Issues of tungsten as a plasma facing material for ITER and DEMO

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22th International Toki Conference

Cross-Validation of Experiment and Modeling for Fusion and Astrophysical Plasmas

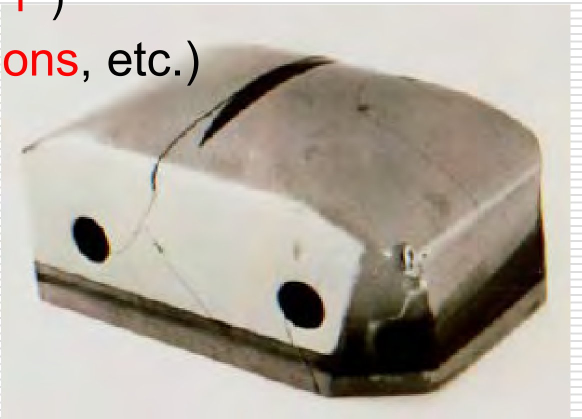
November 19-22, 2012

Outline

- Introduction (W as plasma facing materials)
- Pulsed heat load effects
  - Melting and cracking : experiments and simulations
- Helium effects
  - Nano-structure : formation mechanism and its effects
- Tritium behavior
  - Role of surface mixing layers
- Neutron effects
  - Synergism of radiation damage and transmutation
- Concluding remarks

Tungsten as plasma facing materials

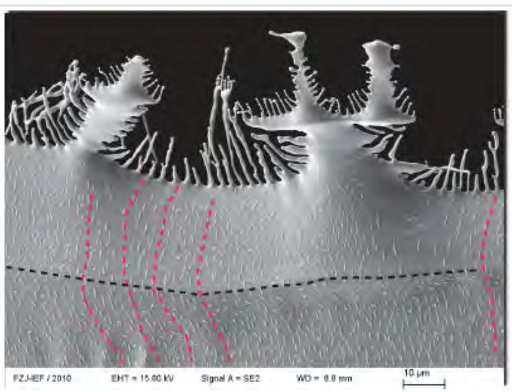
- **Advantages of tungsten as PFM's**
  - High melting point (3693 K)
  - High thermal conductivity
  - Low sputtering yield (high threshold energy for light ion bombardment)
  - Low tritium retention
- **Critical Issues**
  - Avoidance of material degradation under complex fusion environments
    - Steady-state heat load
      - 400s, 10^4 cycles for ITER W, used below DBTT*)
    - Pulsed (Transient) heat load (ELM's, disruptions, etc.)
    - Plasma Irradiation (D/T, He ions)
    - Neutron irradiation
      - Radiation damage, transmutation
  - Avoidance of core plasma accumulation
  - Safety operation (Dust)



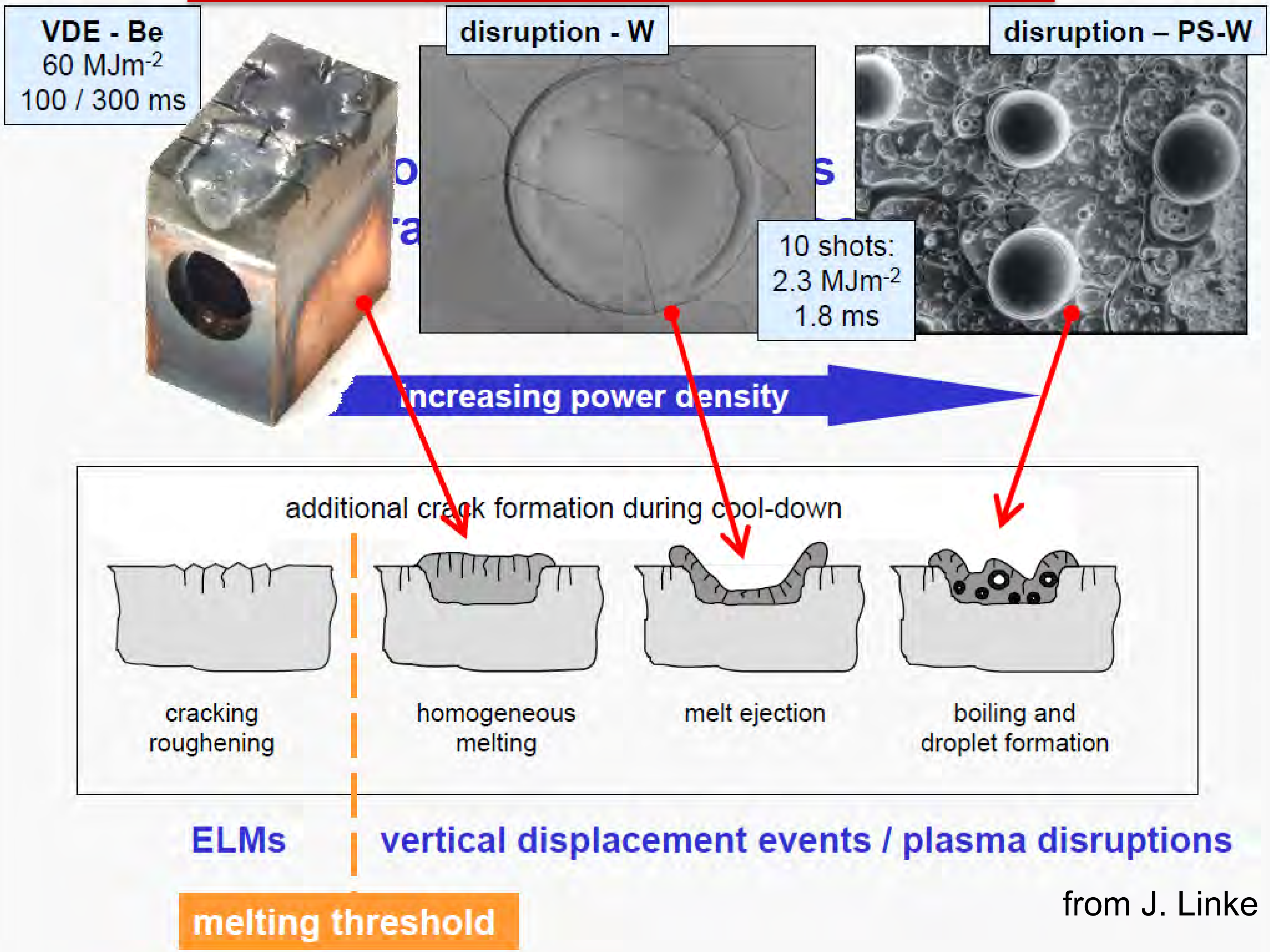
W limiter used below DBTT (TEXTOR experiments)

*DBTT (Ductile Brittle Transition Temperature)

Pulsed heat load effects



Summary of pulsed load effects

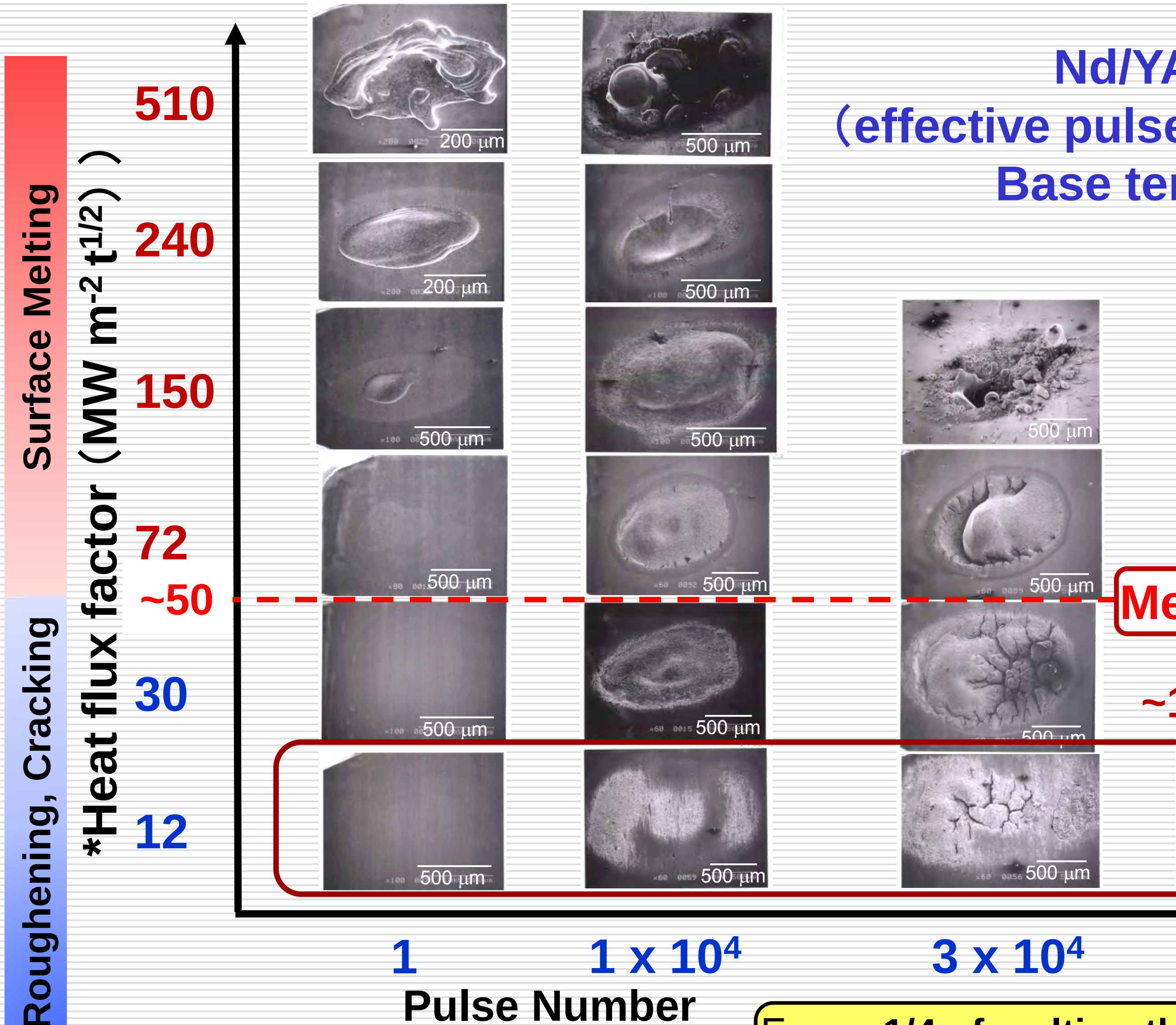


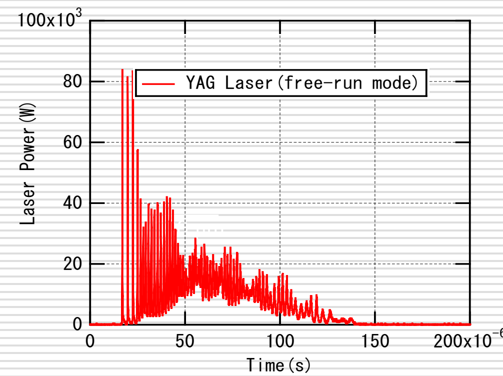
from J. Linke

Surface morphology changes by pulsed load

Osaka University

Nd/YAG laser
(effective pulse length: ~100μs)
Base temp.: 500°C





Even **~1/4 of melting threshold pulse energy** causes surface damage after large cycles of ELMs

*energy absorption ~0.3 is considered.

