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Irradiation Effects in Tungsten-Base Plasma Facing Materials for ITER and Beyond

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Advanced Diagnostics for Burning Plasmas

Introduction

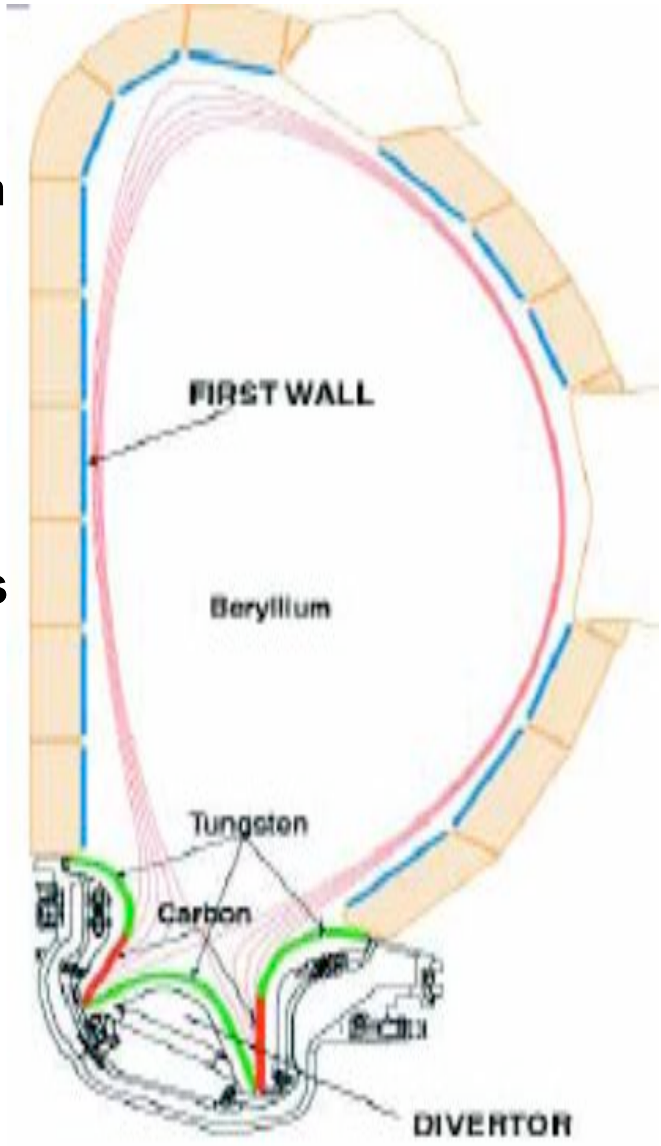
Plasma Facing Materials of ITER for Initial Operation

- **First wall: Be**
- **Divertor: CFC (for very high heat flux areas of th divertor (lower part of the vertical target)**

  W (upper part of the vertical divertor and the dome)

  In future all tungsten divertor (under the discussion)

However, these materials have still critical issues to be overcome before the utilization in ITER.



Critical Issues for W

- **thermo-mechanical stability under high flux pulse heat load such as ELM**

  --- In D-T phase ---

- **effects of neutrons and helium will be added**

Topics of the Present Talk

- **Effects of neutron irradiation in W and W-base alloy**

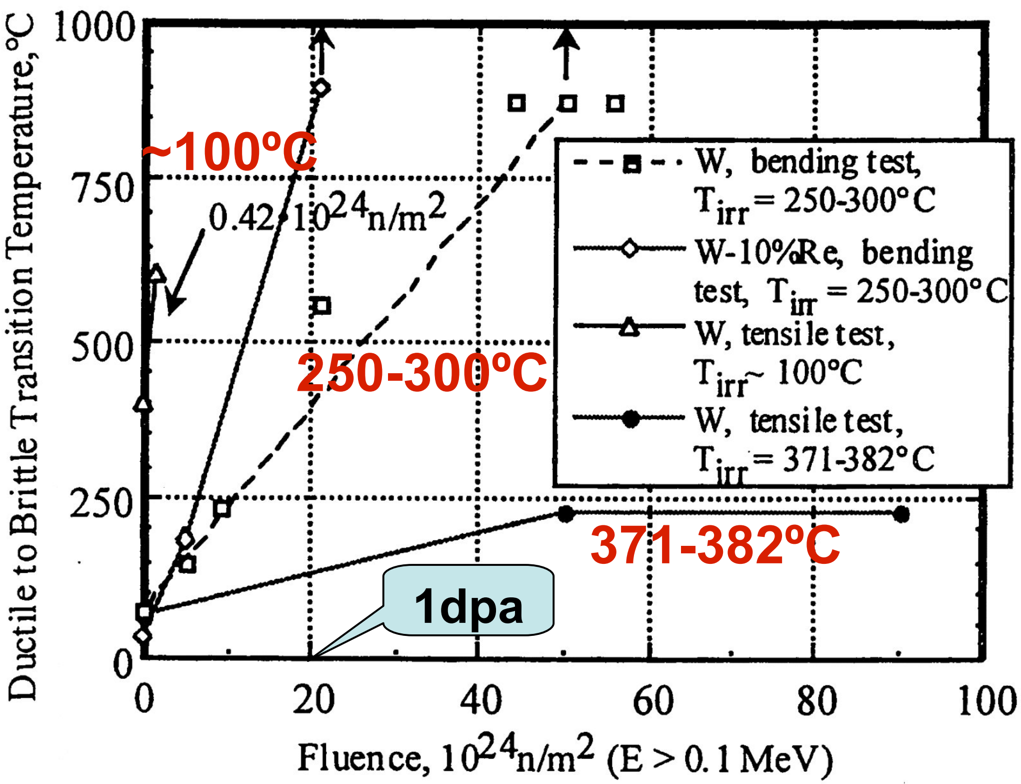
- **Effects of helium plasma irradiation in W**

⇛ ***Necessity of extensive R&D of advanced tungsten alloys with high resistance for neutron- and He-radiation***

Effects of neutron irradiation on W and W-base alloys

Loss of Ductility by Neutron Irradiation

- **N-fluence dependence of DBTT** :rapid increasing of DBTT by n-irradiation at low dose at low temperatures, but not much for high temperatures



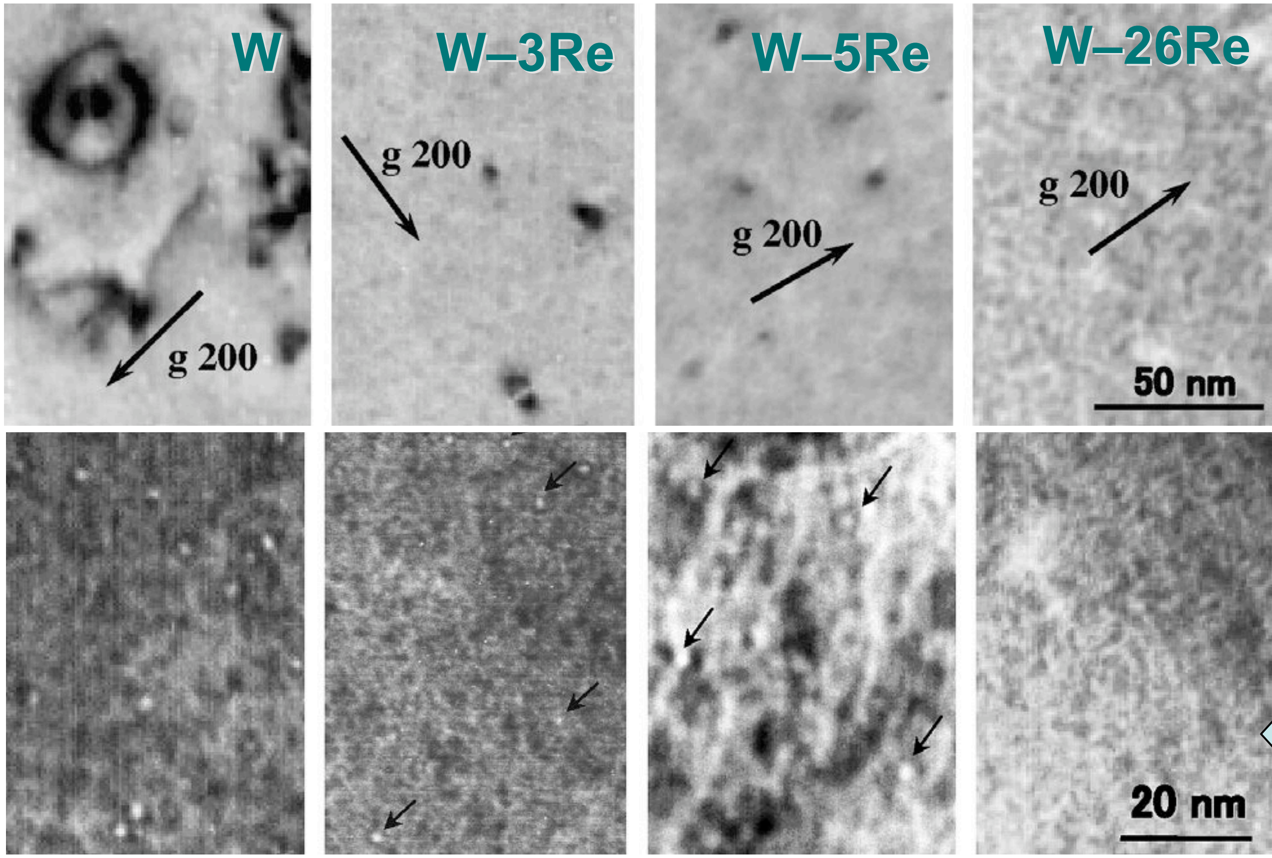
J.W. Davis et al., J. Nucl. Mater. 258-263 (1998) 308

- **Need data of irradiation effects at divertor relevant higher temperatures**
  ➜ExtreMat in EU (W-base alloys, 550-600ºC, 900-950ºC, 3-5dpa)

Microstructure Formation by Neutron-Irr.

