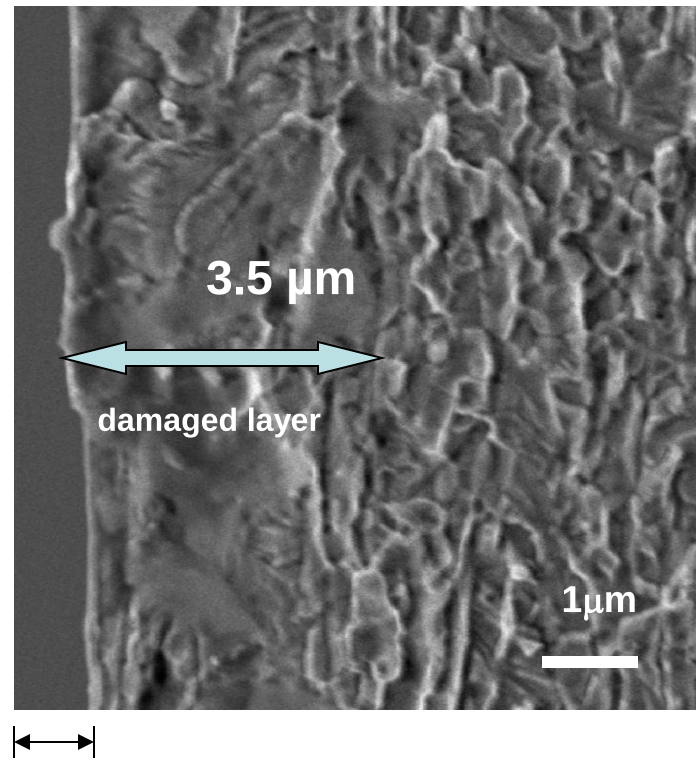


Damaged tungsten surface layer

$^{12}C^{3+} \longrightarrow W$

Tungsten irradiated by C^{3+} (10 MeV, Φ = 2x10^{17} ion/cm^2, T= 50-100 C) after deuterium plasma exposure (1 µm eroded, 1 dpa at the surface, 4.2 dpa av.)