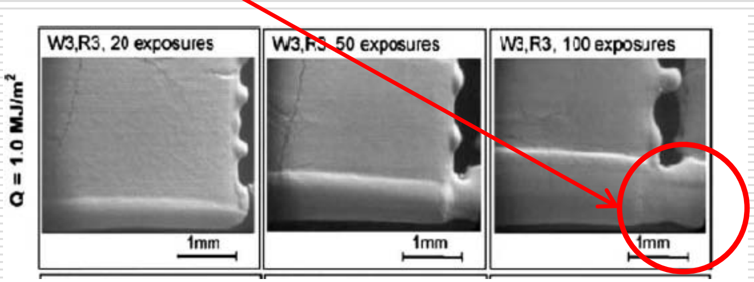
Concerns of melting

- Erosion enhancement and dust formation
- Formation of brittle solidified layers
  - Cracking and rapture
  - Dust release

Cross section of melt layer from TEXTOR exp.

- Formation of leading edge
  - Further melting of leading edge (ITER limit : <u>0.3 mm</u>)
  - Leading edge grows in the next melt event.
- Bridging between adjacent monoblocks
  - Stress to cooling tube

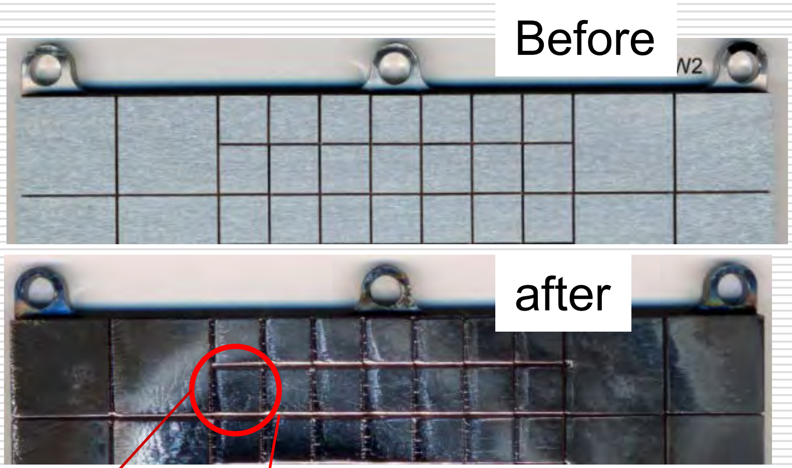
  → May cause Rapture of cooling tube



Excessive melting must be avoided.
<u>What is the acceptable limit?</u>

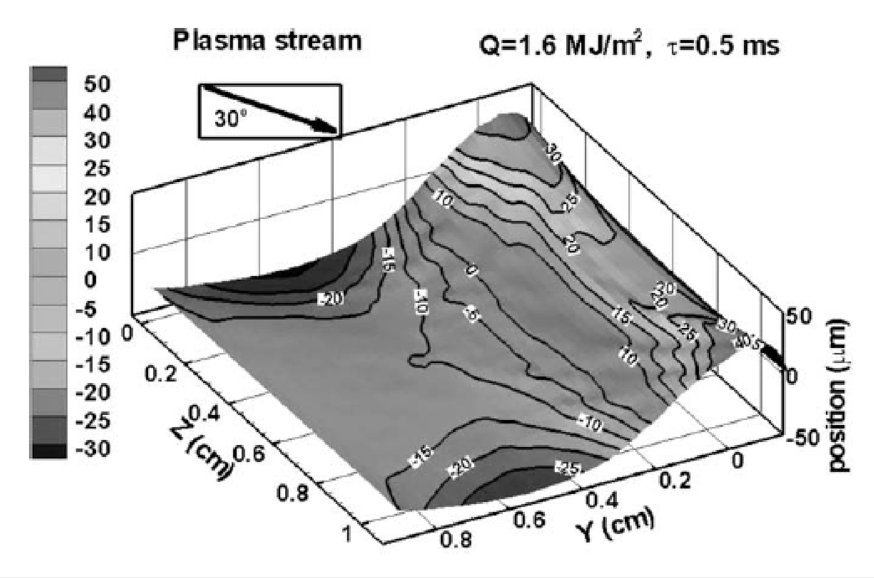
Simulation of Melt layer dynamics (pulsed plasma)

- Base equations
  - Navier–Stokes equations
  - heat conduction equation
- Material parameters (given)
  - Thermal conductivity, viscosity, surface tension, etc.

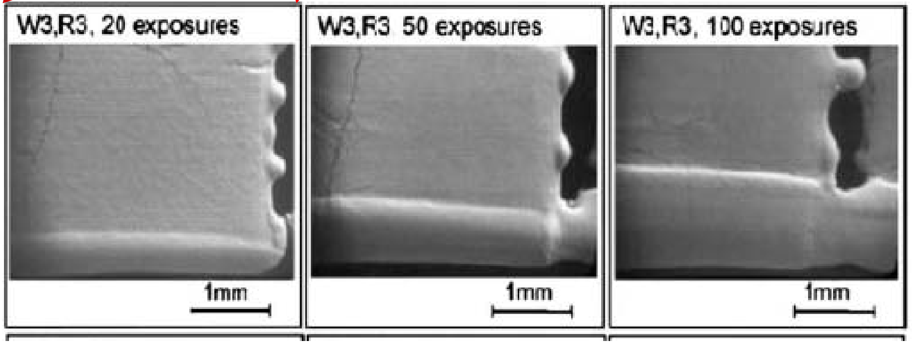


E = 1.0 MJm^{-2} Δt = 500 μs 100 pulses

Plasma Gun exp. (QSPA)



Surface morphology (MOMOS code)

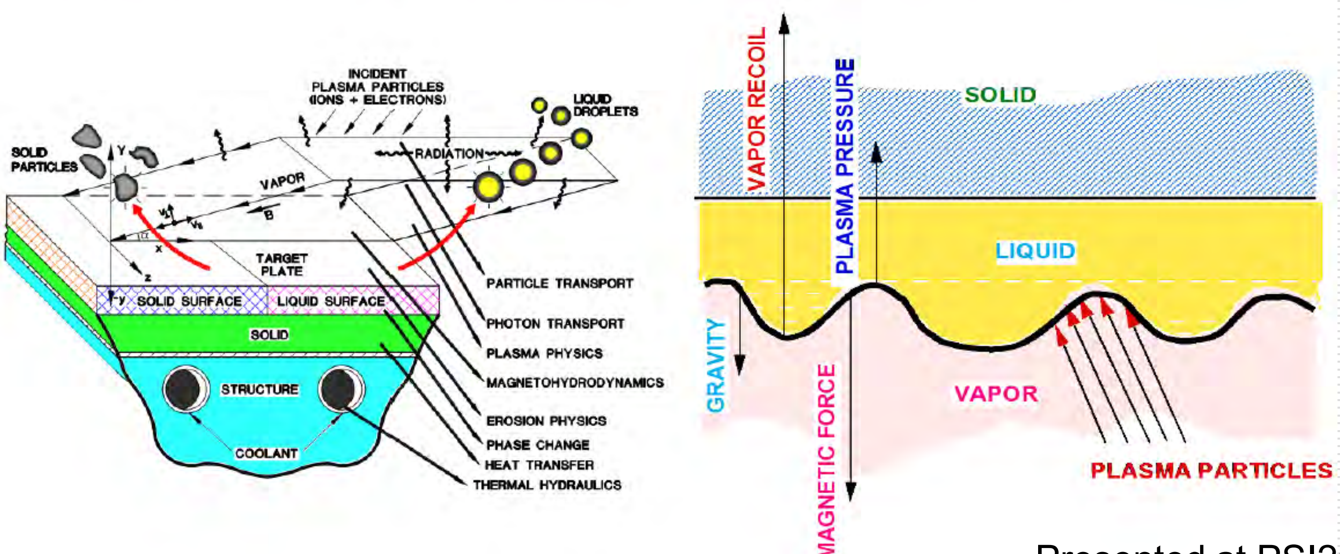


B. Bazylev et al., J. Nucl. Mater.*390-391 (2009)810-813*

Coupling with plasma

- <u>Vapor shielding</u>, <u>surface instability</u> (plasma pressure driven)
- <u>Very few well controlled benchmark experiments.</u>

Models Integration of Plasma-Material Interaction Physics during Plasma Instabilities



Presented at PSI2012
G. V. Miloshevsky
A. Hassanein

Hassanein, *J. Nucl. Mater.* 273 (1999) 326
Hassanein, *Fusion Eng. Des.* 60 (2002)

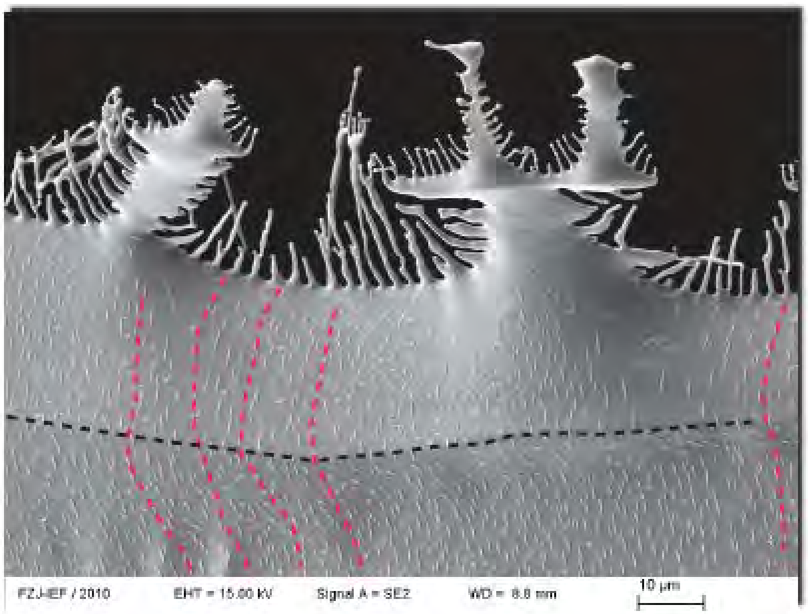
PURDUE UNIVERSITY

Surface instability modeling

- Kelvin–Helmholtz instability
  - Acting Force : Plasma pressure (Plasma flow), Vapor recoil, Magnetic force

Plasma flow

W melt layer



Resolidified layer (TEXTOR exp.)

