Material mixing of tungsten with low Z materials
-Carbon and Helium-

Yoshio Ueda
Osaka University

Scientific Research in Priority Areas
Tritium for Fusion
2007 - 2011

Japan-US Joint Project
TITAN
2007-2012

ITER International Summer School 2009
"Plasma Surface Interaction in Controlled Fusion Devices"
22-26 June, 2009, Aix en Provence, France

Outline of this talk

- Material mixing of C & W : introduction
- C deposition on W
- Effects of C & W mixing on retention/blistering
- Effects of simultaneous He bombardment to W on retention/blistering

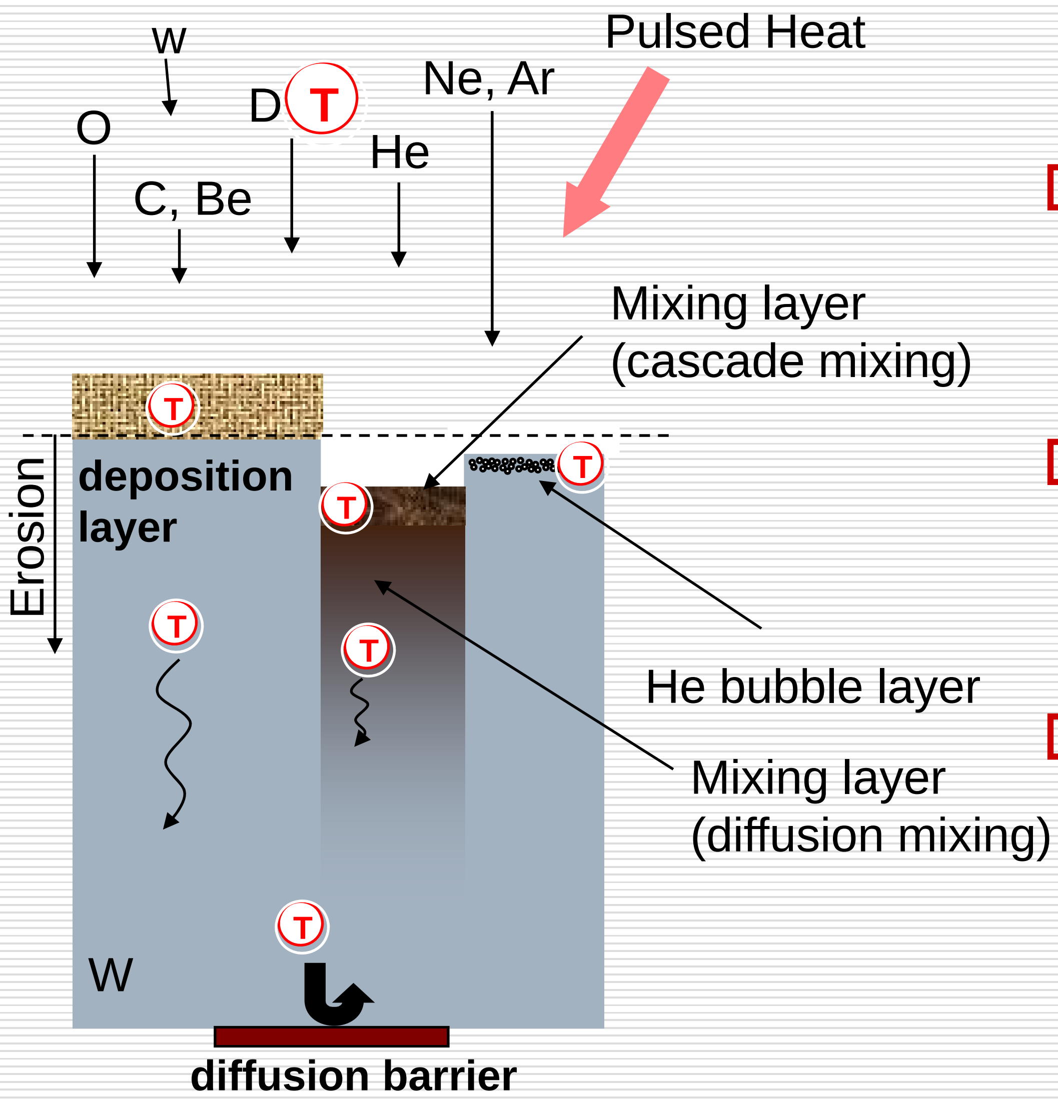
Wall material selection in ITER

- CFC : T retention problem (associated with significant erosion) could greatly reduces DT shots number
- Tungsten : several concerns such as Melting, Cracking, Helium embrittlement, Core plasma contamination.
- In terms of T retention, a full W wall is a better choice.
  - But, several issues need to be settled for the use of full W
  - In H phase, W, C and Be are used to learn ITER plasma operation toward full W.
- W+C (CFC) system is still one option for DT operation.
- Material mixing of C and W is a very important subject.
- In addition, He mixing effects are significant in T retention.
- W-Be and C-Be mixing are also an important issues.
  - Be issues will be discussed in Prof. Tynan’s talk.