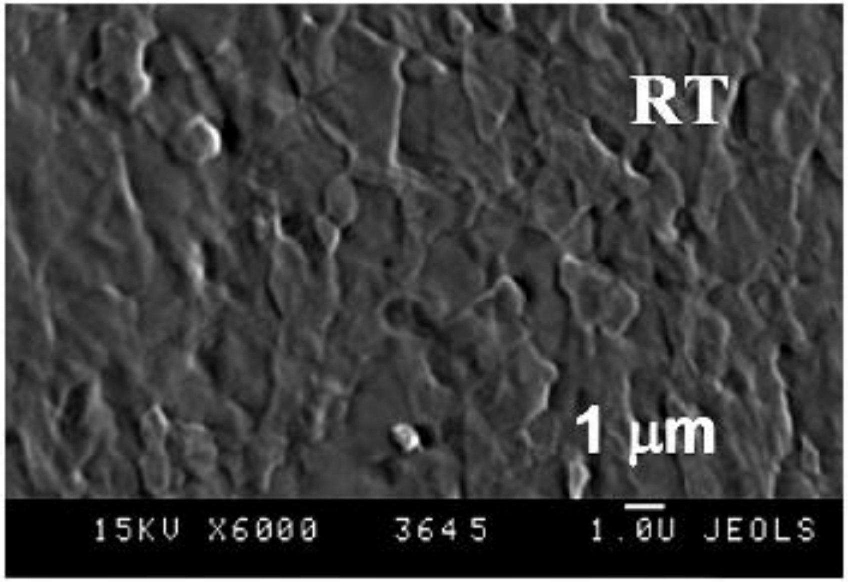


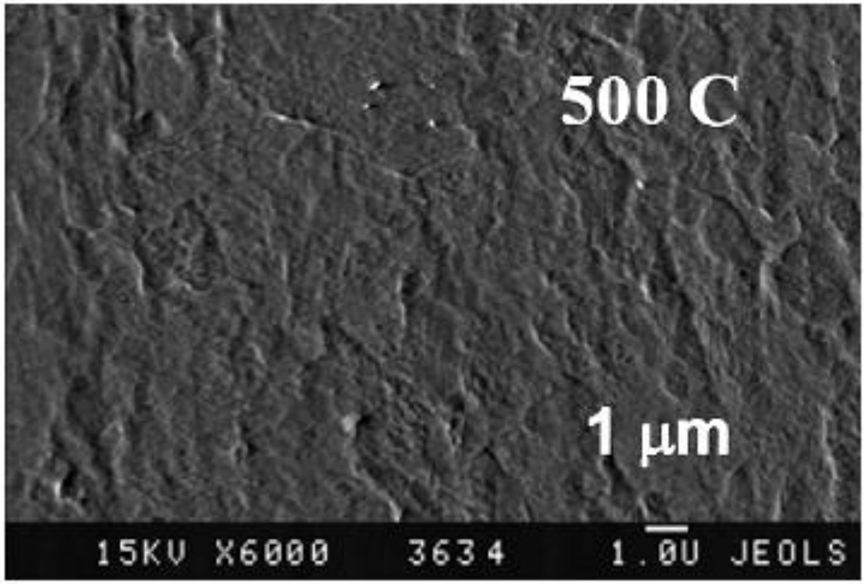
eroded layer

Damaged tungsten surface

$^{12}C^{3+} \longrightarrow W$

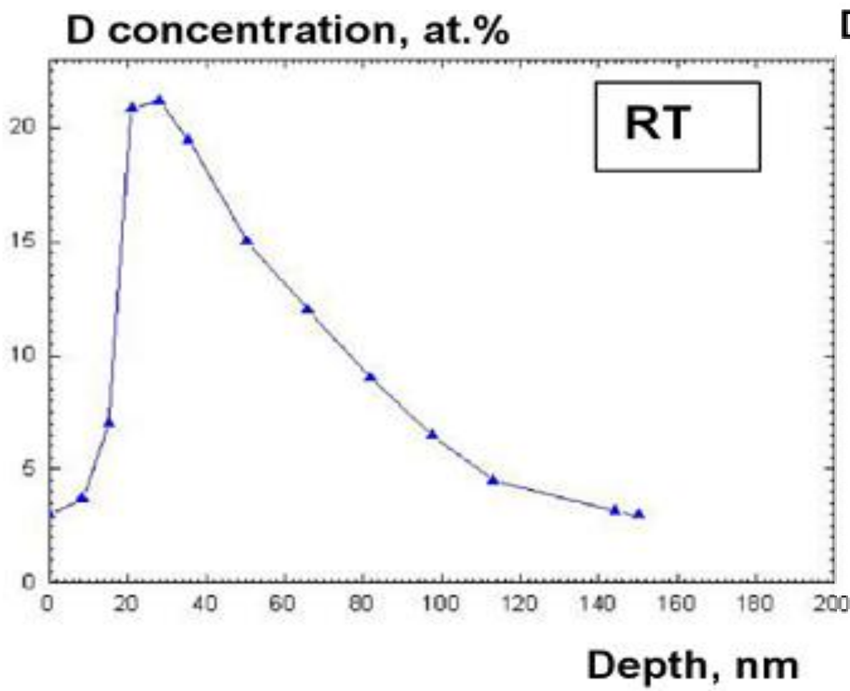
Irradiated tungsten (Φ = 1.5-2x10^{17} ion/cm^2) after deuterium plasma exposure (1-0.8 μm eroded, 1 dpa at the surface, 4.2 dpa av.) at different temperatures

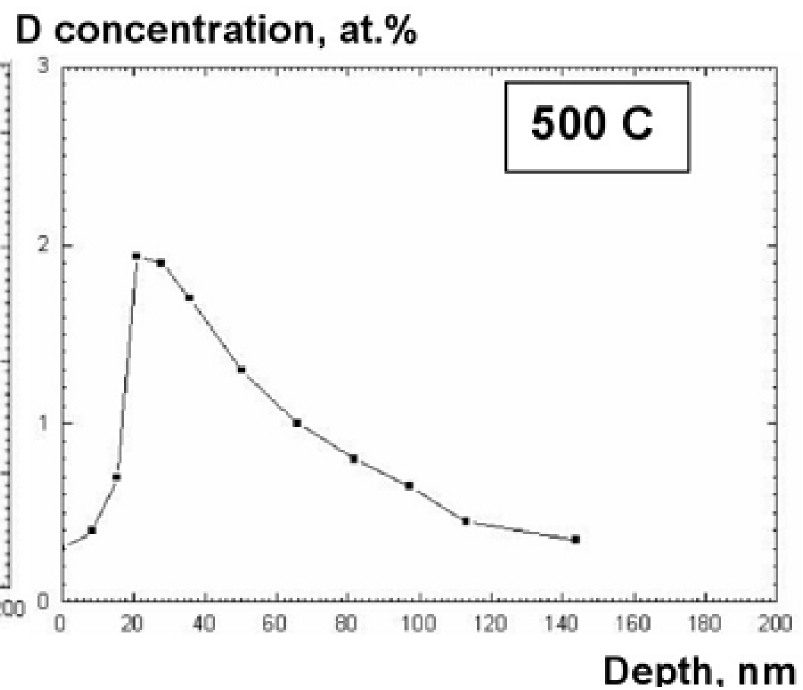




D retention in tungsten after plasma exposure

Deuterium profiles taken by ERDA, $D(^4He,D)^4He$



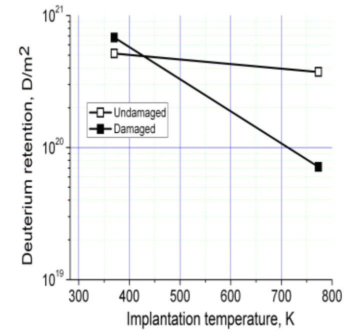


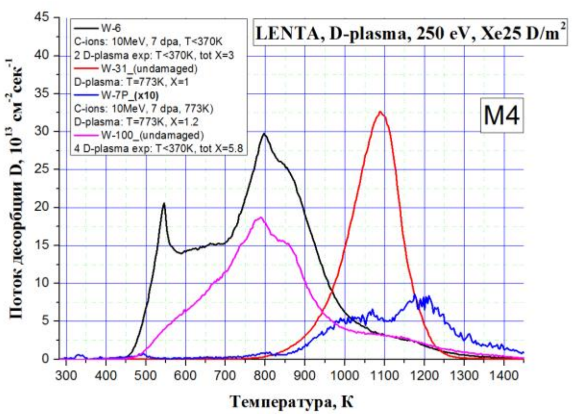
8.7×10^{16} D/cm^2

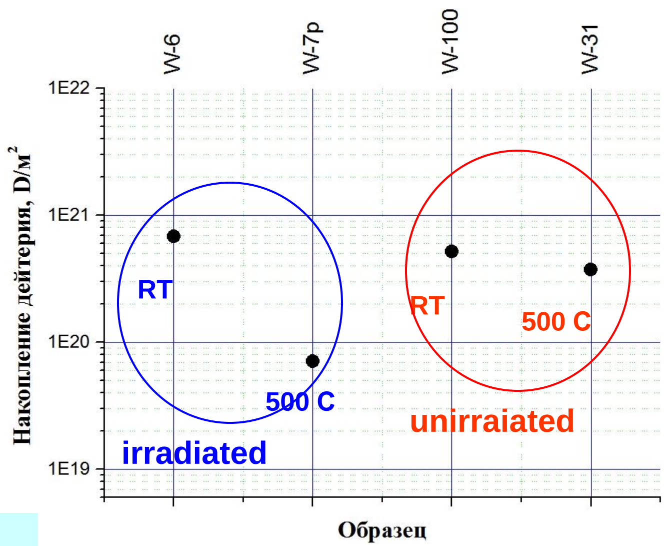
0.8×10^{16} D/cm^2

D retention in tungsten after plasma exposure -TDS

Nr	Ion fluence C^{3+}, cm^{-2}	Primary defects average by 3,5 mcm, dpa	TemperatureТемпература, К	Plasma fluence, D/cm^2	Erosion depth, mcm
W-100	0	0	room<370	$5{,}8\cdot10^{21}$	2,3
W-31	0	0	773	$1\cdot10^{21}$	2,2
W-6	$2\cdot10^{17}$	8,4	room <370	$3{,}0\cdot10^{21}$	1,3
W-7P	$1{,}5\cdot10^{17}$	6,3	773	$1{,}2\cdot10^{21}$	0,8