J. W. Coenen et al., Nucl. Fusion 51 (2011) 083008

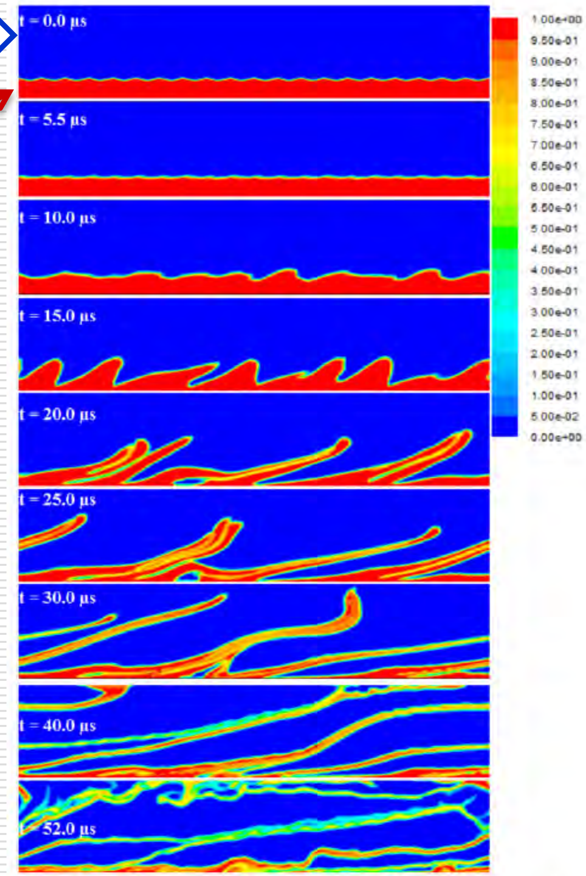
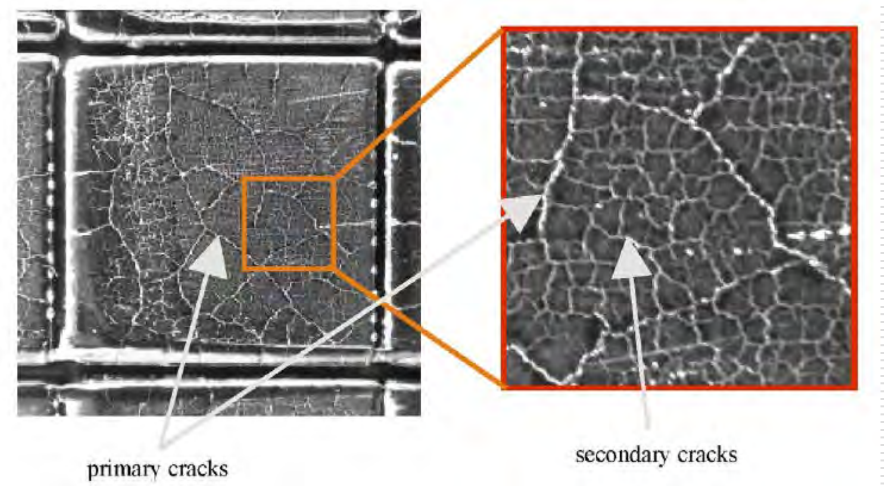


Figure 9. Fields of volume fraction for plasma–liquid tungsten flow at different times. Twenty wavelengths with $\lambda = 0.5$ mm were initially excited at $t = 0.0\,\mu s$.

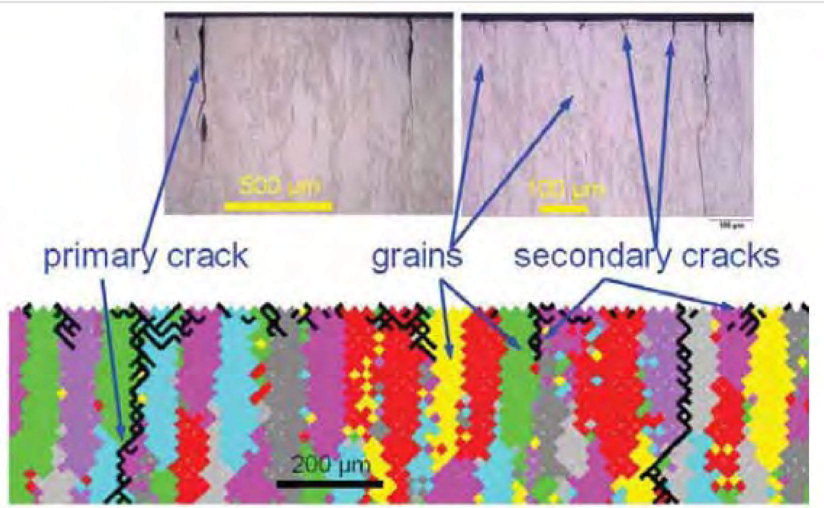
G.V. Miloshevsky and A. Hassanein, Nucl Fusion 50 (2010) 115005

Simulation of cracking

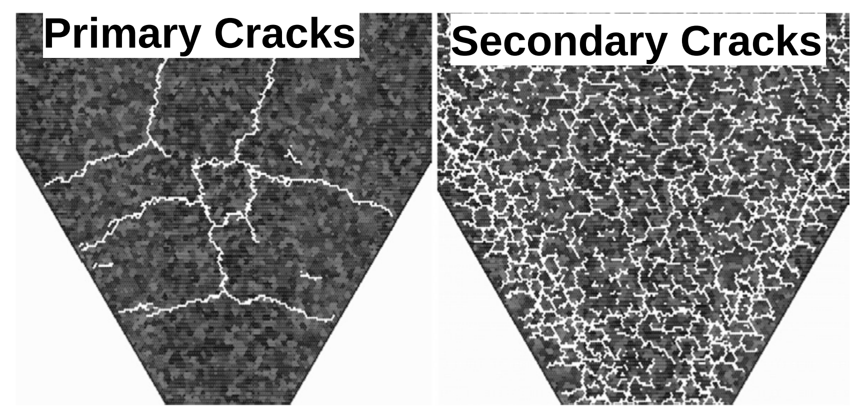
- Simulation code (PEGUSUS-3D)
  - Simulates heating and heat conduction in the sample
  - Calculates thermal stress
  - Cracks formation and propagation
  - Dust particles splitting
  - Material properties (given)
  - Phenomenological approach



Experimental results (plasma gun)



Comparison between experiments and simulation
Cross section



Simulation results (PEGASUS-3D)
Top surface

Future direction : Combination of micro- (MD) and macro-(CIP) simulations to for PFM evaluation

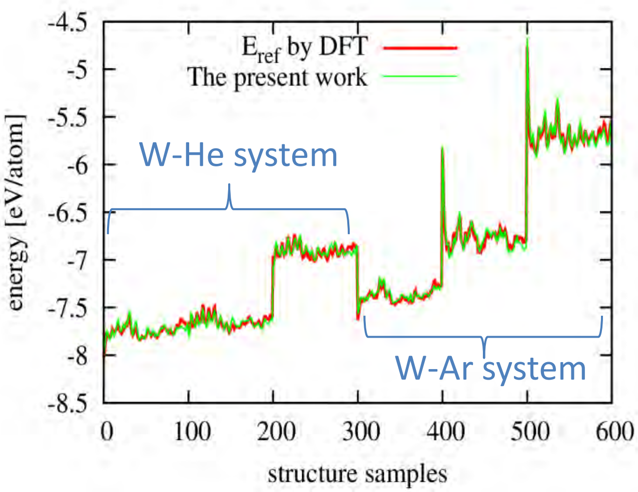
Benchmark experiments (pulsed laser, E-beam, confinement devices)

Molecular Dynamics (MD)

Expanded ensemble MD for rare event

High quality potential

Exam.) DFT energy v.s. new potential for W-He-Ar system.



Material properties

from atomic dynamics

- viscosity coefficient
- surface tension
- equation of state
- diffusion coefficient

from electronic state

- Thermal conductivity
- electric conductivity
- energy of alloy, vacancy, and so on.

feedback

CIP sim. for Melting and evaporation behavior

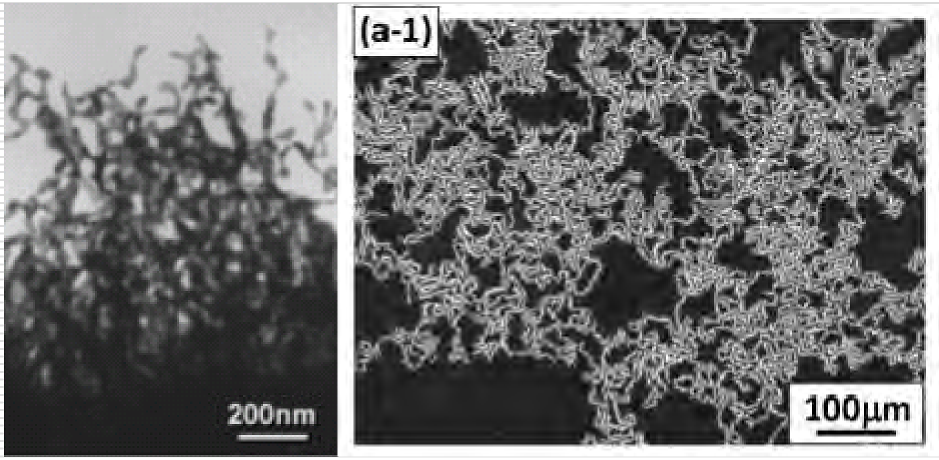
Density Functional Theory (DFT)

Cubic Interpolated Propagation (CIP)

Interaction with plasma (vapor shielding, etc.)

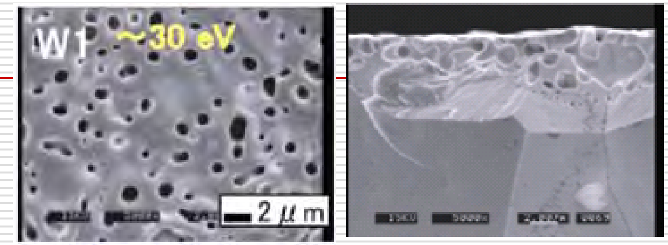
Solidified material performance

Helium Effects



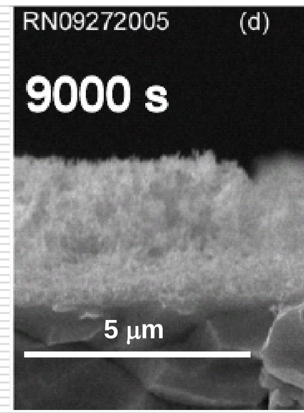
Low energy* He effects on W

- □ **High temperature**
  - Large He bubbles formation with recrystallization
  - Degradation of mechanical and thermal properties

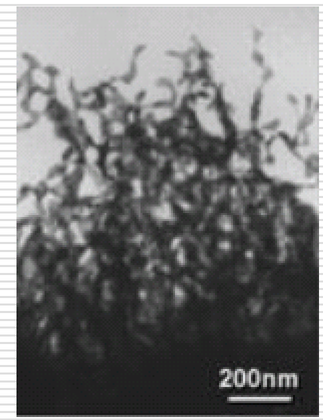


NAGDIS (Nagoya Univ.)
T ~ **2,100 K**

- □ **Medium temperature**
  - Nano-structure (fuzz) formation
  - Porous structure
  - Low thermal conductivity