Research on W & C material mixing

- Many basic studies have been done in C+D→W, but still quite a few remaining issues (deposition, effects on retention)
- Several complicated processes need to be considered.
  - **Dynamic mixing process**
    - Mixed layer formation during ion irradiation (non-equilibrium state)
    - Multiple ion irradiation (D/T, He, Ar(edge cooling), C(wall), O, etc.)
  - **Thermal processes of C (W, D) in mixed layer**
  - **Chemical sputtering of C in mixed layer and deposition layer**
    - Depending on chemical state and micro-structure
  - **Ion radiation enhanced processes**
    - Radiation enhanced diffusion and segregation
- Necessary to consider actual conditions
  - **Roughness**(surface morphology)
  - **Surface impurities** (Ex. Oxide layer)

Effects of material mixing on T retention/permeation



- **Deposition layer**
  - T trap sites
  - Modification of T diffusion
- **Mixing layer**
  - T trap sites
  - T diffusion (barrier)
  - T surface recombination
- **He bubble layer**
  - T trap sites
  - T diffusion (barrier)
  - Diffusion through pore
- **Important Parameters to affect mixed layer**
  - Temperature
  - Energy
  - Deposition rate (ratio)
  - Bulk material characteristics

Balance between C implantation and erosion

- C implanted
  - = C injected – C reflected
- C erosion
  - by all ions
    - Physical sputtering
    - Radiation enhanced sublimation
  - by hydrogen isotope ions (oxygen)
    - Chemical sputtering
      - C in mixed layer
      - C in deposition layer
  - Sublimation (at elevated temperatures)
  - Flaking, exfoliation, or dust emission (for thick D deposition)
- C diffusion into the bulk

The simplest model for C balance (H+C ions)

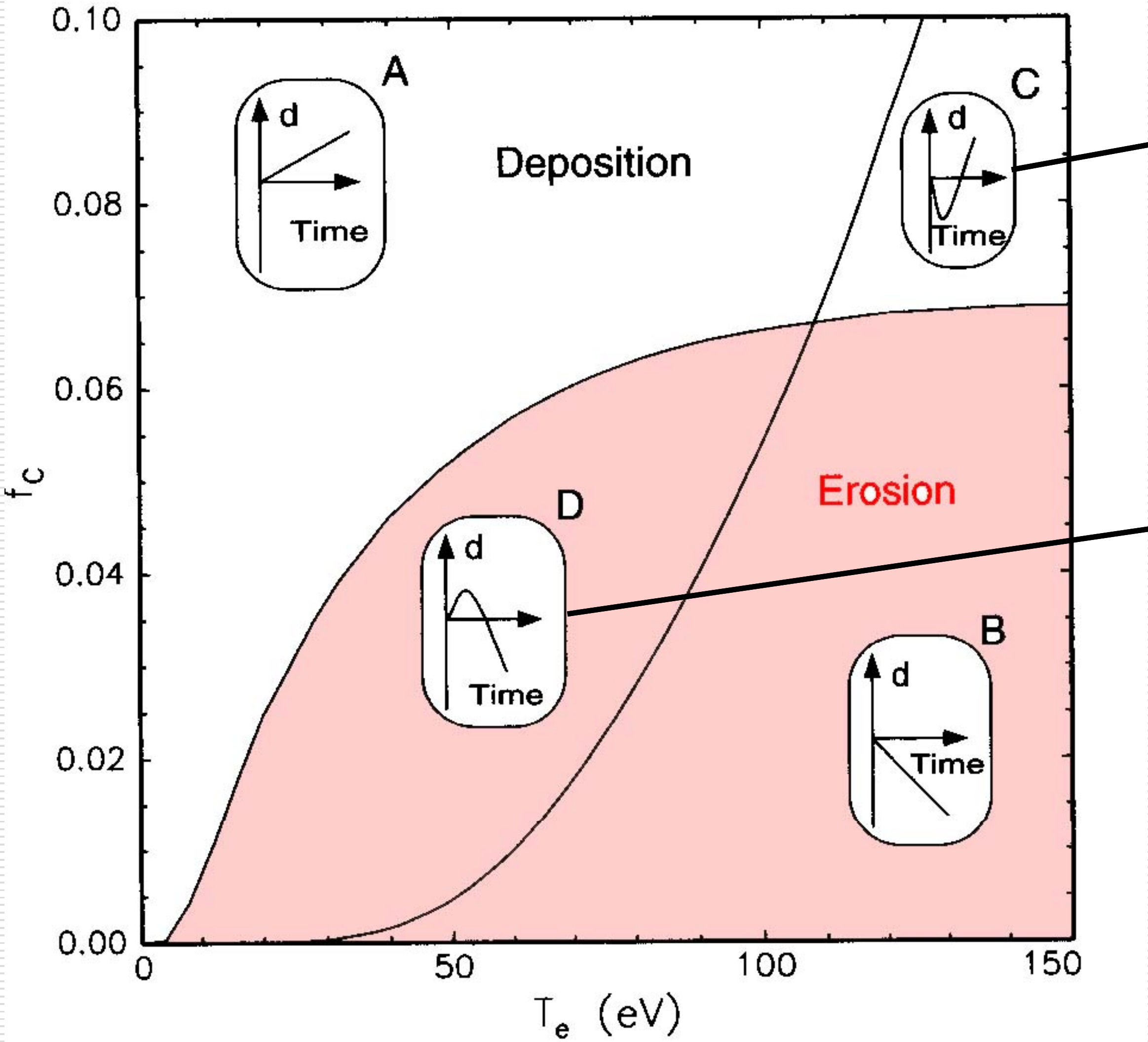
$$\Gamma_i f_C \left(1 - R_{CC}\Delta_C - R_{CW}\left(1-\Delta_C\right)\right) = \Gamma_i\left(\left(1-f_C\right)Y_{HC}\Delta_C + f_C Y_{CC}\Delta_C\right)$$