Neutron irradiation at 600°C to 0.15 dpa (E_n > 1 MeV)

J.C. He, A. Hasegawa, K. Abe, J. Nucl. Mater. (2008) in press



Interstitial loops in W, W-3Re and W-5Re

Voids in W, W-3Re and W-5Re

- Dislocation loops and voids cause hardening, especially in W.
- No serious effects on mechanical properties at low dpa.
- Synergistic effects with plasma particles diffusing from the surface should be examined.

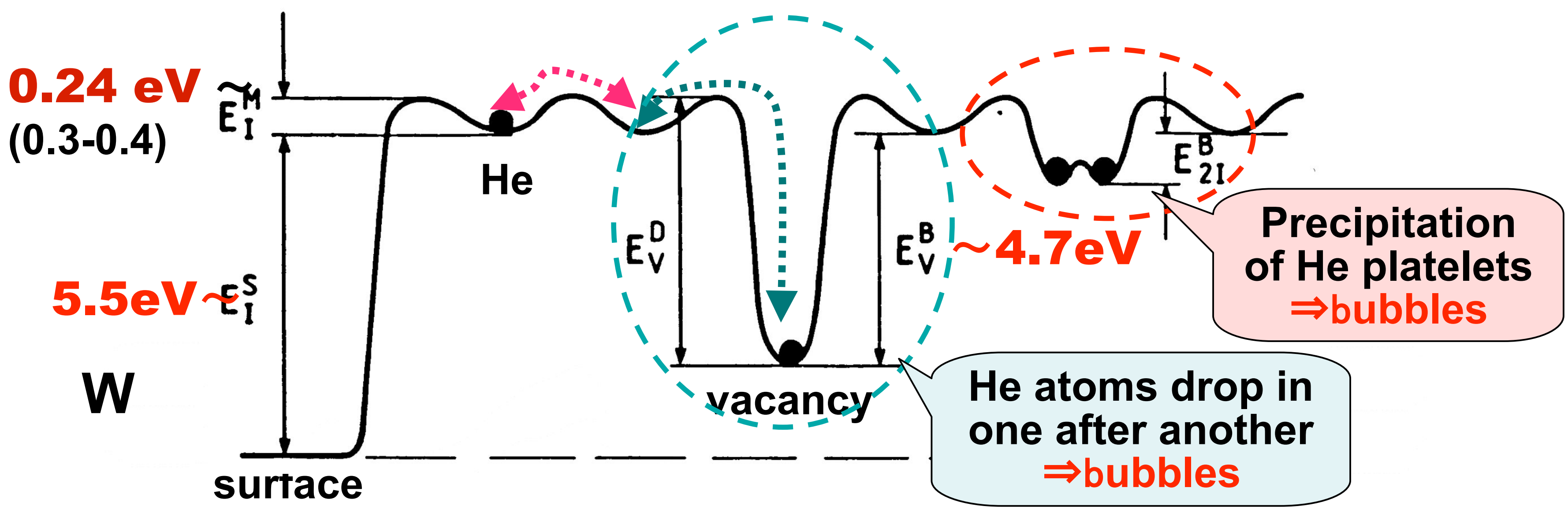
Effects of helium plasma irradiation in W

1. Structure

Basic Behavior of He in W

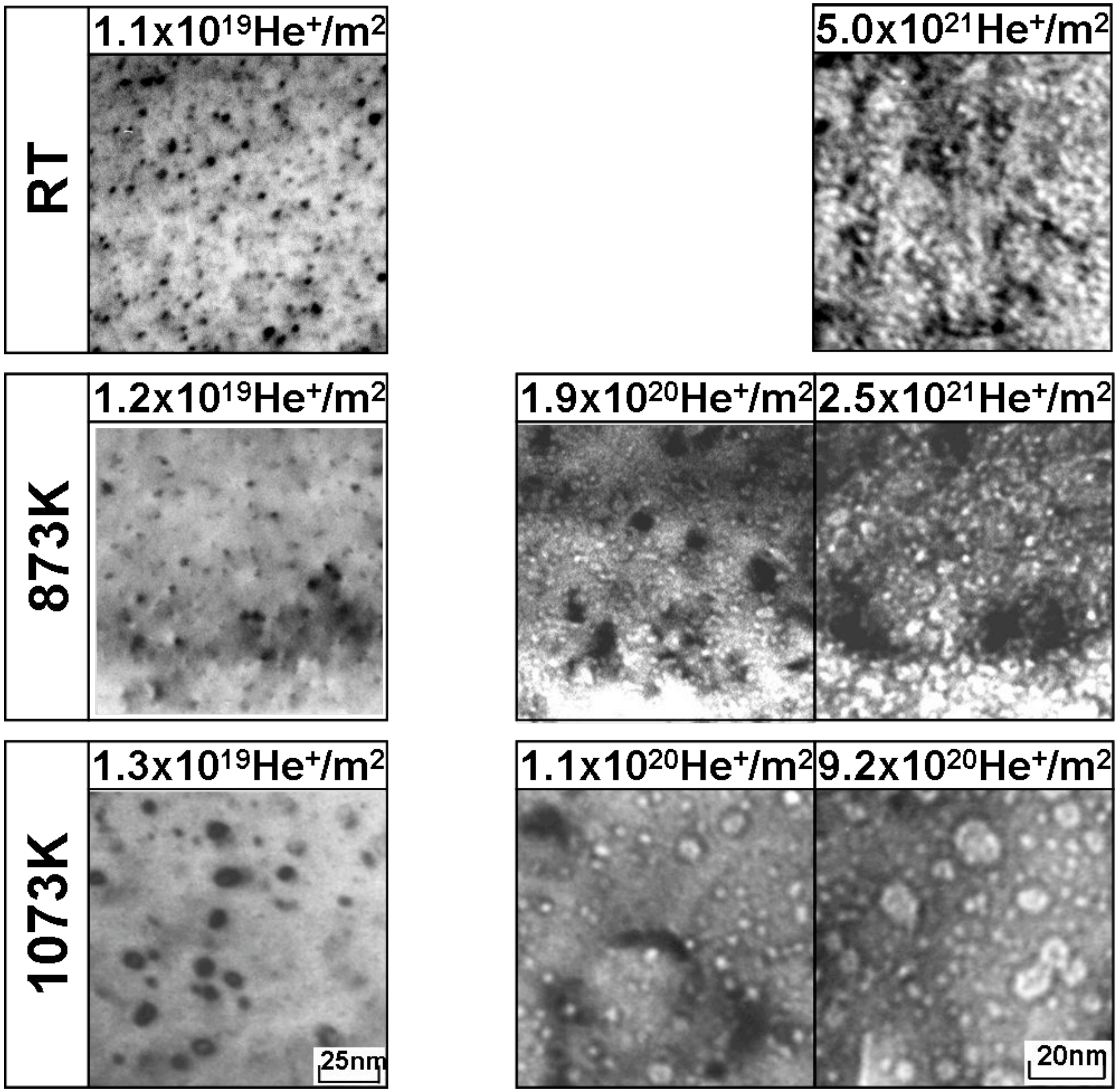
- Very low solubility.
- Very fast thermal migration via interstitial sites (very high mobility even at R. Temp.)
- Very deep trapping in a vacancy (Large E_V^B)
- Comfortable positions of He in W lattice:

  empty sites such as vacancy, bubble, grain boundaries, dislocations etc. ⇐ *closed electron shell structure*
- He enhances the formation of voids (bubbles) and dislocation loops even above 1000ºC ➔hardening, embitterment
- He atoms can aggregate by themselves ➔ He atoms can form clusters once get in the lattice ($E>E^S_I$) ➔ no need displacement damage



Formation of Defects by sub-E_d He^+ Irr.