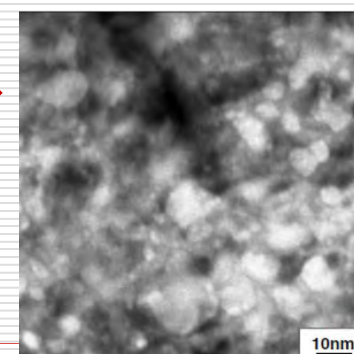


PISCES (UCSD)
T ~ **1,120 K**



NAGDIS (Nagoya U.)
T ~ 1,400 K

- □ **Low temperature (< ~900 K)**
  - Small He bubble formation (a few nm)
  - Degradation of mechanical and thermal properties
  - Affects D/T retention



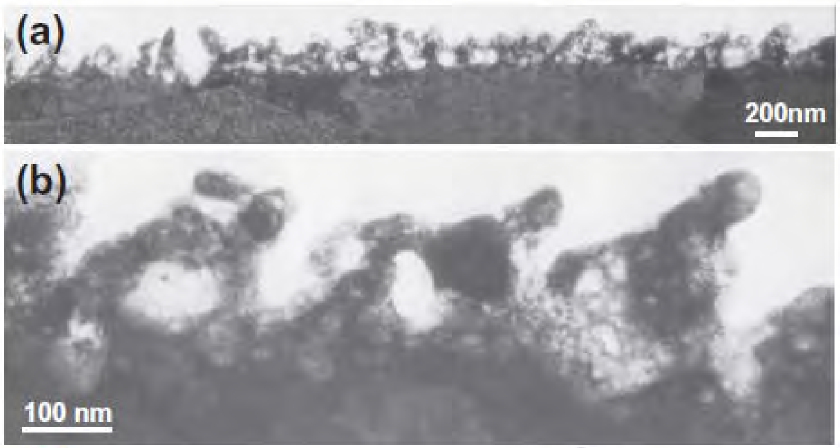
PISCES (UCSD)
T ≤ **773 K**

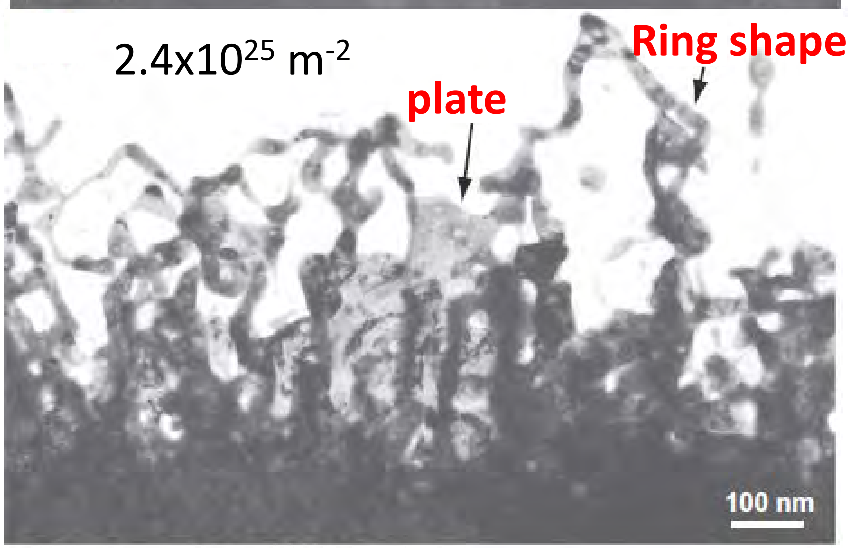
Low energy* :around 100 eV or less

TEM observation of nanostructured tungsten: formation mechanism

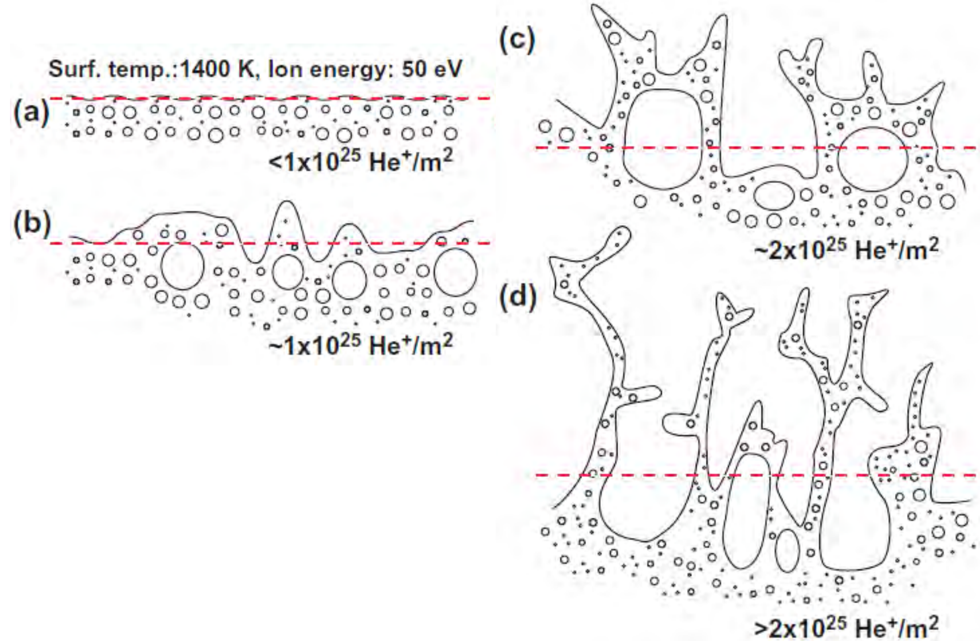
NAGDIS

1.1×10^{25} m^{-2}





He irradiated W in NAGDIS-II at 1400 K and 50 eV.



- Many **nanometer sized helium bubbles** are formed on the surface by the exposure to helium plasmas.
- With the help of an active surface diffusion, **pinholes, dips, and protrusions** are formed on the surface.
- The shape of structure becomes complicated ones such as **plain-like or pillar-like structures**.

S. Kajita, N. Yoshida *et al.* JNM **418** (2011) 152–158

Layer growth follows kinetics that are controlled by a diffusion like process.

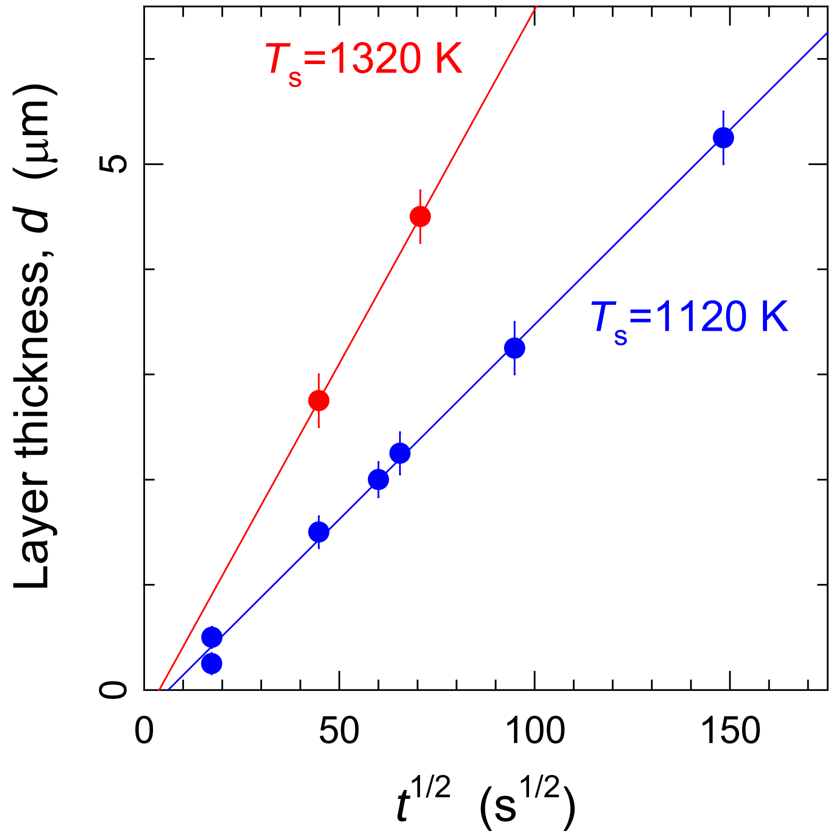
- Observed $t^{1/2}$ proportionality.

- The thickness of the nano-structured layer, *d*, agrees well with

$$d=(2Dt)^{1/2},$$

with,
$D_{1120\,K} = 6.6 \pm 0.4 \times 10^{-16}$ m^{2}s^{-1}
$D_{1320\,K} = 2.0 \pm 0.5 \times 10^{-15}$ m^{2}s^{-1}

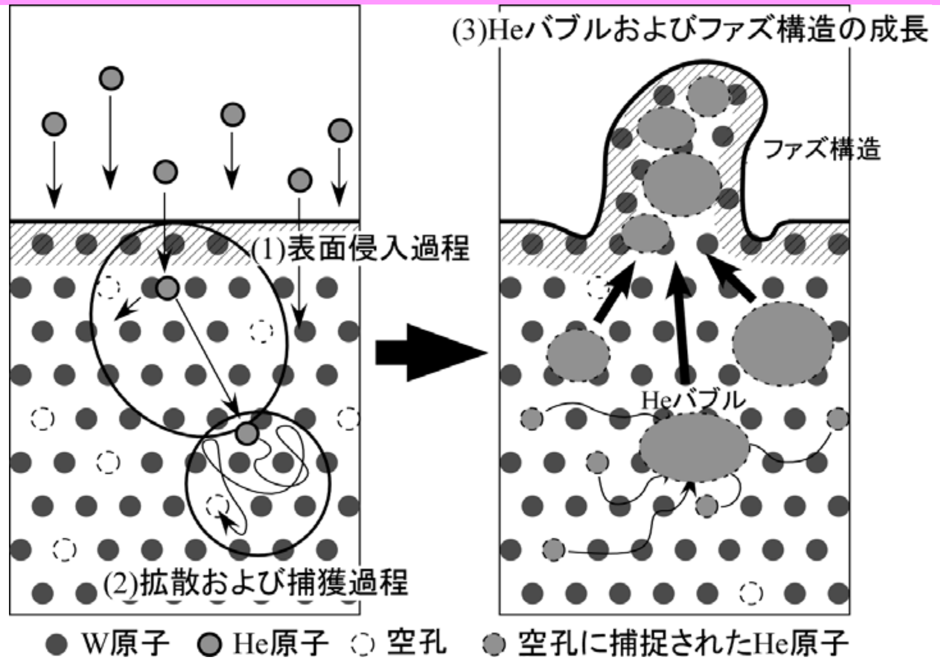
- Overall process is consistent with an activation energy of ~0.7 eV.