Injected C — C reflection by C (1) — C reflection by W (2) — C sputtered by H(3) — C sputtered by C (4)

Δ_c : Surface coverage of C (Δ_c=1 : fully covered by C)
Γ_i : Ion influx
f_C : C concentration in injected ions
R_{CC} : C reflection coefficient on C, R_{cw} : C reflection coefficient on W
Y_{HC} : Sputtering yield of C by H, Y_{CC} : Sputtering yield of C by C (self-sputtering yield)

- More complicated for real system
  - How to determine the thickness of layers for Δ_c
    - Actually, for (1), (2), (3), and (4), thickness is different.
  - Sputtering and reflection are not simple linear function of Δ_c .
  - How does thermal effect play roles?
    - Surface segregation, diffusion

Initial surface evolution under D+C →W



Carbon concentration in plasma

Electron temperature (corresponding ion energy)

Initially, energetic C ions erode W.

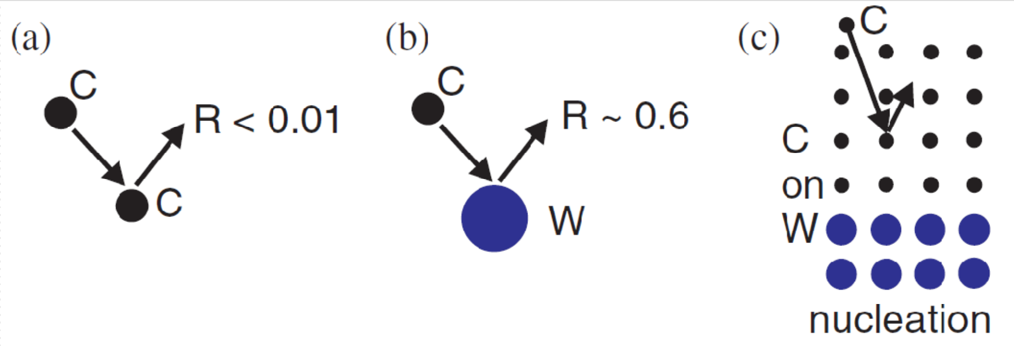
Initially C deposition prevails W erosion because of low C energy.

"Plasma Material Interaction in Controlled Fusion", D. Naujokes, Springer

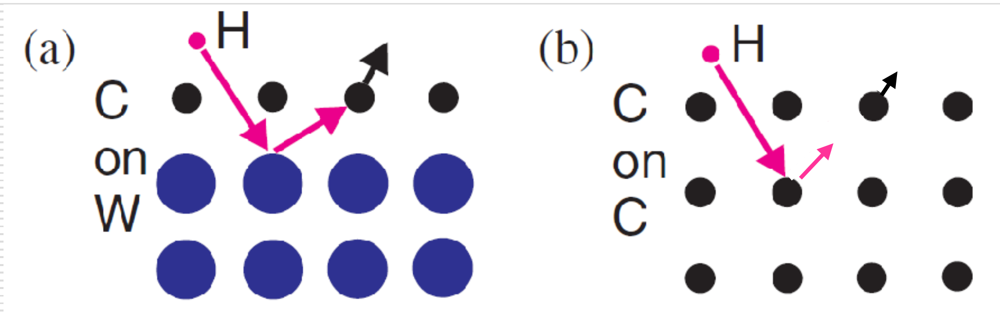
Reflection and phys. sputtering of C on W

- Reflection coefficient is lower than that on W
  - R~**0.6** (50eV C to W)
  - R~$\mathbf{10^{-4}}$(50 eV C to C)
- Carbon mono-layer is easily re-sputtered by reflected H from W substrate.