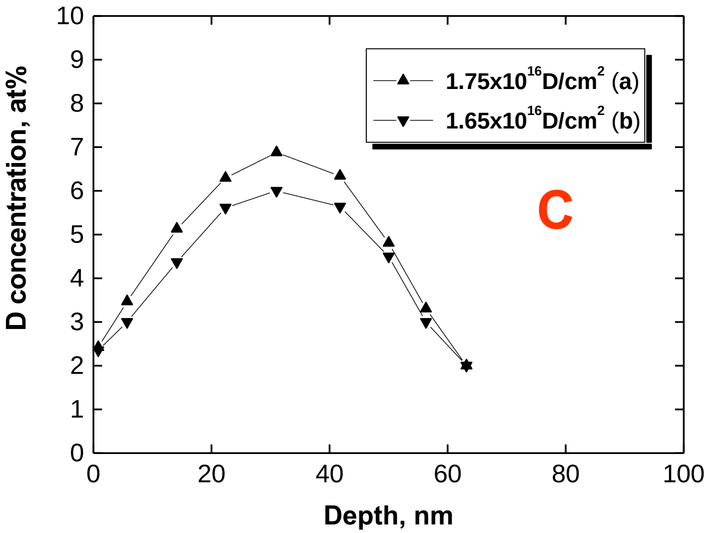


Retained deuterium integral values

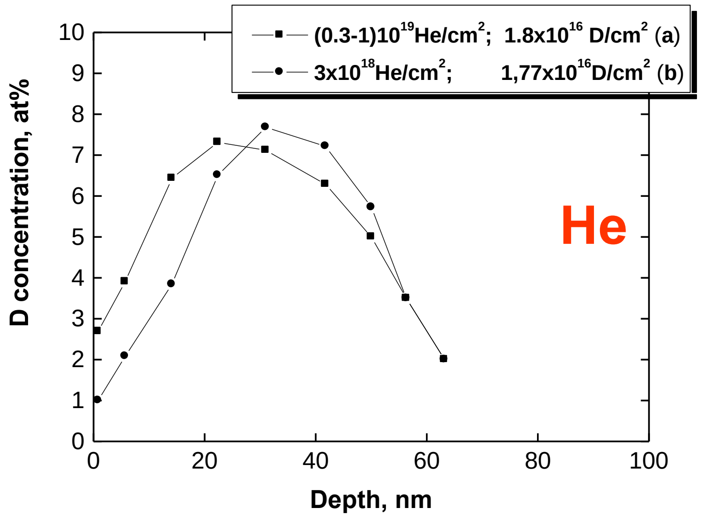
Increased retention in irradiated tungsten
Important decrease in retention at elevated temperature

Deuterium retention in tungsten. Comparison of He- and C-ion irradiations

ERDA, $D(^4He,D)^4He$



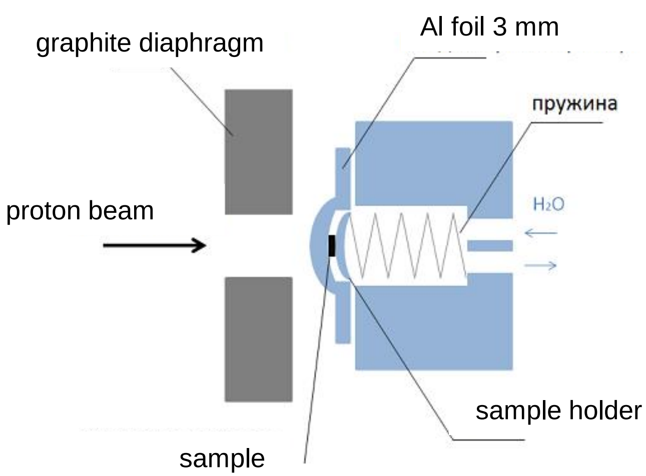
Irradiated tungsten (2×10^{17} C^{3+}/sm^2) after plasma exposure (RT): 2 dpa at the surface;
a) Plasma fluence 1×10^{21} D/cm^2 , erosion 0.5 μm; b) 2×10^{21} D/cm^2, 0.9 μm eroded.

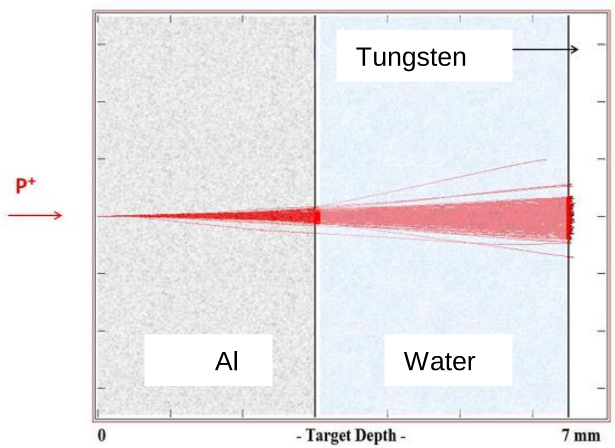


•Deuterium in tungsten damaged by He-ions after plasma exposure (RT): 2 dpa at the surface, a) plasma 2.9×10^{21} D/cm^2, erosion 1.2 μm; b – plasma 1.0×10^{21} D/cm^2, erosion 0.7 μm.