Simulation Research for Tungsten Nano-Structure

A. Ito et al., Physical society meeting, March 2012

To understand tungsten nano-bubble and fuzz structure formations, multi-simulation process is three phases



1. penetration： range（depth）v.s. sputtering

- Depending on injection energy

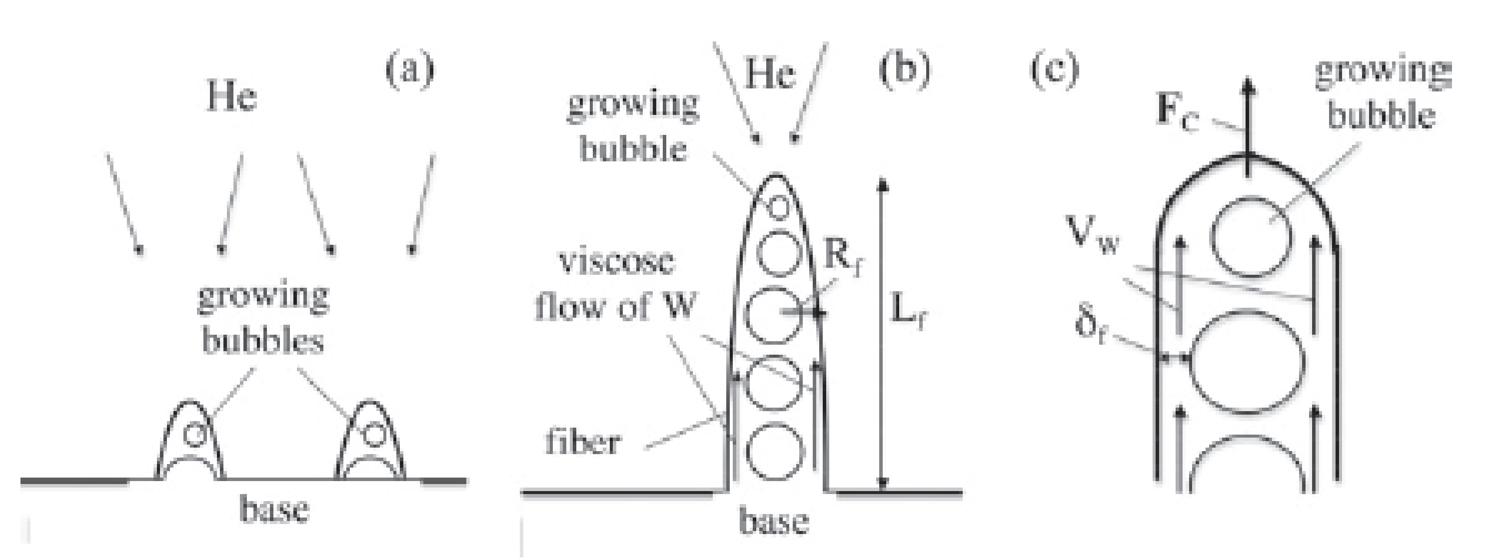
2. diffusion： He diffusion, thermal vacancy, He-v traps.

- Depending on trap energy and temperature

3. growth： growth to bubble and fuzz (sub micro meter)

Growth mechanism of fuzz

- Key physics necessary to understand
  - Tungsten atom diffusion to tips of nano-structure
  - Role of He bubbles
  - Role of ion bombarding energy (≥ 20 eV)
- Viscoelastic model
  - Viscose flow of W to the tip of the fiber due to the force caused by the pressure of He in the growing fiber.

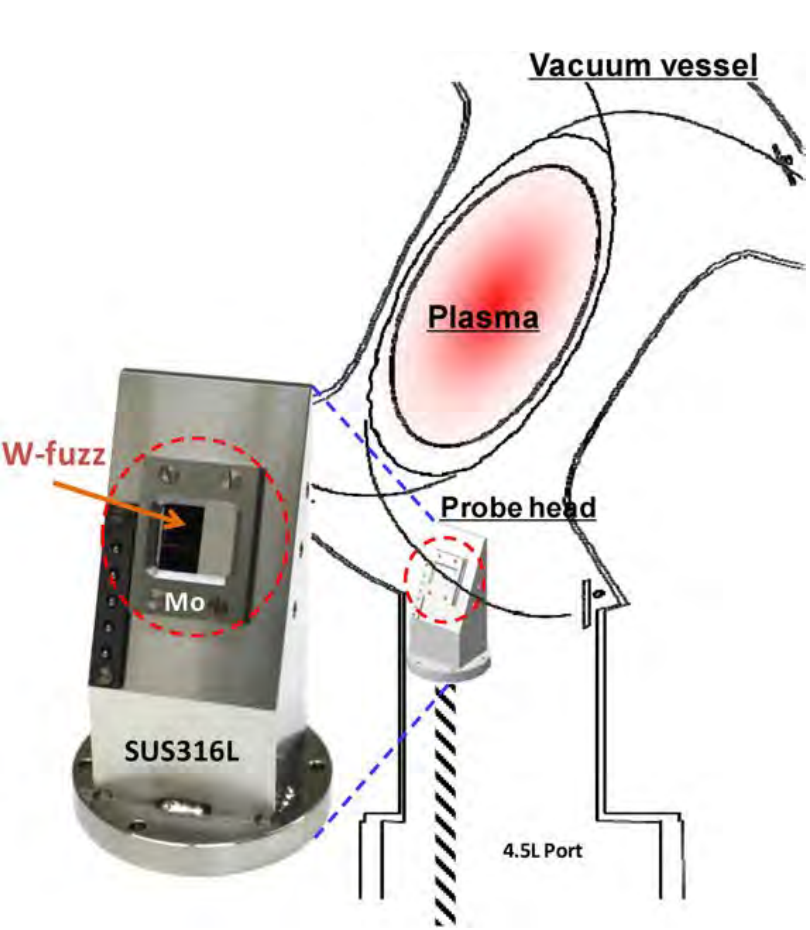


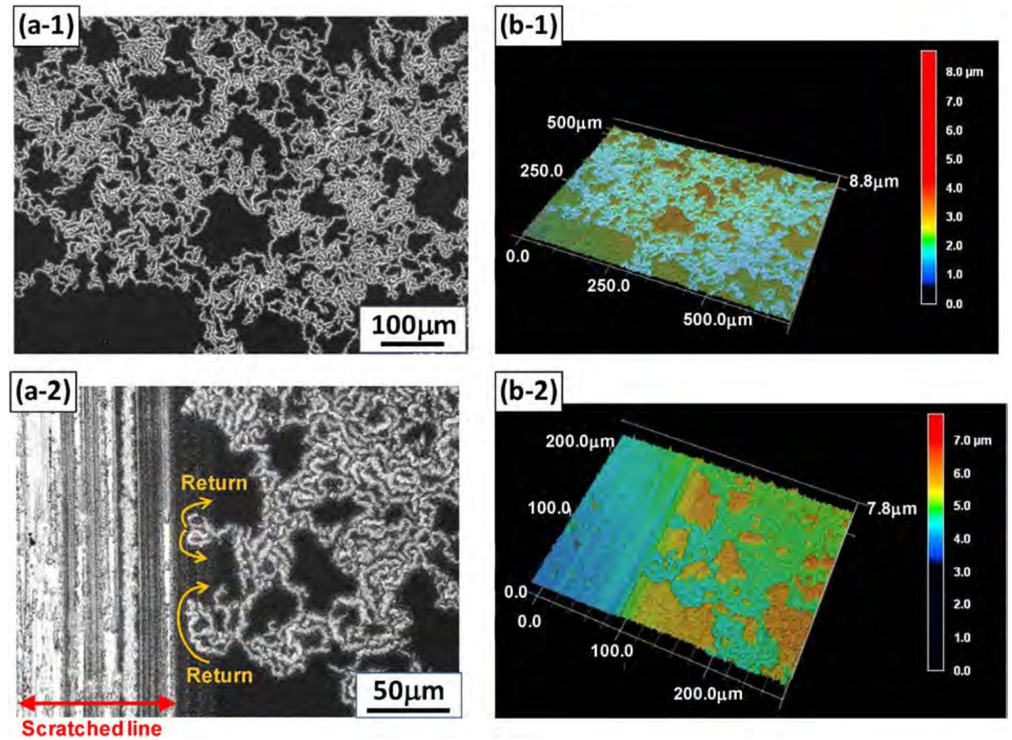
S I Krasheninnikov, Phys. Scr. T145 (2011) 014040 (4pp)

Present understandings on W nano-structure

- W fuzz looks common for all high density plasma devices (linear plasma & magnetic confinement plasma).
  - Alcator C-Mod (Magnetic confinement device)
  - Pilot-PSI (High flux device relevant to ITER)
- W fuzz has advantages and disadvantages for fusion reactors
  - Advantages
    - Low physical sputtering yield (1/5~1/10 of flat surface)
    - Mitigation of pulsed heat load (no cracking)
    - Thermal annealing (> 1400 K)→extinction without release to plasma
  - Disadvantages
    - Unipolar arcing → <u>still under discussion</u>

Demonstration of arcing on fuzz-W in LHD





-Nanostructured W formed in the NAGDIS-II was installed in LHD.

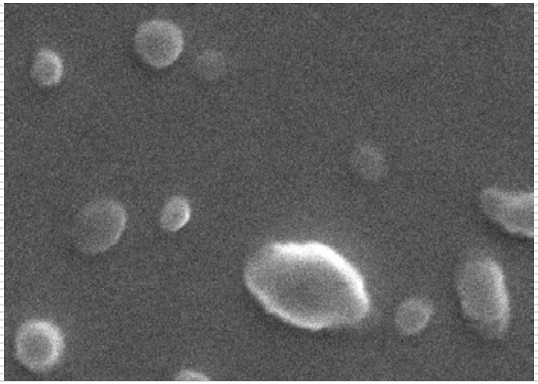
-Arcing was initiated by the exposure to the LHD plasma, the duration of which was 2s.

-Since the magnetic field direction was almost normal to the target, the motion was Brownian-like.

-This results strongly suggest that arcing can be easily initiated when the nanostructure is formed on the surface.

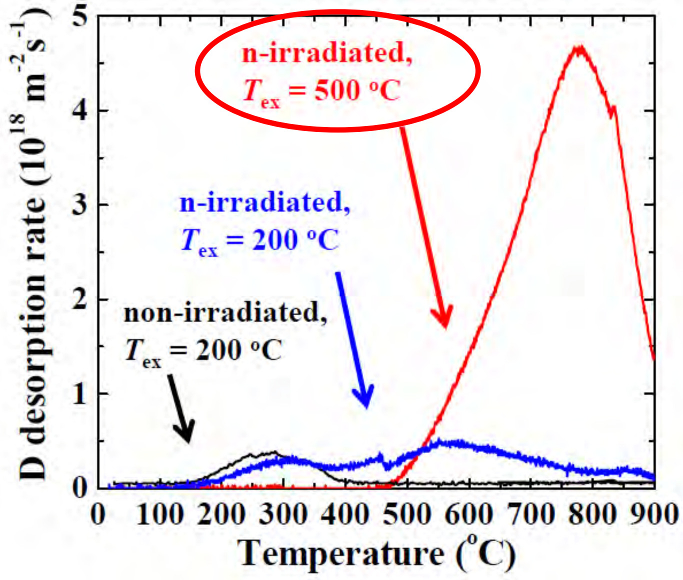
M. Tokitani *et al.* Nucl. Fusion 51 (2011) 102001.