→ Carbon deposition is more pronounced on graphite.



Difference in reflection

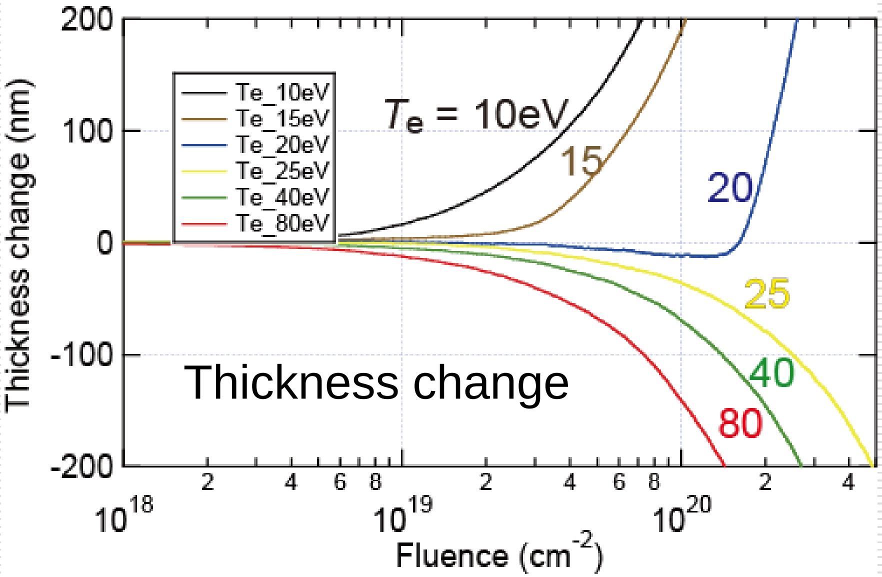


Enhancement of sputtering of surface C

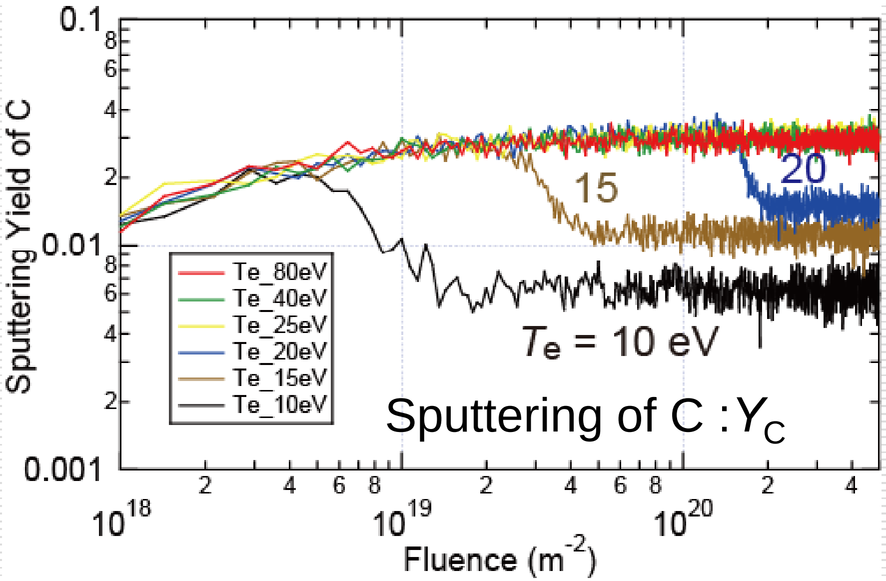
A. Kreter, et al.,
Plasma Phys. Control. Fusion 48 (2006) 1401