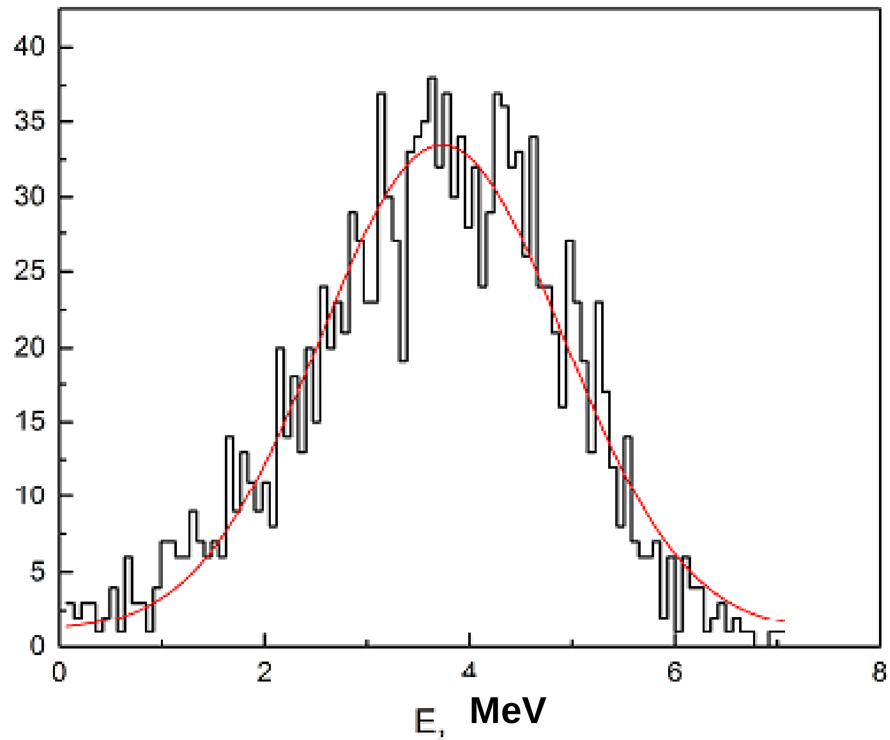
- **Similar D-profiles for different irradiations (He-, C- ions) for equal damage near surface (about 2-3 dpa) after D-plasma exposure**