Tritium Behavior in tungsten



Tritium issues for DEMO

- Neutron irradiated W
  - It was believed that T retention is low for W.
  - However, neutron irradiated W has deep traps and uniform trap site distribution.
  - → Need more investigation and proper modeling
- Dynamic behavior of T
  - Dynamic retention in blanket and divertor and permeation of T to bulk materials and coolant are important to control T in fusion reactors.
  - One of the important issues for dynamic T behavior is effects of surface conditions on T behavior.



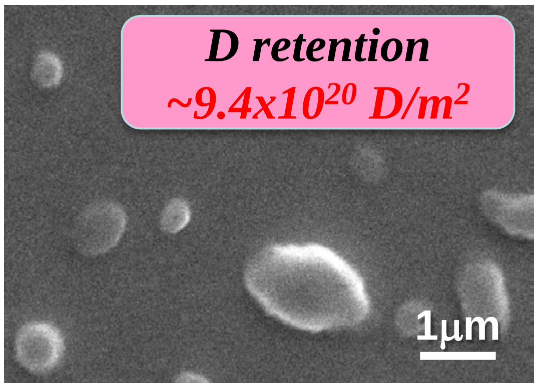
TDS spectra of n-irr. and non-irr. W at T_{ex} = 200 and 500 °C.

Y. Hatano et al., PSI2012

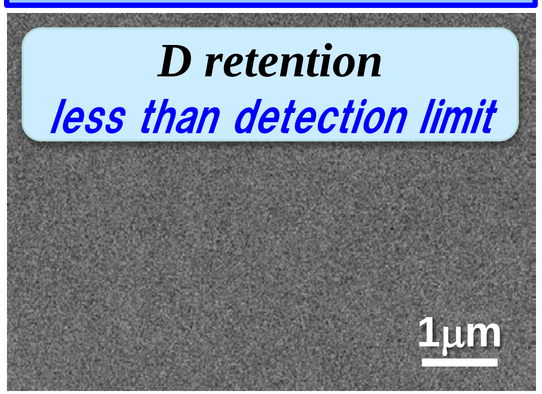
Suppression of D retention by He

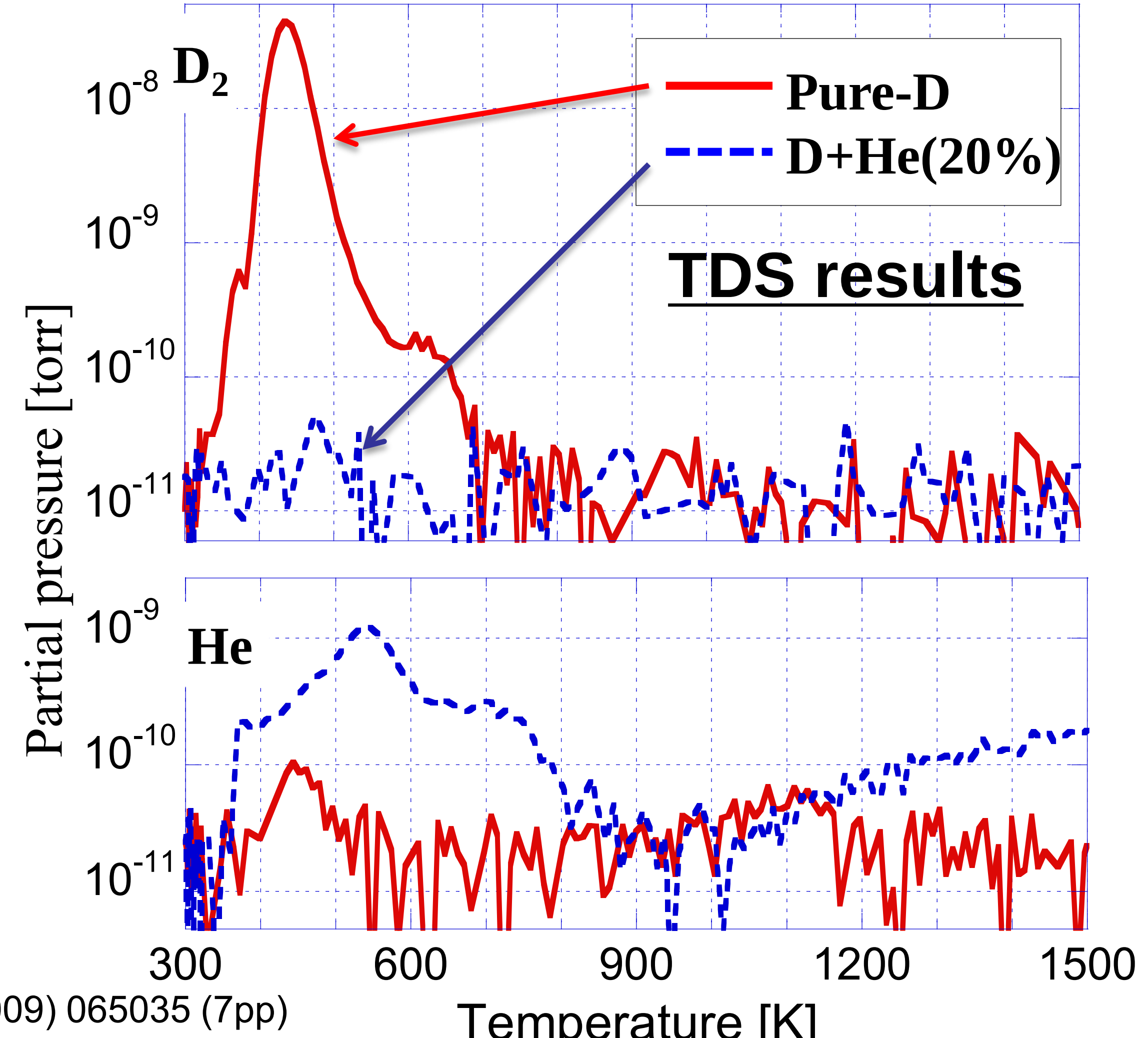
■SR-W, $5x10^{25}$ D/m^2, @573K

Pure-D



D+He(20%)



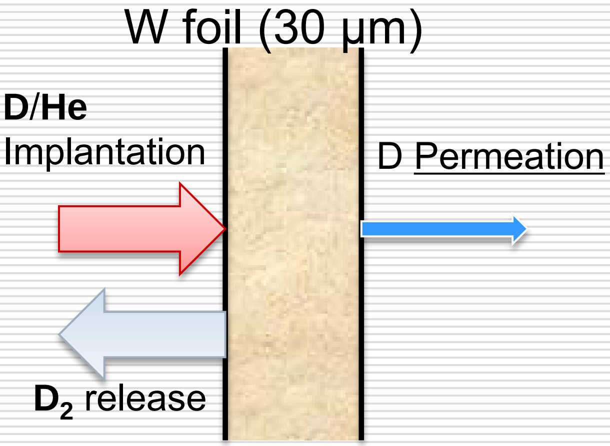


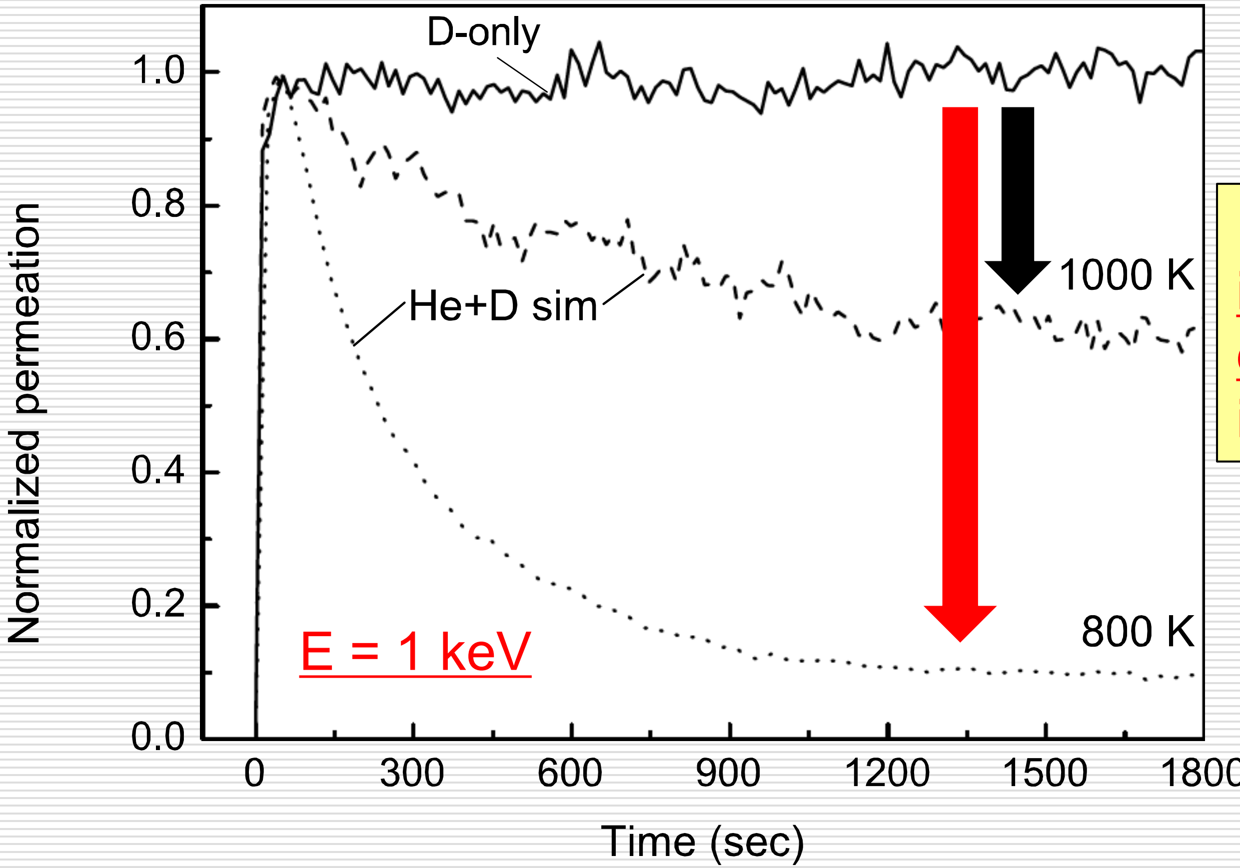
M. Miyamoto et al., Nucl. Fusion 49 (2009) 065035 (7pp)

He/D mixed ion driven permeation

Osaka University

- Addition of He (2%) greatly reduces permeation flux.
- Saturation time almost corresponds to He bubble formation time.