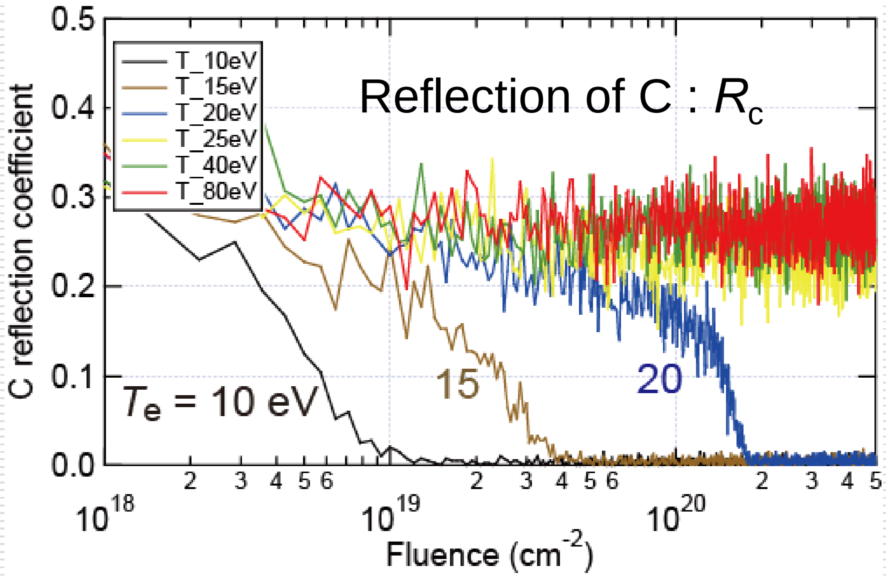
Computer simulation by EDDY

Acknowledgment (K. Ohya)



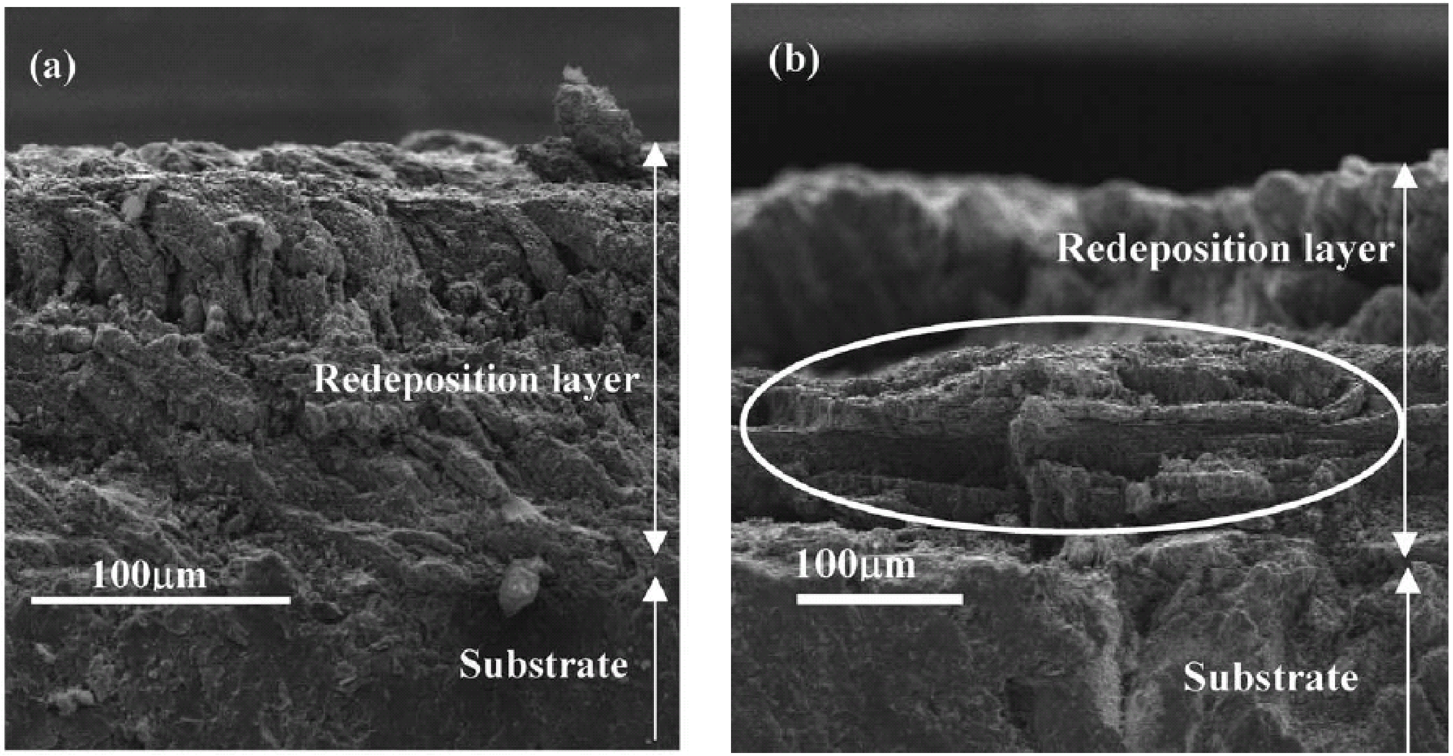
- D$^+$ + C^{4+} mixed ion irradiation to tungsten
- Simulated by EDDY code
  - D : 96%, C : 4%
- No chemical sputtering
- As deposition proceeds, Y_c and R_c drastically decrease.