W PLANSEE irradiation by protons

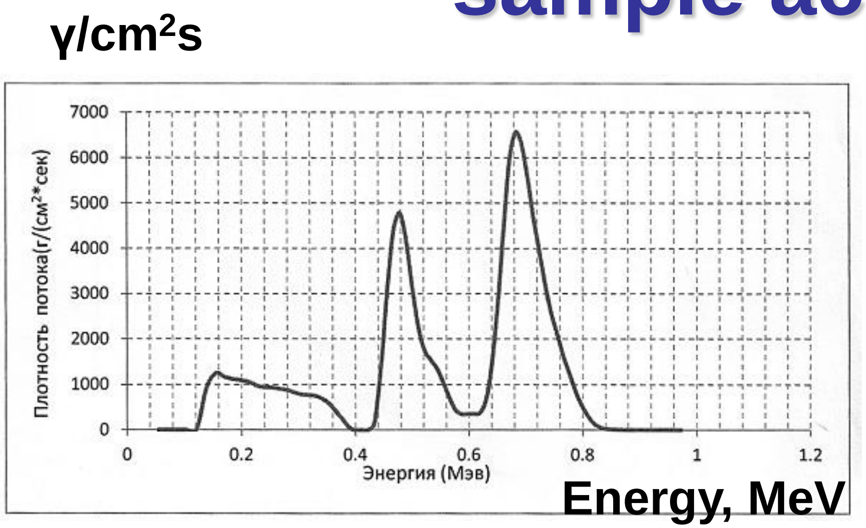


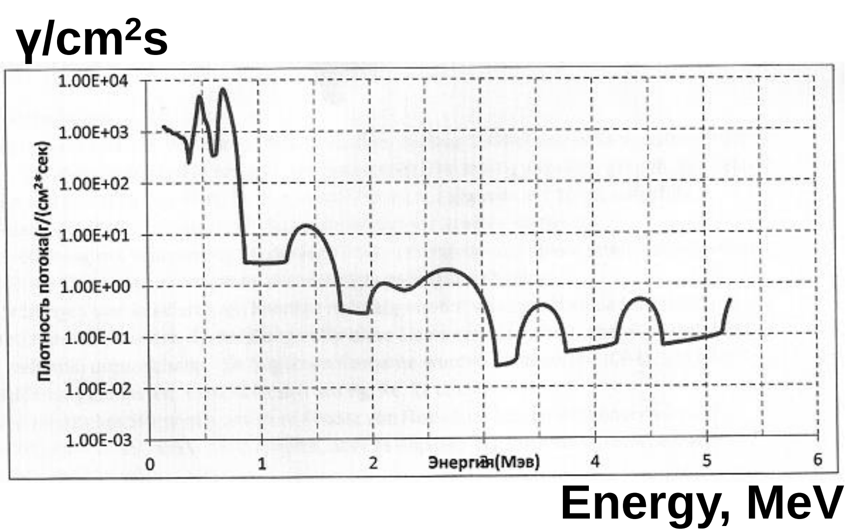


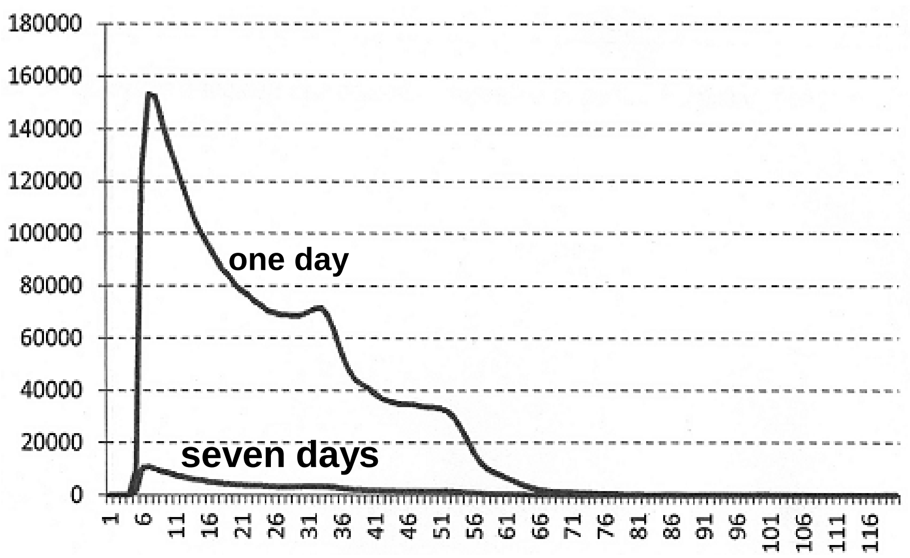
protons



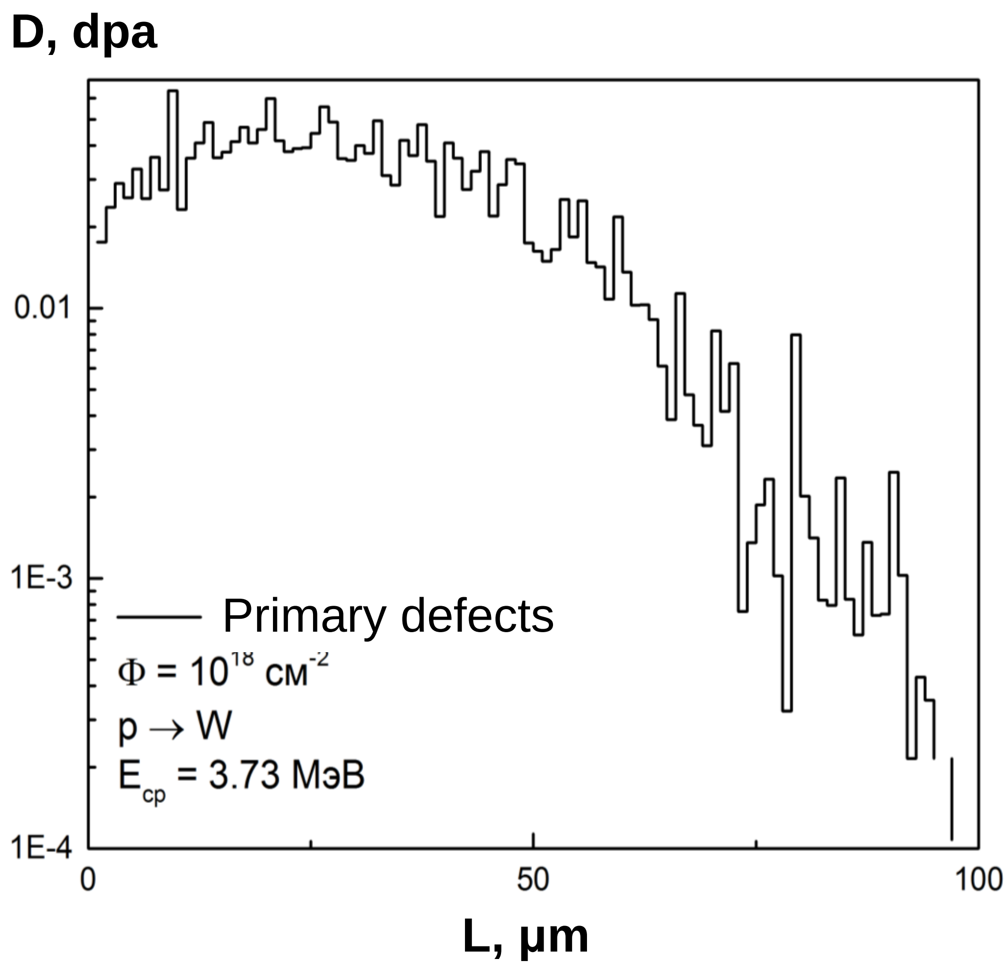
P-irradiated W PLANSEE sample activity detection