0.25keV-He^+ ➜ W@ R. Temp. , 873K, 1073K

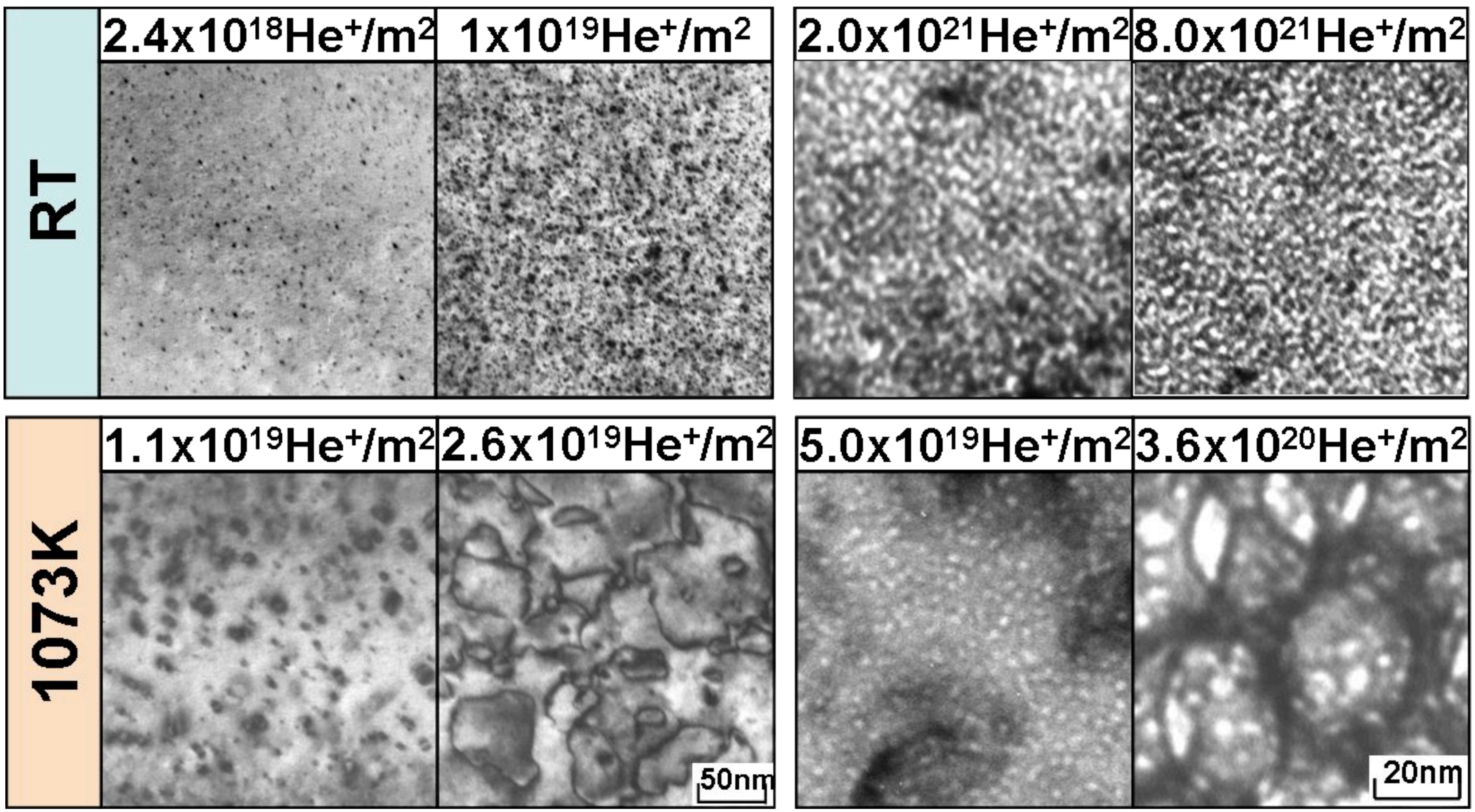


- Radiation induced defects are formed at very wide temperature range.
- He platelets and dislocation loop at low dose.
- He bubbles become visible at high dose.
- Growth of bubbles is remarkable at 1073K.

Damage by He^+ Causing Displacement

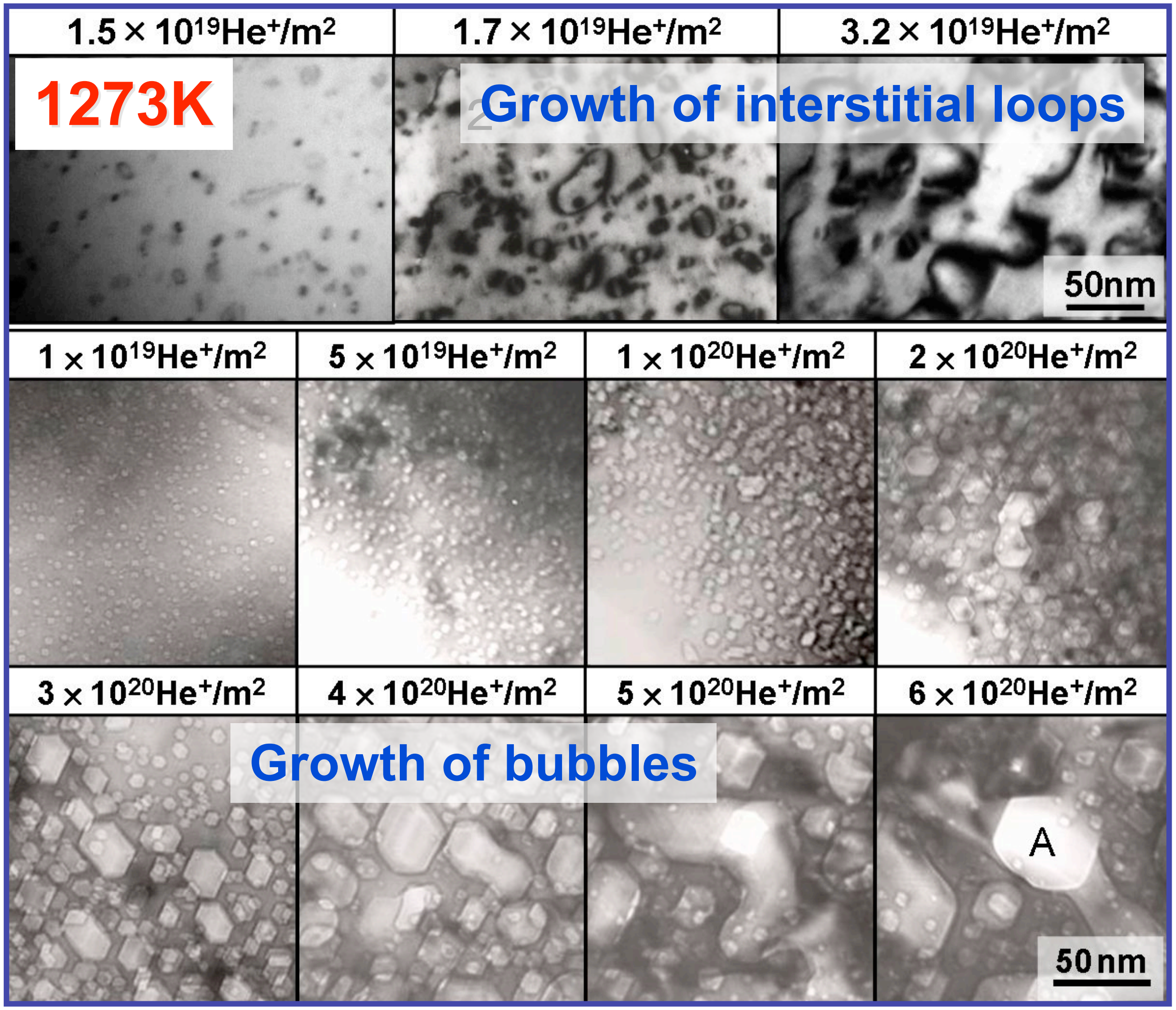
8keV He^+ ➜ W @ R.T., 873K, 1073K

- Dense dislocation loops even at 1073K ←pinning effects of He
- Very Dense fine He bubbles (sponge structure).