Deposition layer : quite different from solid C

- Different structure depending on Temperature, flux, D ratio, etc.
- C deposition layer is not dense (0.91 g/cm^3 on JT-60U tiles (2.23 g/cm^3 for graphite crystal)).
  - Y. Ishimoto et al., J. Nucl. Mater. 350 (2006) 301.



Structure of C deposition layer (JT-60U)

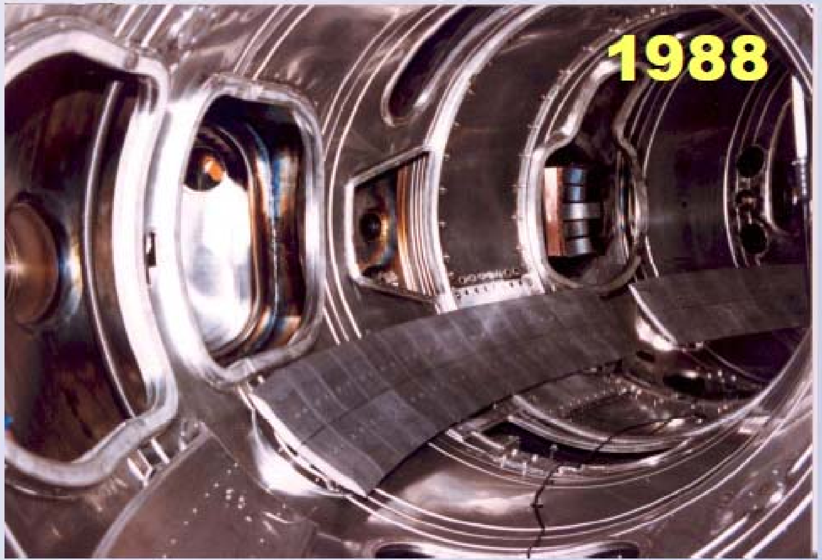
Some comments on erosion

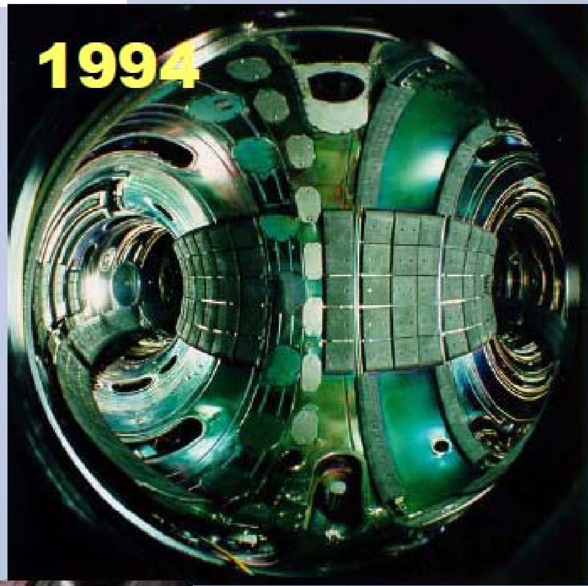
- Chemical erosion of C deposition layer
  - Depends on bulk properties (Soft C-H film (H/C~1), Hard C/H film (H/C~0.4))
    - W. Jacob, J. Nucl. Mater. 337-339 (2005) 839.
  - Local ^{13}C deposition experiments and their simulations suggest enhanced re-erosion of C deposition layer.
    - A. Kirschner et al., J. Nucl. Mater. 328 (2004) 62.
- Chemical erosion of C in mixed layer with W
  - In general, C in mixed layer has lower chemical sputtering yields than graphite.
  - Temperature dependent C-selfsputtering was reported. But mechanism is not well known.
    - H. T. Lee, K. Krieger, J. Nucl. Mater. 390–391 (2009) 971.