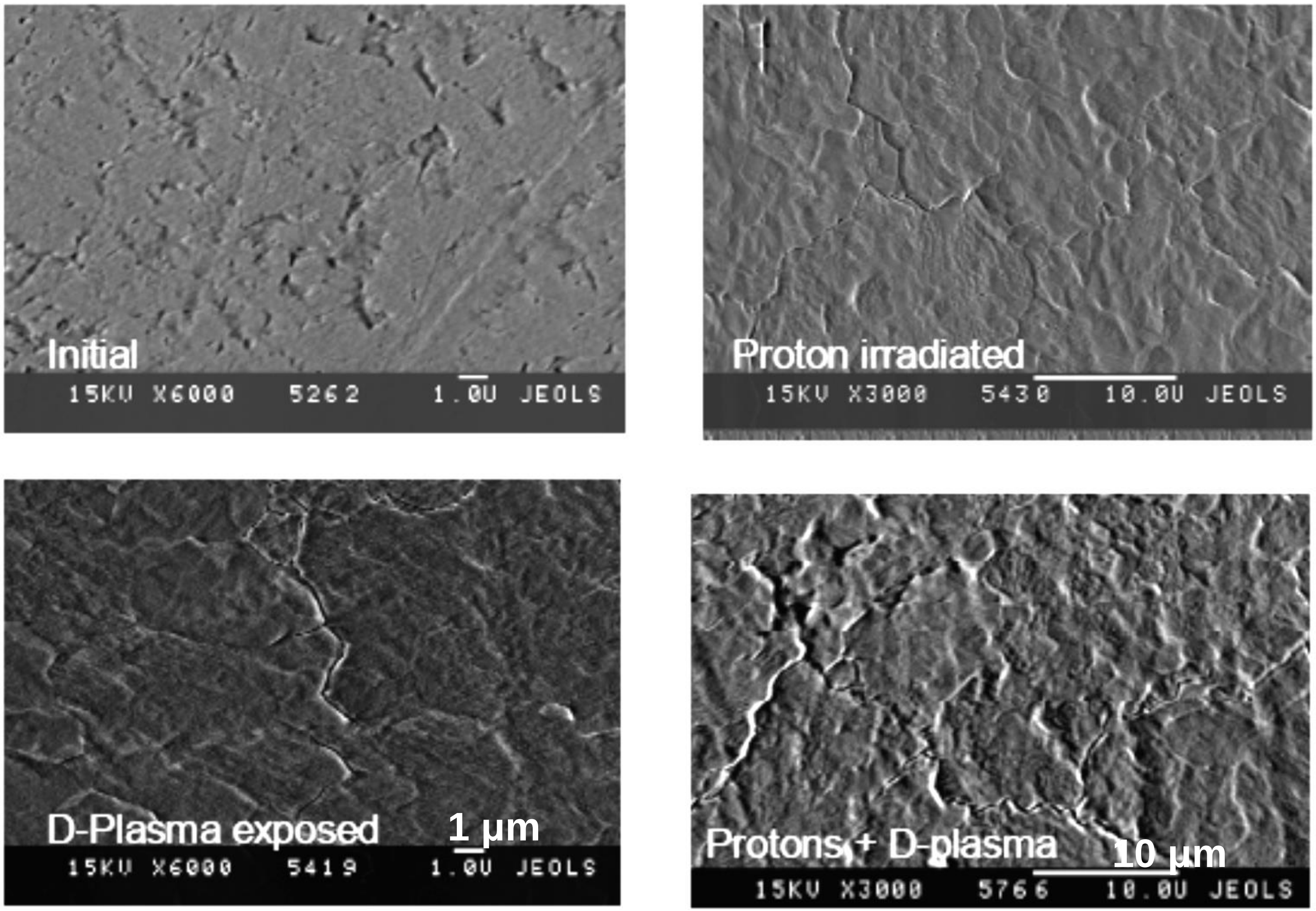


W PLANSEE damage by protons



Method:
Acceleration of protons to 32 MeV needed for maximal beam current generation at the target
Beam slowing down in aluminum and water (sample cooling) layers to average energy 3,7 MeV at the sample surface.