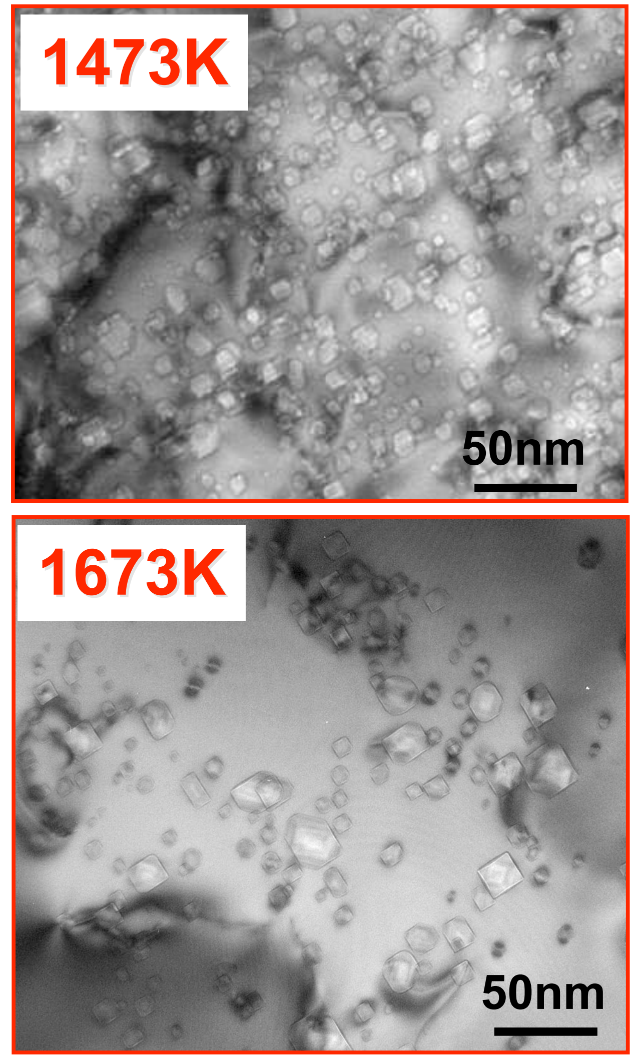


Damage at High Temperature (8keV-He^+)

8keV-He^+ ➜ W



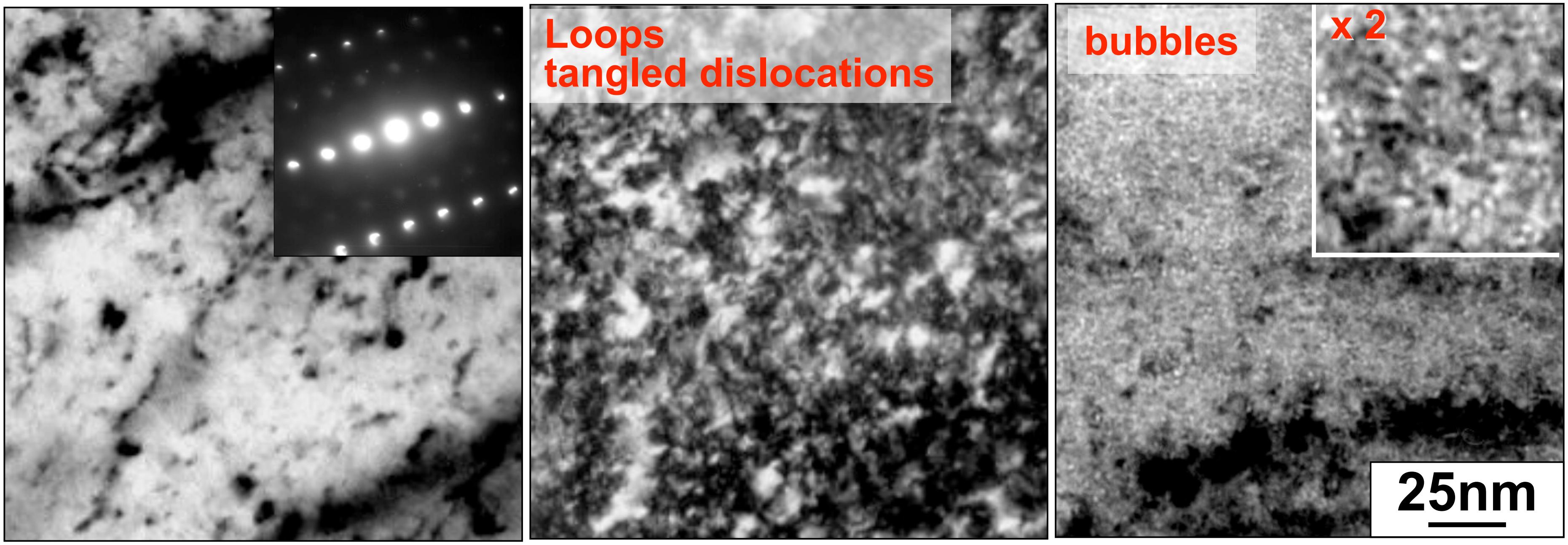
5keV-He^+, $1x10^{21}He^+/m^2$



Damage by He Plasma at Wall in LHD

W at wall eq. position @R. Temp, discharge time=75s

BF image (s~0)	DF image	BF image (s>>0)

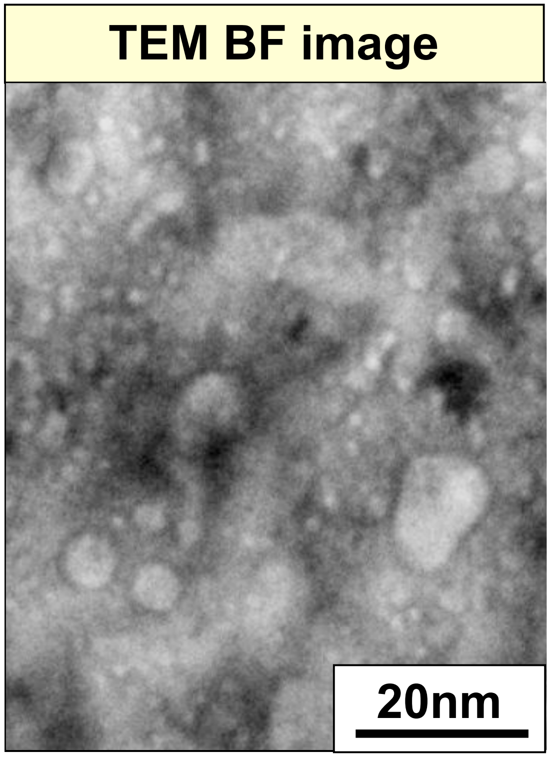


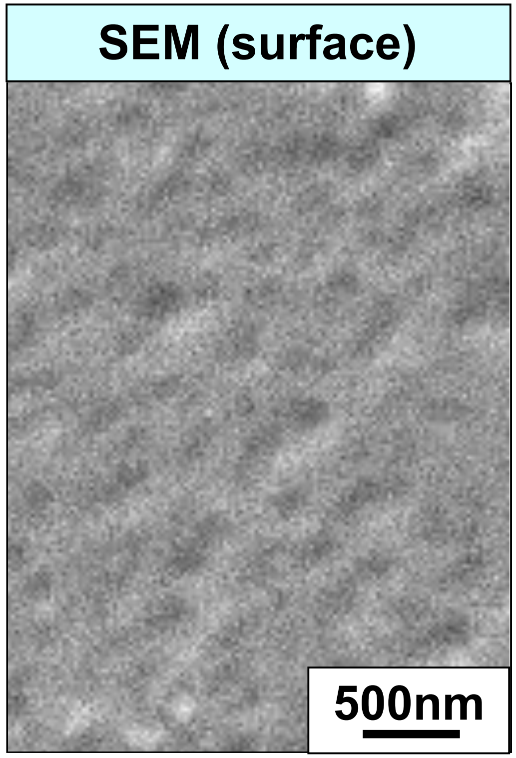
- Typical damage by He irradiation
- Damage by charge exchange He neutral
- Damage structure, depth distribution of He