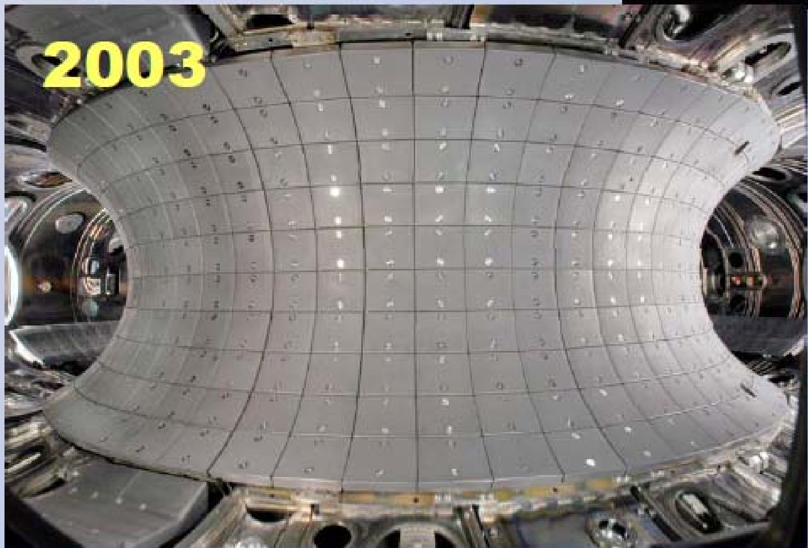
Carbon deposition on W

(TEXTOR test limiter experiments)

TEXTOR – a test bed for power exhaust concepts ...

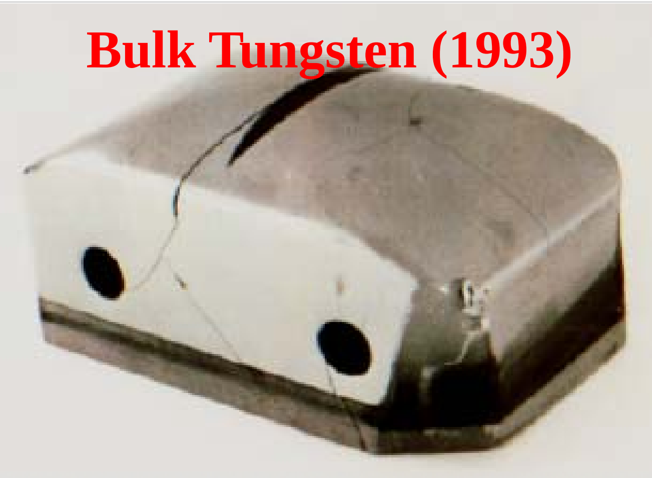




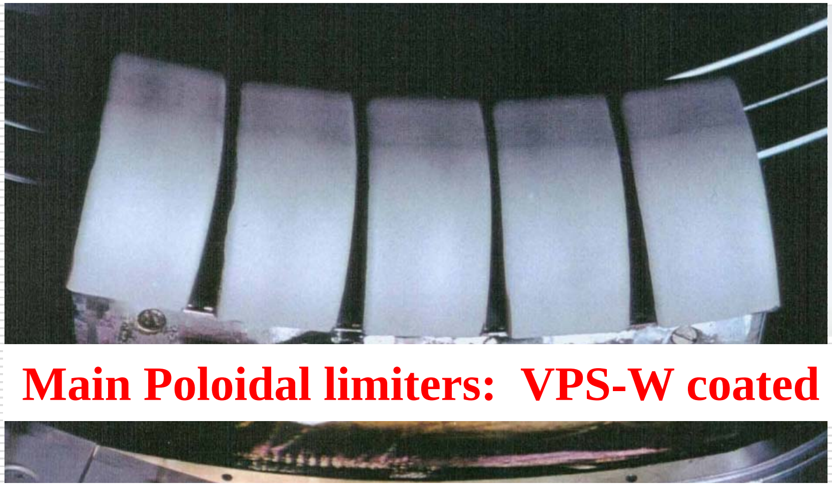


Forschungszentrum Jülich

High Z test limiter experiments

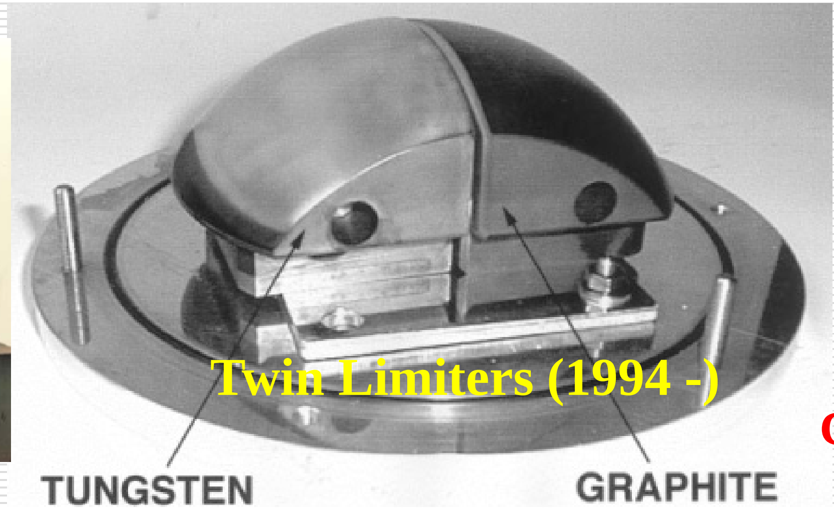


Bulk Tungsten (1993)