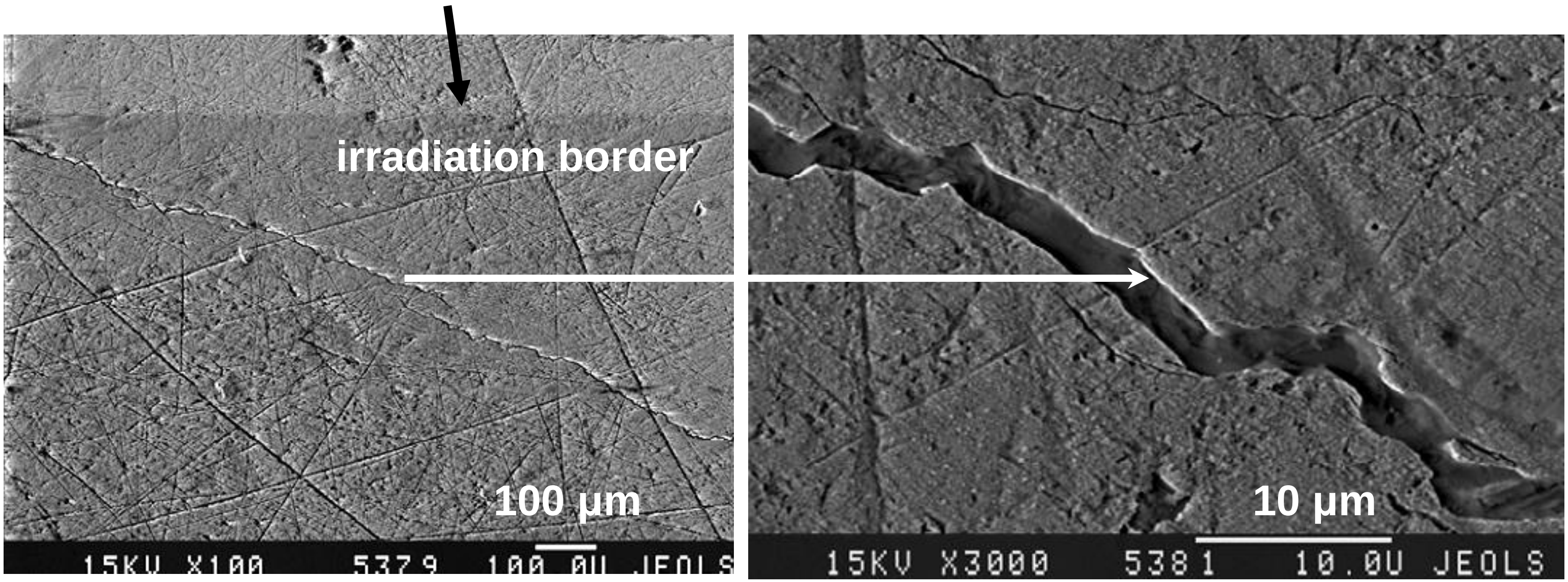
W PLANSEE – surface erosion



Grain boundaries developed

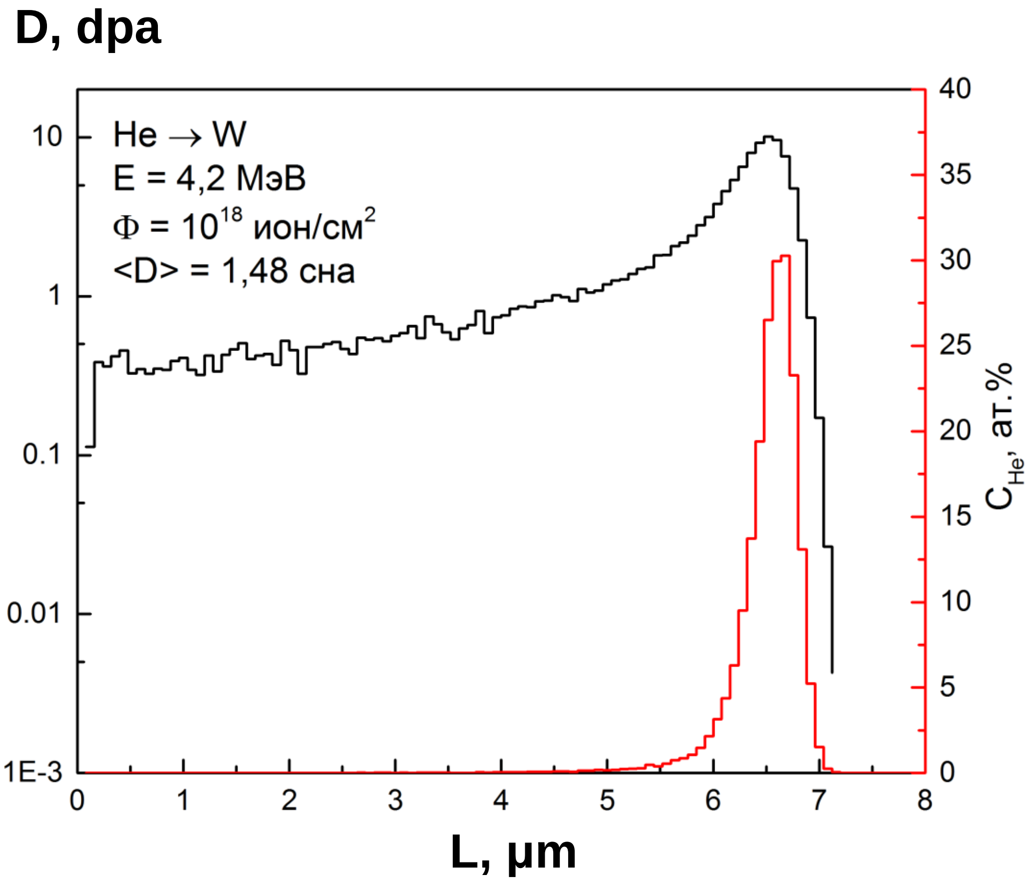
W PLANSEE after irradiation by protons

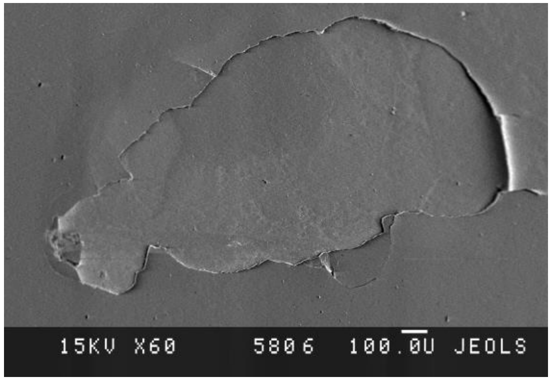
p → W



The surface after irradiation. Crack appeared.

He ions → W PLANSEE



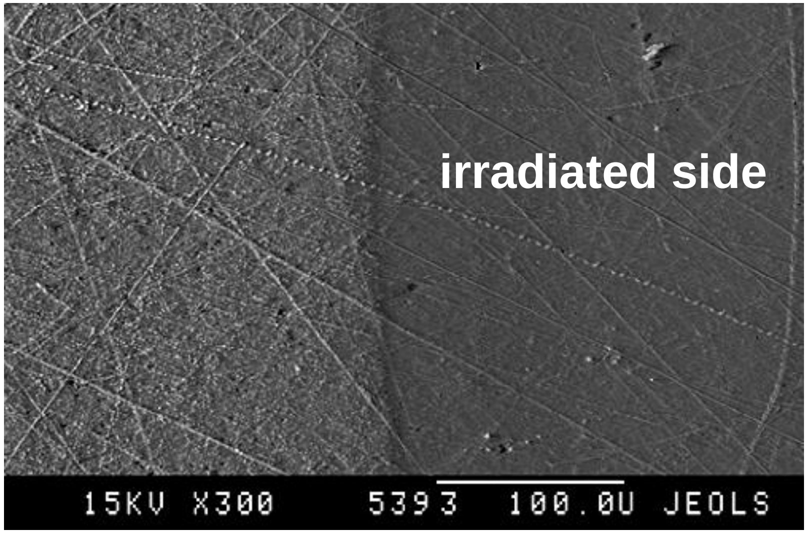


Tungsten surface microstructure after He-ion irradiation (4.2 MeV) to $1{,}5\cdot10^{18}$ ion/cm^2. Flake thickness 6,3±0,6 mcm.

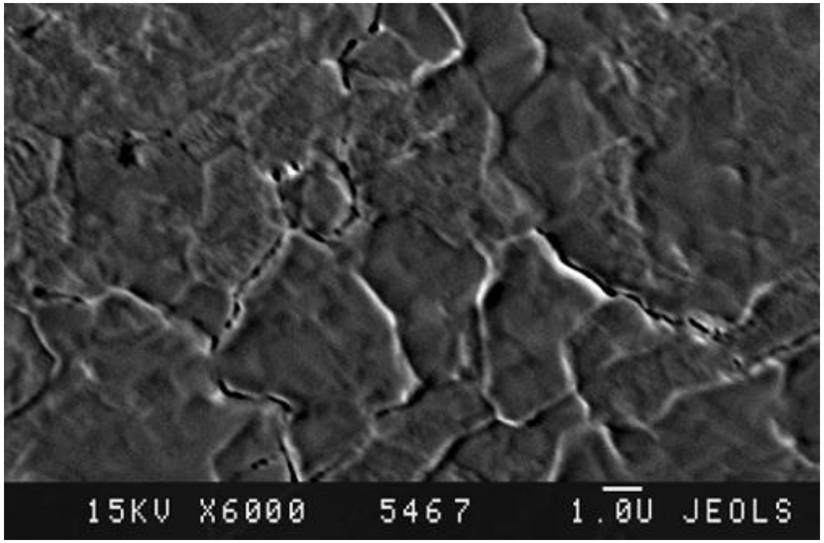
W PLANSEE: He^{+} ions, D-plasma

- Plasma ion energy 250 eV
- Plasma flux $2{,}8 \cdot 10^{17}$ ion/cm^{2}s,
- Deuterium fluence $0{,}8 \cdot 10^{22}$ ion/cm^2,
- Surface temperature < 100 C,
- Exposure time 248 min

Erosion rate 0,7 mg/cm^{2}h.
Erosion yield in D-plasma $Y_{D\text{-}W+}$ = $9 \cdot 10^{-4}$ at/ion