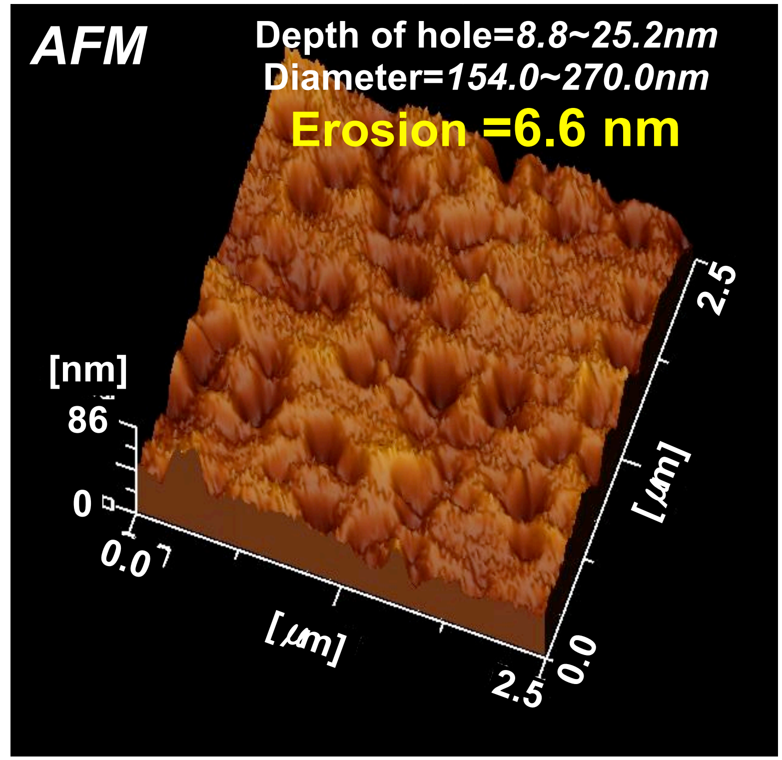
➔Energy~1keV, flux~$1x10^{19}He^0/m^2s$

Damage by He Plasma at Divertor in LHD

W (about 9mm away from the strike point), only one shot for ~1s





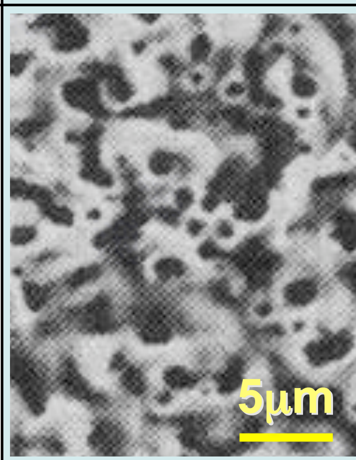
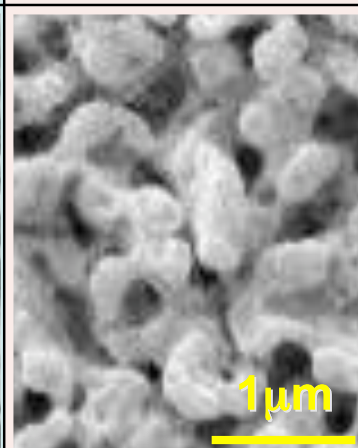
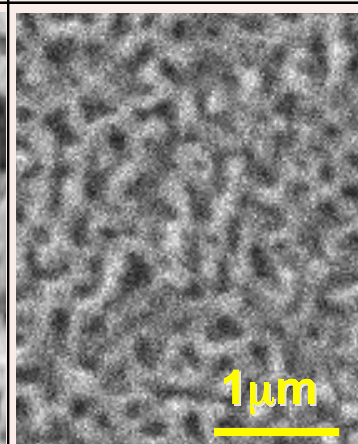
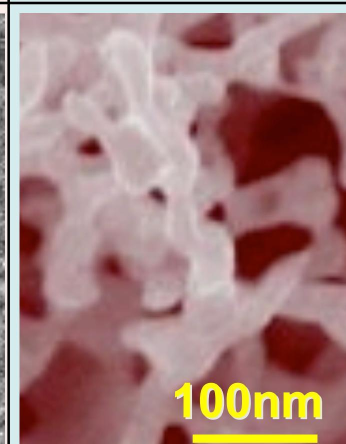


- **Serious He irradiation damage**
- **Large spherical bubbles ➜ abrupt temperature increase above 1273K ➜*synergistic effects of He irradiation and high flux heat load***
- **Erosion by blistering =6.5nm**

Fine Projections at Elevated Temp.

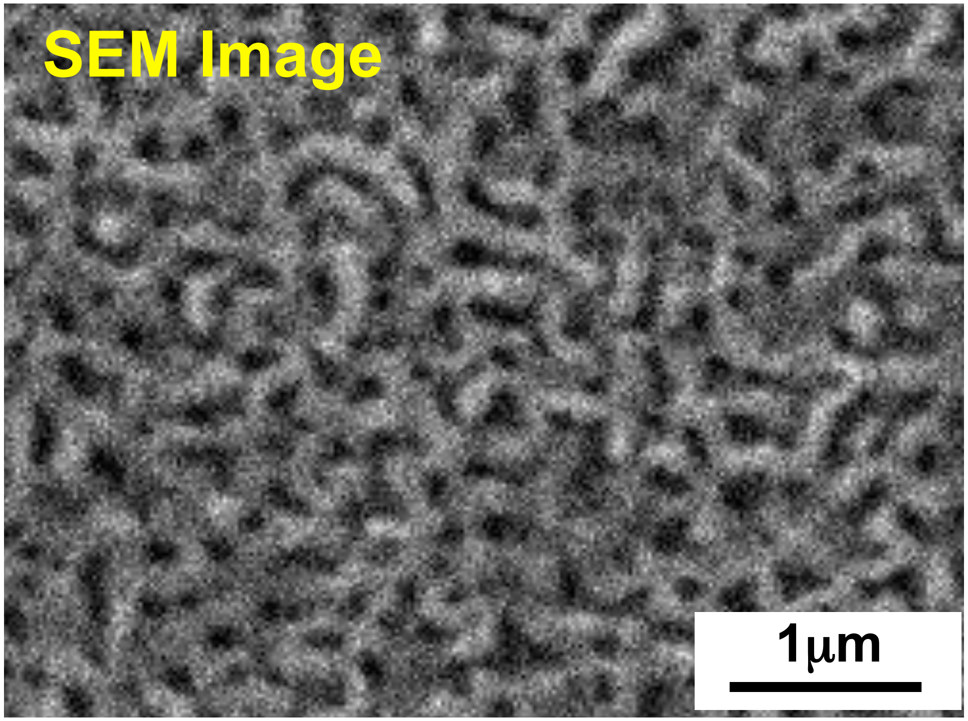
Irradiated surface is covered by meso-scale projections at wide irradiation conditions

He ion energy ≥ ~10eV, temperature ≥ ~900ºC

Material (ref)	PM-W [1]	PM-W [2]	PM-W [3]	VPS-W [4]
Irr. Temp.	2600K	RT →2873K	1273K	1600 K
Ion Energy	90eV	18.7keV	8keV	~10eV
Fluence (He$^+$/m^2)	$1.0x10^{26}$ (continuous)	$3.3x10^{23}$ (3.5s pulse)	$1.5x10^{22}$ (continuous)	$4x10^{27}$ (continuous)
Surface Morphology				

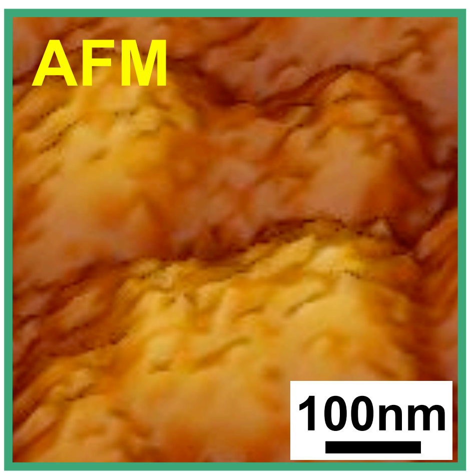
(1) M.Y. Ye et al., J. Nucl. Mater. 241-243 (1997) 1243., (2)K. Tokunaga et al., J. Nucl. Mater. 329-333 (2004) 757., (3)T. Baba et al., Mater. Trans. 46 (2005) 565., (4) S. Kajita et al., Nucl. Fusion 47(2007) 1358.

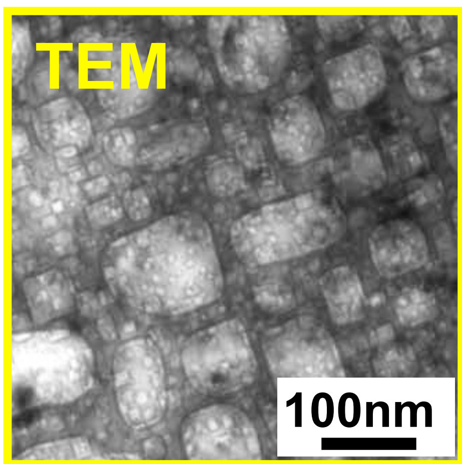
Surface Morphology of He Irr. W

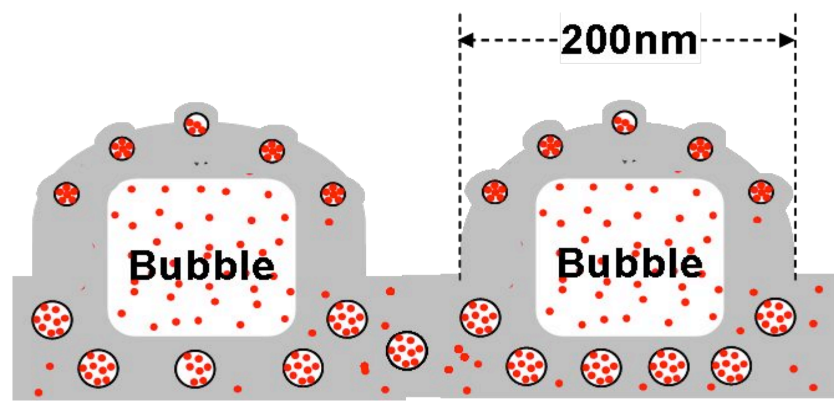


Sample : PM-W
Ion energy : 8 keV
flux : $1.5x10^{22}He^+/m^2$
Irradiation temp. : 1273 K

- Large bubbles cause local blisters at the surface
  ➜surface roughing
- Holes are also formed.