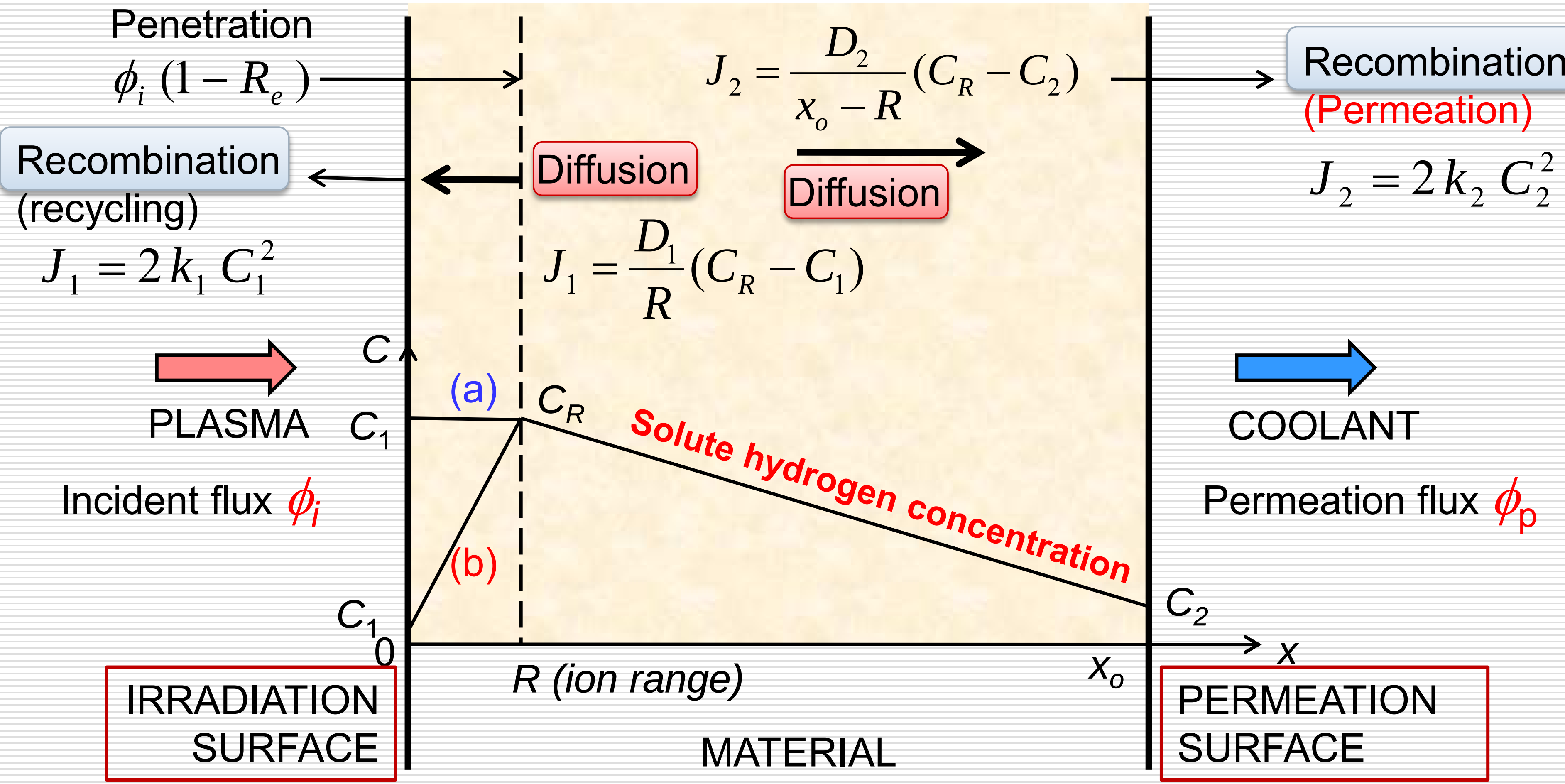


Detailed studies showed increase in effective diffusion of D to ion implantation surface.

< 800 K
more reduction
(less than detection limit)

H. T. Lee et al., J. Nucl. Mater. (2011) in print.

Ion driven permeation model (Brice & Doyle)



(a) Recombination limited condition : $\phi_p = \frac{D_2}{x_0\sqrt{k_1}}\sqrt{\alpha\phi_i}$

(b) Diffusion limited condition : → $\phi_p = \frac{RD_2}{x_0 D_1}\alpha\phi_i$

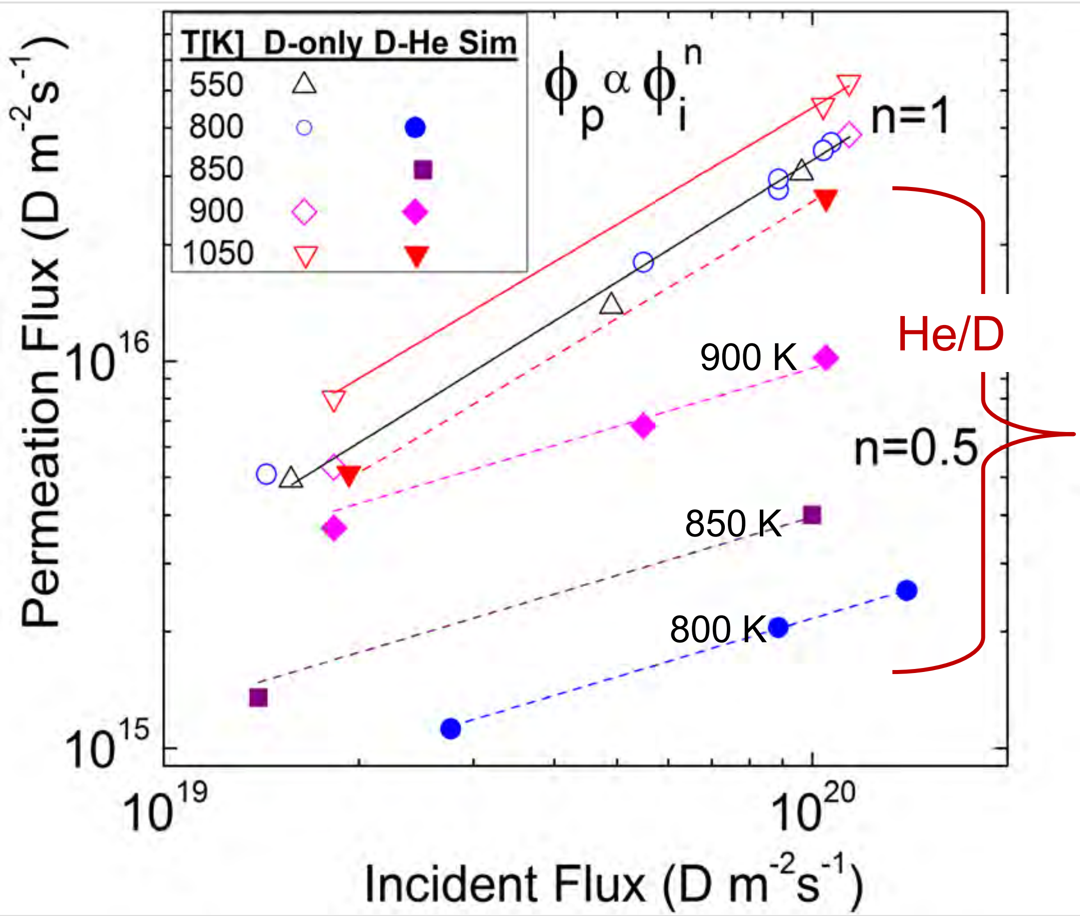
Brice D.K. and Doyle B.L., J. Nucl. Mater. 120 (1984) 230-244.

Incident flux dependence

Osaka University

- $\phi_p \sim \phi_i$ (D only irradiation)
- $\phi_p \sim \phi_i^{1/2}$ (D/He irradiation)
  - ϕ_p : Permeation flux
  - ϕ_i : Incident flux
- Change of flux dependence suggests D release from the front surface could change from diffusion limited (D) to recombination limited (D/He).
  - Front surface diffusion increased.

E = 1 keV He:2%



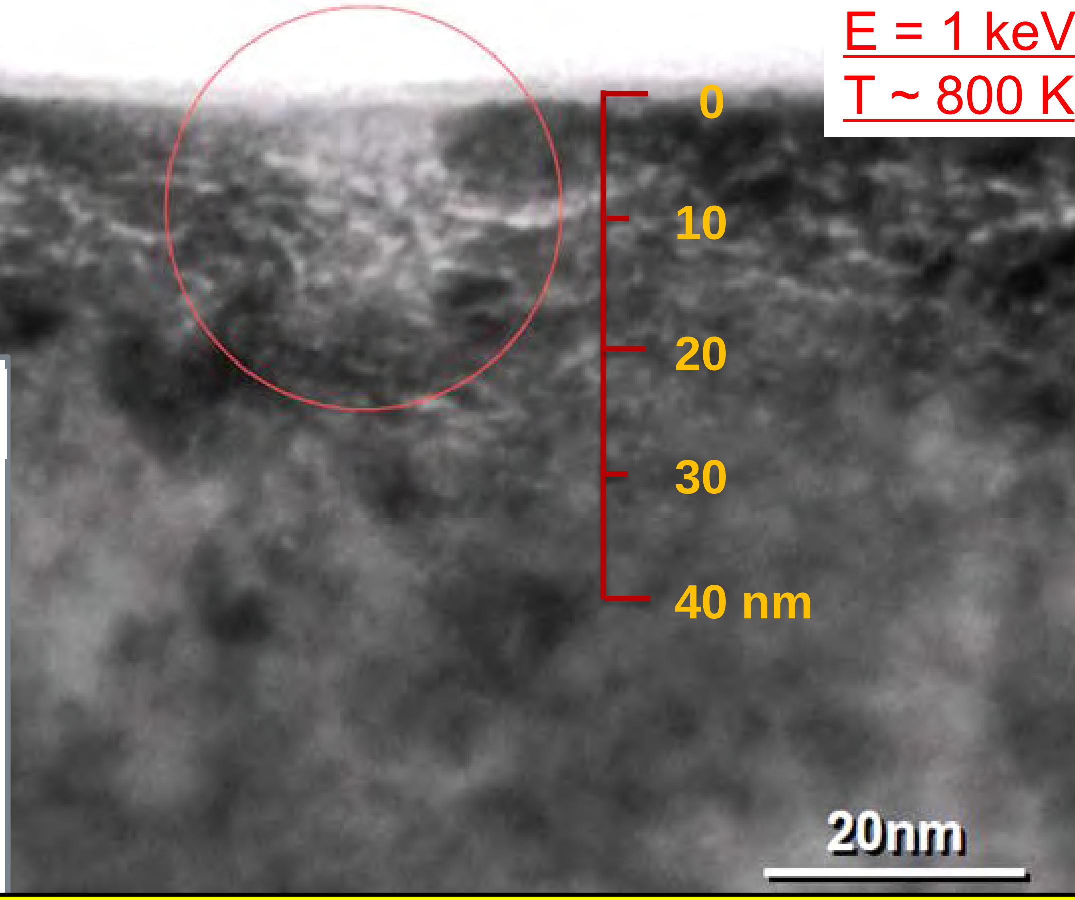
Permeation flux ϕ_p vs. Incident flux ϕ_i

Enhanced D desorption by He bubble layer

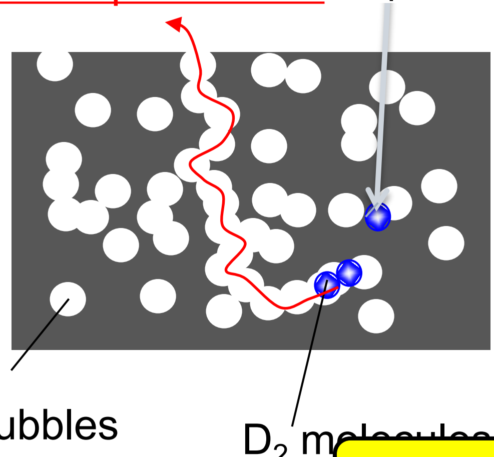
Osaka University

- He bubble layer was observed up to the depth of about 20 nm.
- Thickness of He bubble layer was larger than ion range (~10 nm).
- He bubbles could be interconnected to form pores to the surface.