W PLANSEE - the right side area was irradiated by He-ions



Plasma exposed W PLANSEE after He-irradiation

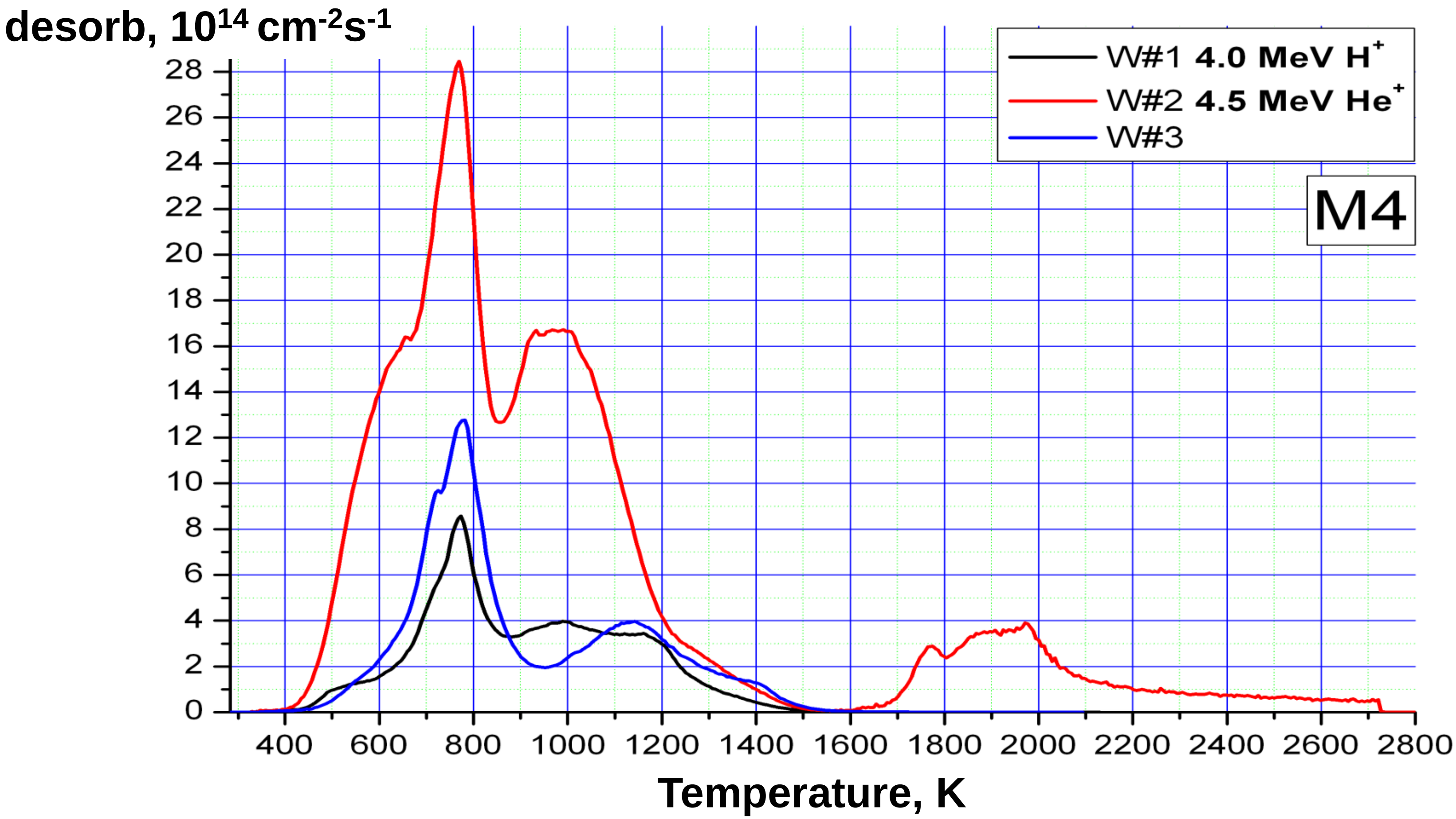
TDS analysis W PLANSEE

D-Plasma exposed samples – Comparison irradiated/non-irradiated

Proton-irradiated (1) black

helium irradiated (2) red

Non-irradiated (3) blue



Summary

- Deuterium plasma impact on tungsten at **high level of radiation damage** has been investigated
- Damage of the material was produced by high-energy ions $^{12}C^{+3}$ (10 MeV), protons (4 MeV) and $^{4}He^{+2}$ (3-4 MeV) from accelerator to simulate neutron effect.
- The level of radiation damage relevant to fusion reactors reached on **tungsten** samples. The primary defects generation obtained experimentally ranged in **1- 60 dpa** interval in the surface layer of **3.5-6 μm** .
- **Swelling** effect observed both on He- and C-irradiated tungsten. at maximal damage. Tungsten showed linear deformation **2-3 % in He-irradiations** and **0.1-2 % in C-irradiations.**
- **Strong microstructure modifications** of tungsten detected after plasma exposure of irradiated material surface – micron-sized structure, cracks, blisters, delamination, bubbles, large cavities with accumulated helium (in case of He-irradiations) in damaged layer.
- Erosion yield of irradiated tungsten evaluated at $Y_{d\text{-}w} \cong (2\text{-}4)\cdot 10^{-3}$ in deuterium steady-state plasma in simulated SOL conditions. **No correlation of** damage and **erosion** rate found so far for ITER relevant levels. Blistering enhances erosion.

- **Deuterium retention** in irradiated tungsten analyzed in plasma-induced erosion dynamic condition at 250 eV of D-ions energy. Deuterium found in the **100-150 nm** layer at different levels of damage from **1.8 to 20 % at**.
- **Increased concentration** of deuterium uptake (**$2 \cdot 10^{17}$ D/cm^2**) in the layer of maximal defect concentration around the He-ions range.
- Implanted **Helium accumulation 8-10% at.** was detected at the depth of ion range as a **2-3 μm wide** peak.
- He- and C-irradiations showed close distributions of the retained deuterium for 2-3 dpa at the surface at room temperature.
- Proton irradiated **W PLANSEE (0.05 dpa)** showed minor difference as to deuterium retention compared to non-irradiated material for low damage.
- The presented approach appears to be efficient in providing data on the behavior of radiation-damaged materials at high level of displacement damage under plasma impact for evaluations of neutron effect on the first wall and tritium retention in a fusion reactor PFMs - temperature, helium effects, impurities.

Thank you for your attention!