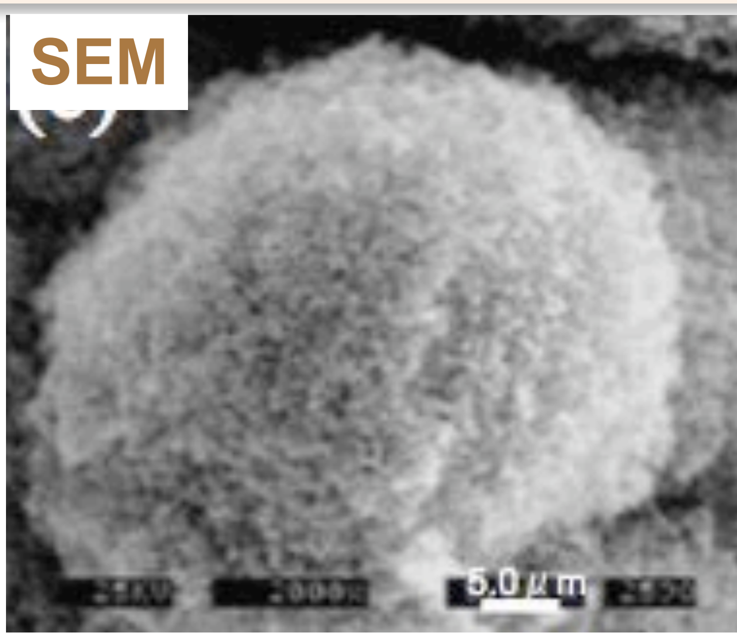


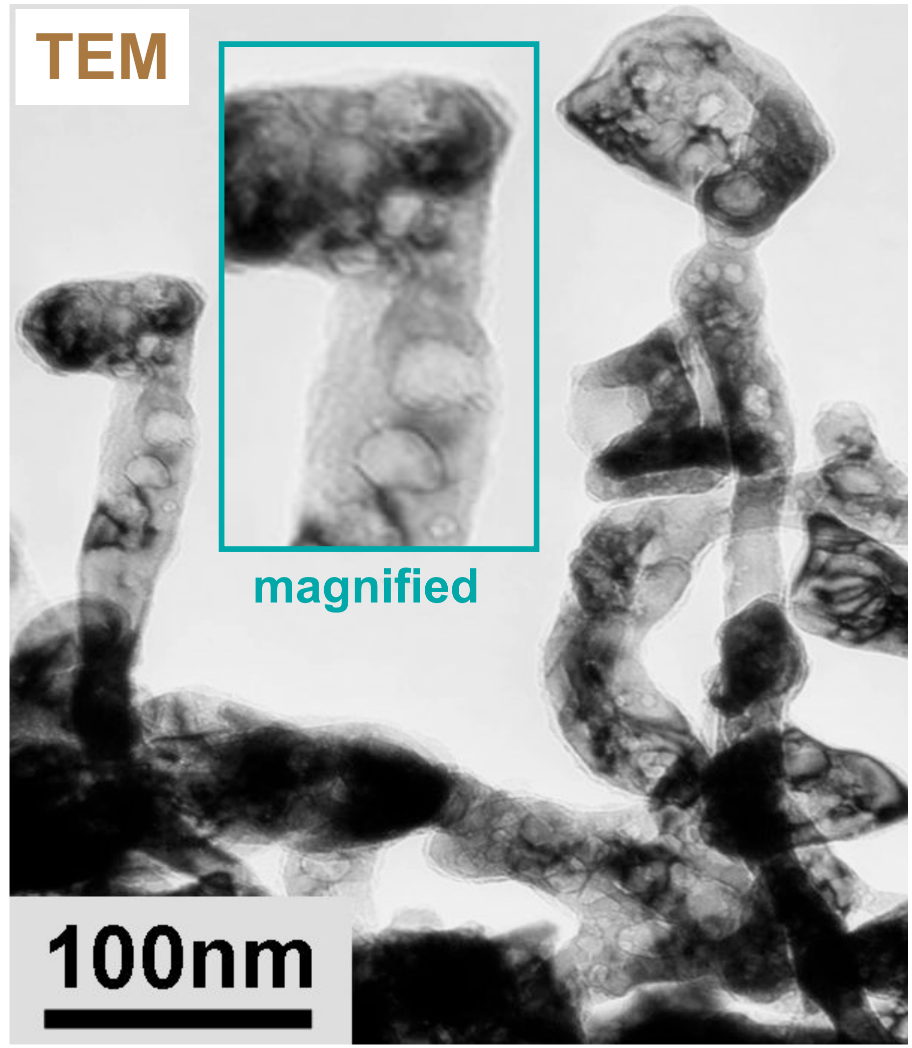
He Bubbles by He Plasma Bombardment

11.3eV-He^+ ➜ VPS-W@1250K, $3.5\times10^{27} He^+/m^2$

S. Kajita et al., Nucl. Fusion 47(2007) 1358.

- Simulation of W Divertor
- Meso-scale objections with hollow structure like bamboo shouting (He-bubbles inside)
- This causes serious reduction of heat load resistance, dusts formation, etc.!





Formation Processes of Meso-Scale Projections under He^+ Irradiation

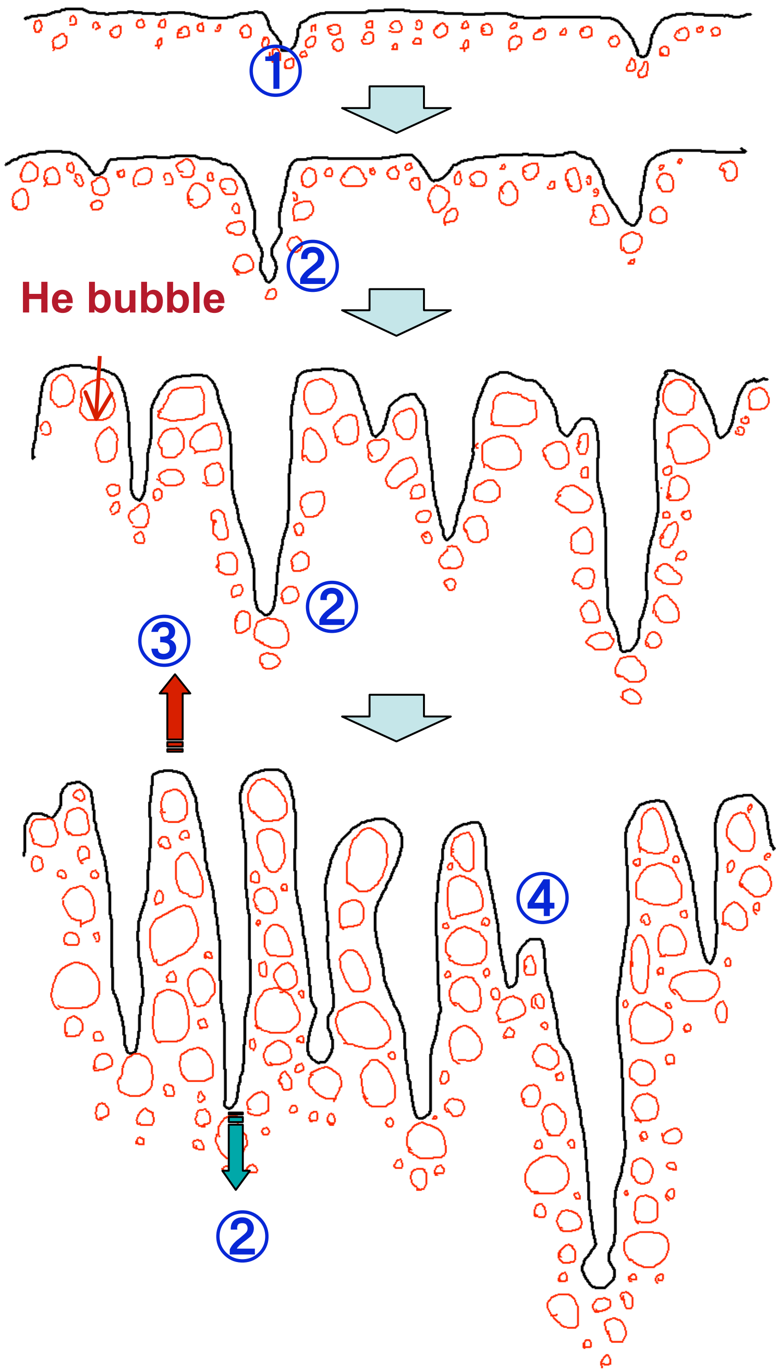
Low Energy Case

①Initiation of grooving by the movement of He bubbles to the surface.

②Deepening of the grooves by absorbing bubbles formed nearby.

③Elongation by the crowded bubbles inside (swelling by He bubbles).

④Blanching.