E = 1 keV
T ~ 800 K

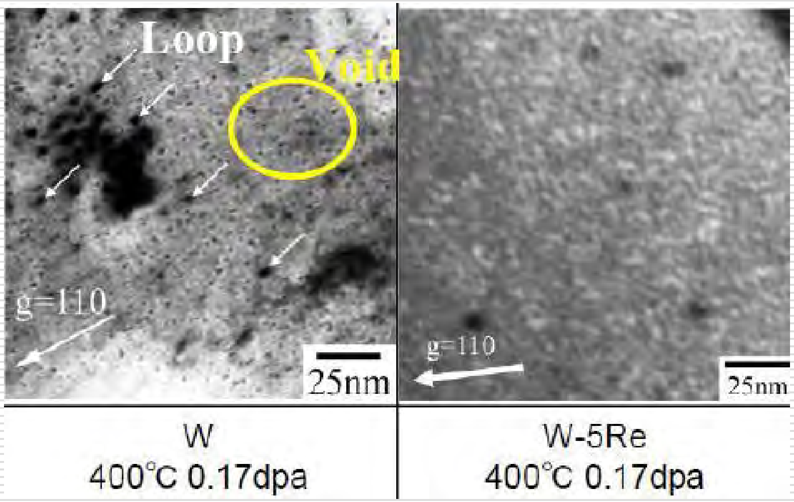


Possible Mechanism for decrease in permeation



Necessary to make proper modeling and simulation!

Neutron Effects

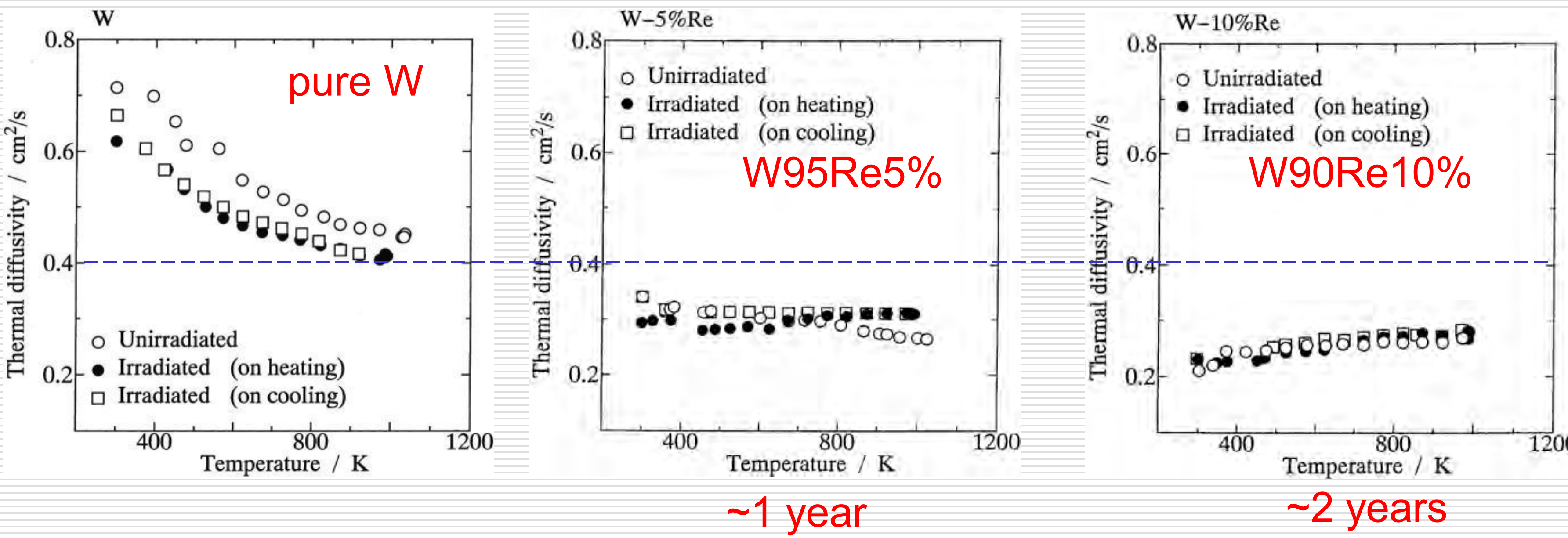


Neutron effects of tungsten

- Neutron irradiation damage effects
  - Increase in DBTT (Ductile Brittle Transition Temperature)
  - Reduction in thermal conductivity due to lattice damage
  - Void swelling
  - Increase in T trapping
- Transmutation (W → Re (→ Os)) effects
  - Mainly, neutron capture reaction ($^{184}W(n, \gamma)$ and $_{186}(n, \gamma)$)
  - Increase in impurity elements concentration reduces thermal conductivity.
  - Increase in embrittlement (especially Os)
- For DEMO
  - Up to 15 to 20 dpa →both damage and transmutation are important.
- For ITER
  - Even for low dpa (up to 0.7 dpa), damage effects (T retention) needs to be taken care of.

Transmutation of W

- Transmutation of W (Noda et al. J.N.M. 258-263(1998) 934.)
  - W:5% Re:0.02% Os (3 MW y/m^2)
  - W:10% Re:0.1% Os (6 MW y/m^2)
  - W:25% Re:1.0% Os (15.5 MW y/m^2)
- Thermal diffusivity of W decreases with the increase in Re
  - Fujitsuka et al. JNM 283-287 (2000) 1148.



Neutron load (3 MW/m^2)

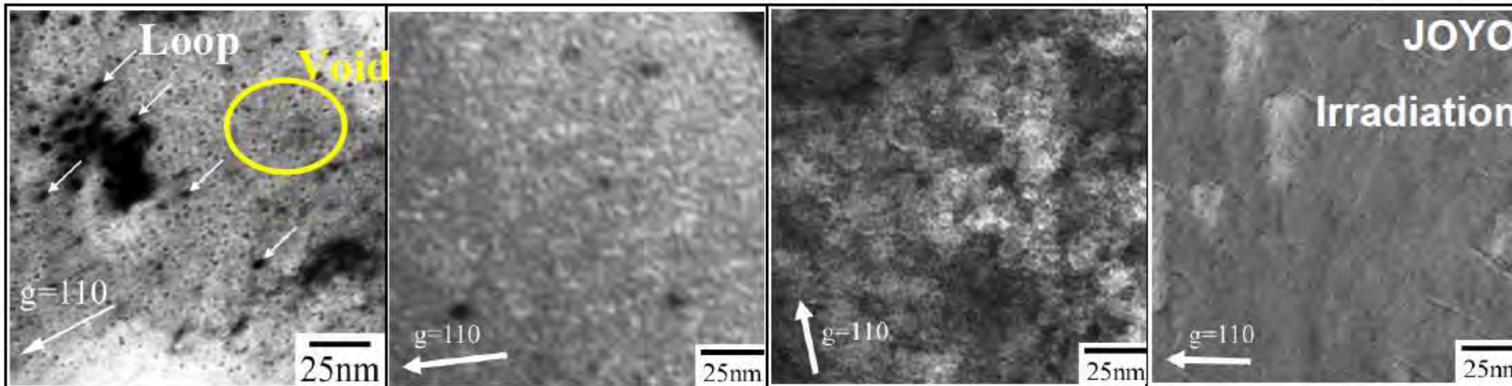
Microstructure of Irradiated W and W-Re-Os Alloys

Dept. Quantum Science & Energy Engineering, Tohoku University

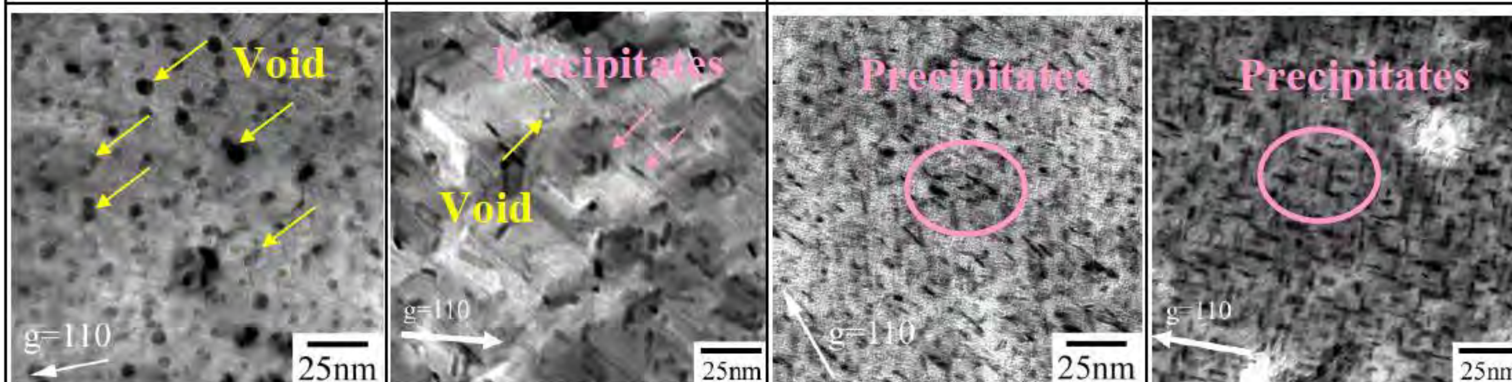
- Void and loop formation were suppressed by Re and Os addition and fine and dense precipitates were formed after irradiation in the alloys.

Tanno, et.al. J.N.M. 386-388(2009) p.218

Tanno et al. Mater. Trans.,10(2008) p.2259



W	W-5Re	W-3Os	W-5Re-3Os
400℃ 0.17dpa	400℃ 0.17dpa	400℃ 0.17dpa	400℃ 0.17dpa



W	W-5Re	W-3Os	W-5Re-3Os
750℃ 1.54dpa	750℃ 1.54dpa	750℃ 1.54dpa	750℃ 1.54dpa

Synergistic effects of radiation damage and transmutation elements

Concluding remark

- Melting and roughening by pulsed heat load
  - Acceptable surface damage level by pulsed heat load is still not clear. Experiments and proper modeling need to be done to understand and evaluate W performance under complex fusion plasma environments.
- He surface effects
  - Surface damage and new structure (nano-structure) are developed by He ion irradiation. Whether its effects are serious or not, is under discussion.
  - Modeling of nano-structure is in progress.
- Tritium behavior in tungsten
  - Effects of surface modified layers (He bubble, material mixing layer) need to be understood. Dynamic processes will become more important for DEMO.
- Material modeling and simulation
  - Microscopic (MD, DFT) and macroscopic simulation (Hydrodynamics, CIP, rate process) are in progress. Combined simulation of microscopic and macroscopic models could be a new direction in fusion science and engineering.