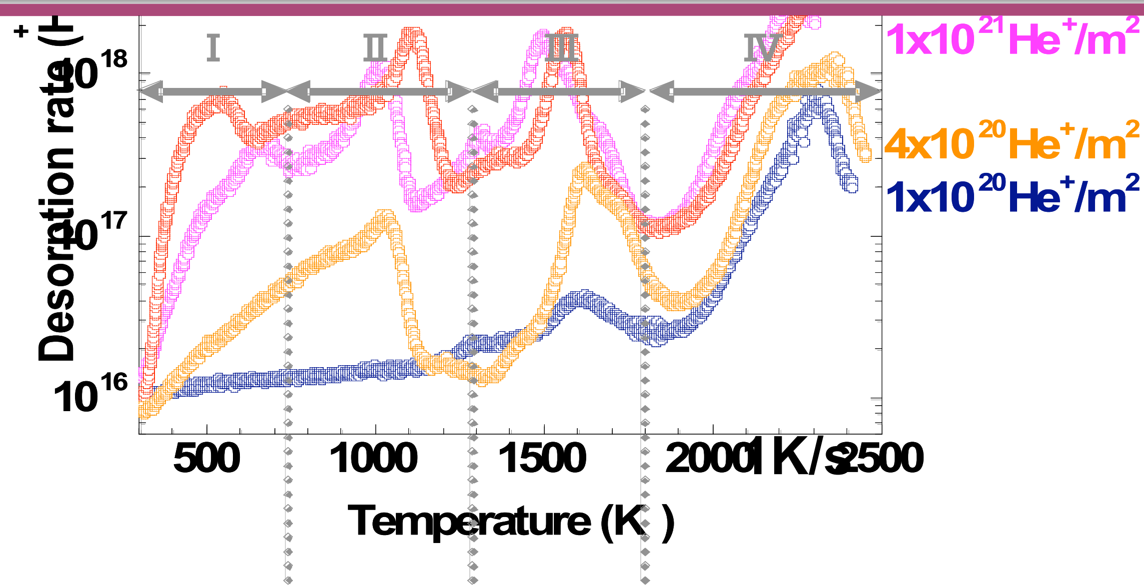


Conditions for Projection Formation

Low Temp Limit

- Bubbles should be mobile and enough vacancies should be supplied:

  $T_{pf} > 1100K$



High Temp. Limit

- Nucleation rate of bubbles should be reasonably high

  strongly depends on He beam flux and microstructure (dislocations, grain boundaries)

- He atoms should stay in the bubbles

  $T_{pf} <$ latter half of stage IV (2500K?)

Possible Formation Temperature T_{pf} for W

$1100K < T_{pf} < 2500K$

How to Reduce Projection Formation

1. ***Reduction of bubbles mobility (increase of T_{III})***

Diffusion Coefficient of Bubbles

$$D_b = D_s(3\grave{U}^{4/3})/(2\partial r^4)$$

Ω: atomic volume
r : bubble radius
D_s: coefficient of surface diffusion

➜ reduction of surface diffusion coef. D_s ➜ alloying

2. ***Reduction of E_{IS} (decrease of T_{IV})*** ➜ alloying

3. ***Reduction of thermal vacancy supply*** ➜ Reduction of effective mobility and increase of formation energy of vacancies ➜ addition of miner elements

There are some possibilities to satisfied the above conditions for reduction of projection formation.

Effects of helium plasma irradiation in W

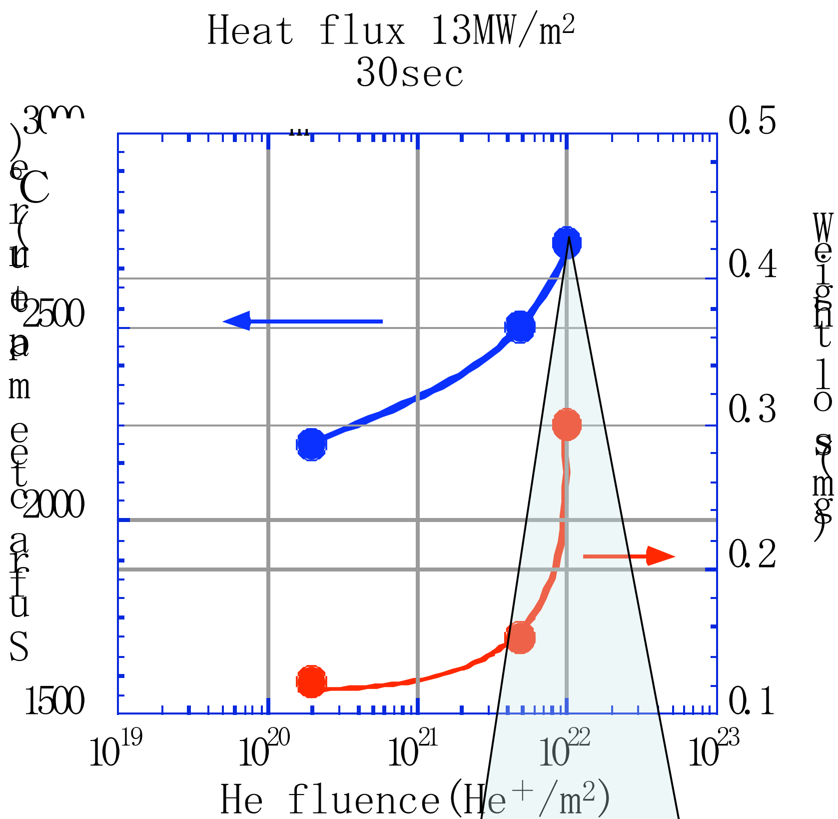
2. Synergistic effects with heat load

Influence on Thermal-Shock Resistance

K. Tokunaga et al., J. Nucl. Mater. 307-311(2002) 130-134

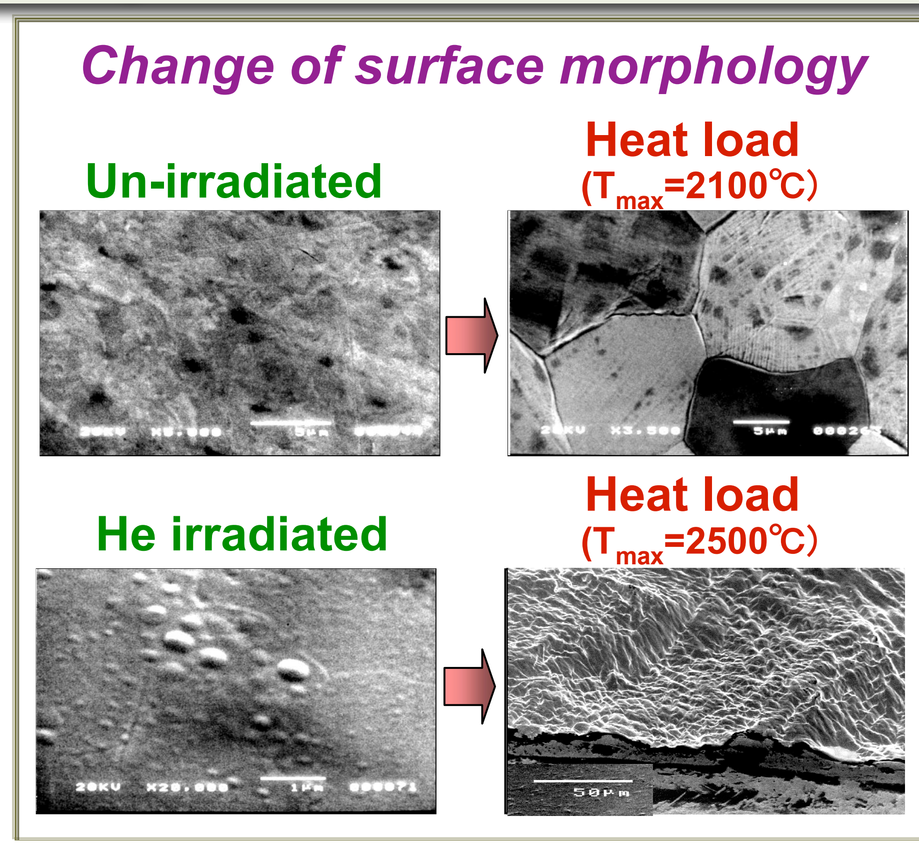
He Pre-irradiation: 8keV-He^+ ➔W@R. Temp,, $5x10^{21}He/m^2$

Heat load (electron beam); 13 MW/m^2, 30s



Erosion= 0.8 μm
(10 times thicker than the He ion projection range)

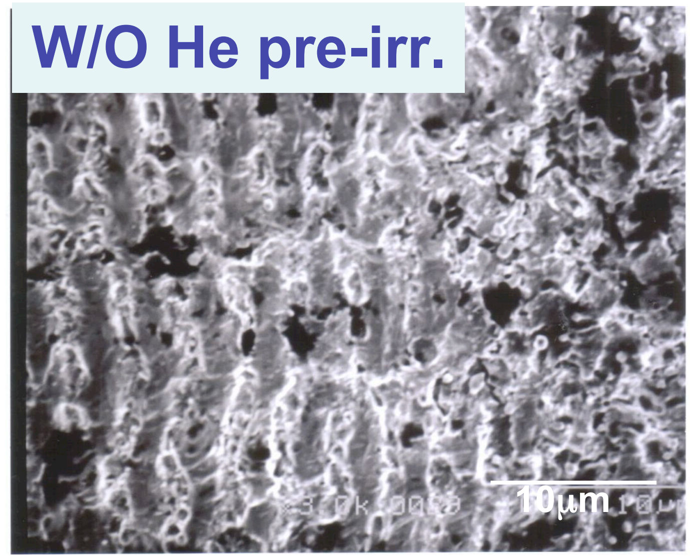
Formation of He bubbles layer ➔ weaken thermal-shock resistance ➔larger erosion

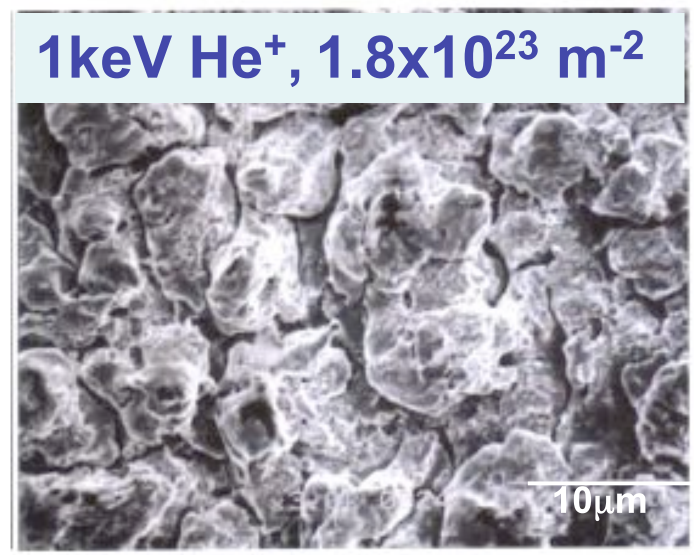


Influence of Short Pulse Heat Load on He Irradiated PM-W

Y. Ueda et al. (Osaka U.)

- <u>He Pre-Irradiation</u>
  - 1 keV, $1.8x10^{23}$ m^{-2}
  - Irr. Temp.：773K
- <u>Laser Irradiation</u>
  - Q-SW mode：50 MW/cm^2 （0.5 J/cm^2）, 10ns
  - Base Temp.：773K
  - Max. Surface Temp. (cal.)：~1673K
- <u>He Irradiated W</u>
  - Very strong grooving and cracking along grain boundaries.
  - It is likely that He accumulated along GB's weaken them.
  - Deep penetration of He along GB.



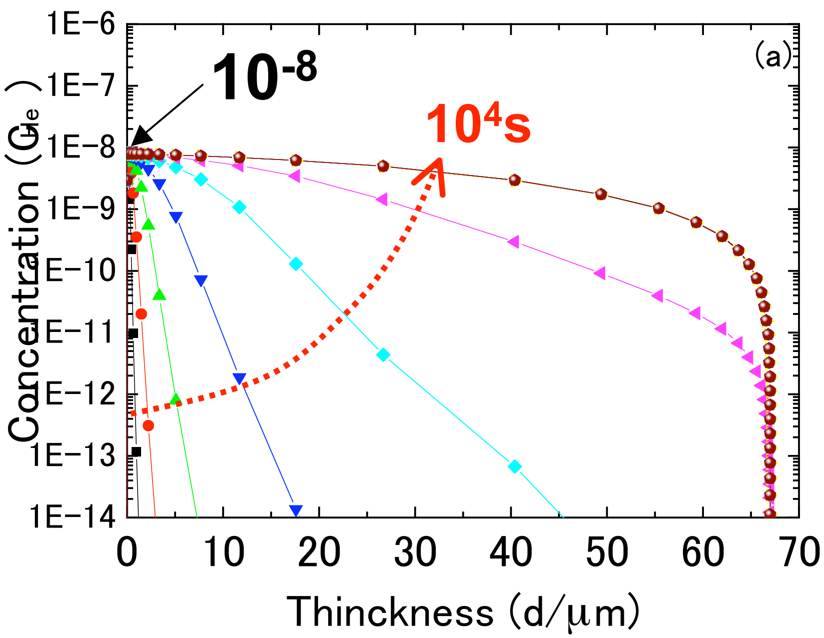


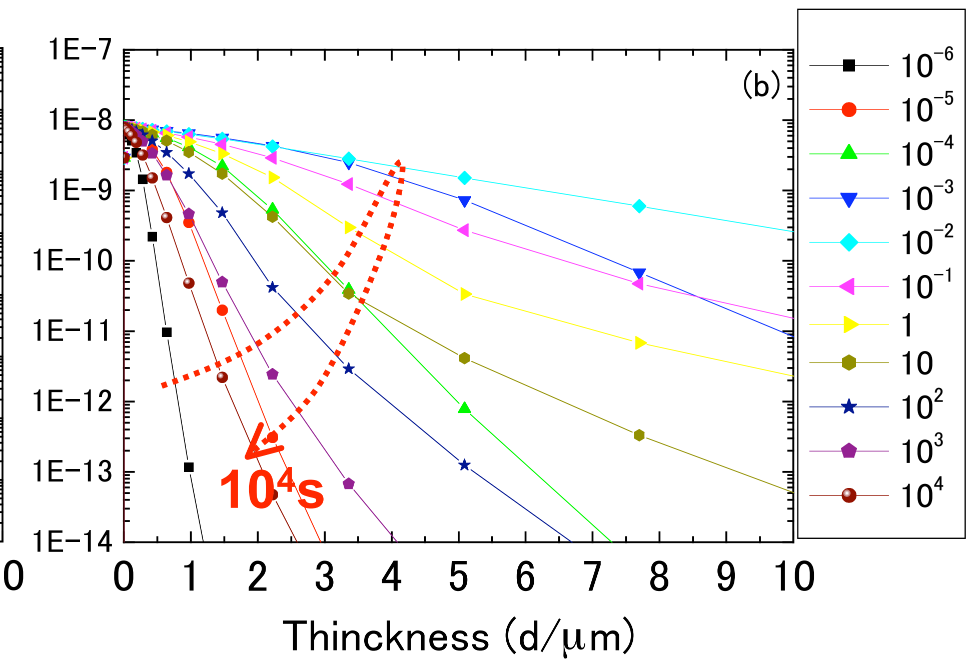
Synergistic Effects of Neutron Irradiation and He plasma Bombardment

Depth Distribution of Free He under Irradiation ($t \leq 10^4$sec) calculated by using rate theory

30eV-He$^+$(10^{22}He$^+$/m^{2}s) ⇛ W@873K

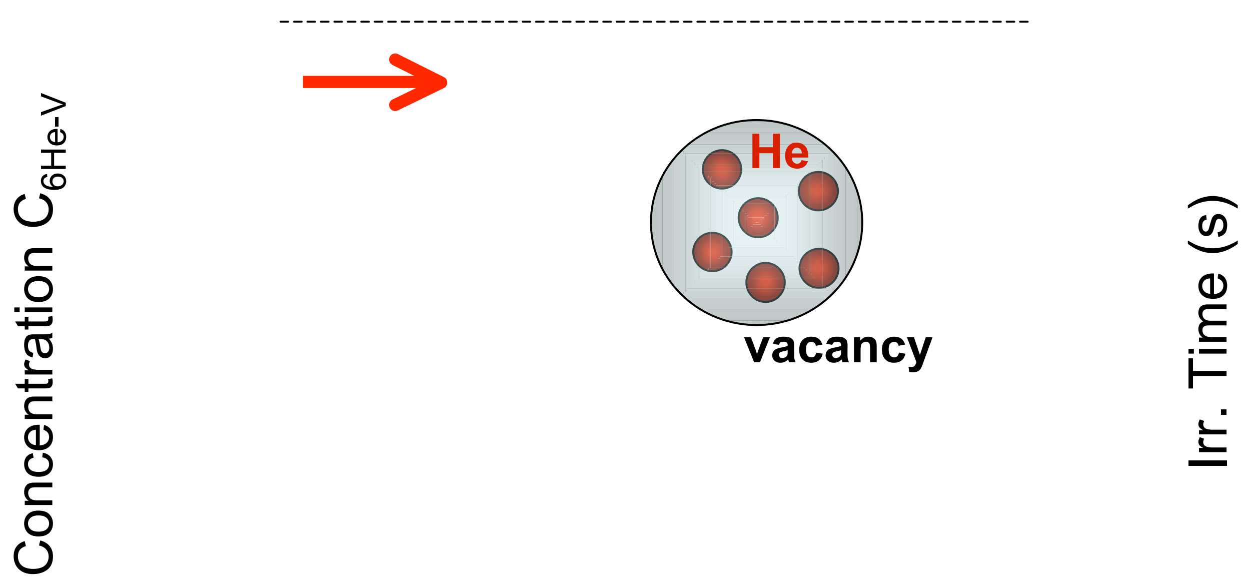
30eV-He$^+$(10^{22}He$^+$/m^{2}s) + Neutron (P_n=1x10^{-6}dpa/s) ⇛ W@873K





Acc. of He-V Complexes under Simultaneous Irradiation of He Plasma and Neutrons

30eV-He^+ ($10^{22} He^+/m^2s$) + Neutron ($P_n = 1x10^{-6}$ dpa/s) ⇛ W@873K



- At the sub-surface region up to 3μm deep, large fraction of the vacancies formed by neutron irradiation are occupied by He diffusing from the surface. →Very high accumulation of He (10^{-4}~10^{-2})
- This region expands with increasing irradiation
- This may cause serious irradiation damage at rather thick sub-surface region

What We Should Do for beyond D-T Phase? (as an Summary)

- irradiation effects of neutrons in the present W
- irradiation effects of helium plasma in the present W
- Their synergistic effects

Very critical issues for Application of W in D-T burning conditions

- Evaluation of He effects under ITER condition
- Genuine R&D of W-base alloys which endure neutron irradiation and helium irradiation