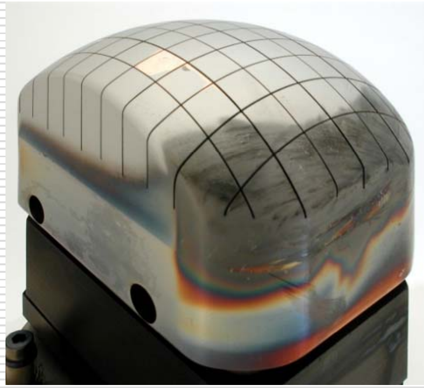


Main Poloidal limiters: VPS-W coated grahite (1998-1999)

Bulk Tungsten (1996 -)



Twin Limiters (1994 -)



Castellated W (1999-)

Subjects: Material test, erosion and transport, melt layer behavior, carbon redeposition

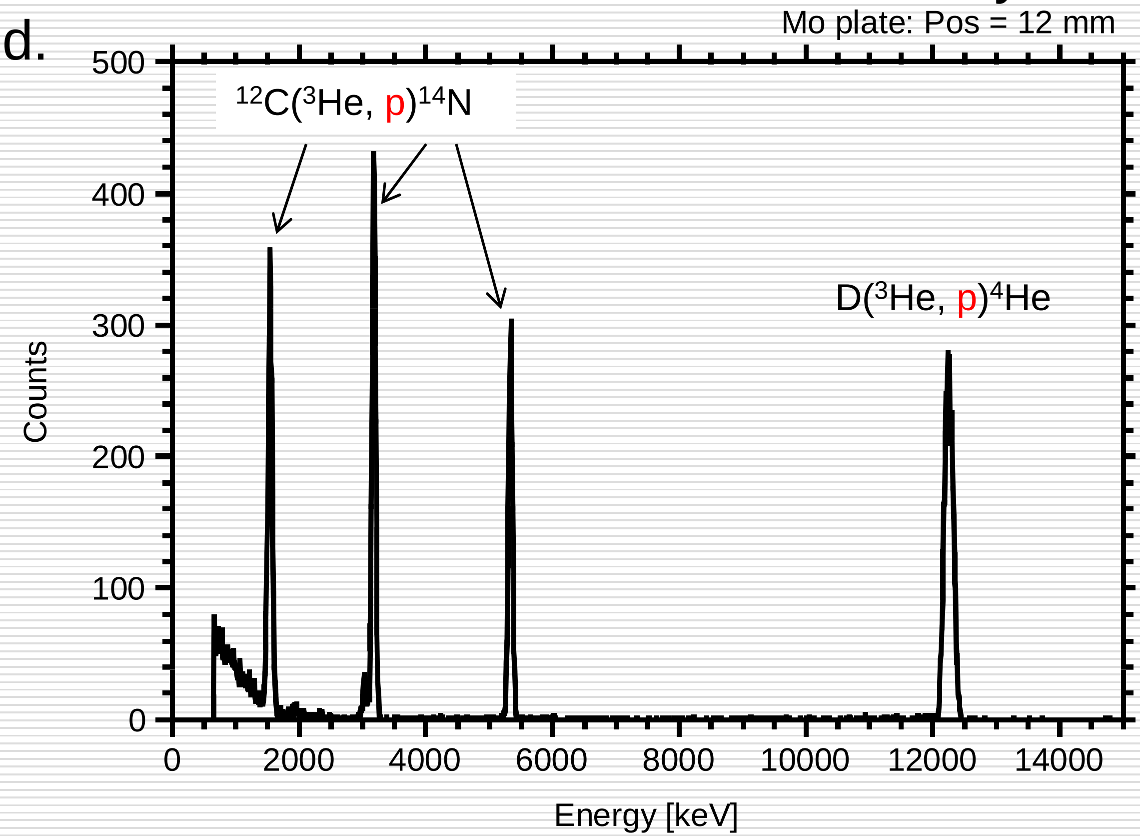
Experimental conditions for TEXTOR experiments

- Effects of surface roughness on C deposition
  - Tungsten
    - Roughness R_a = 9 ~180 nm
  - Graphite (fine grained graphite)
    - Roughness R_a = 70 ~700 nm
  - He plasma pre-exposed W
    - Nano-structure formed
- C deposition on tungsten at elevated temperatures
  - Temperature range
    - ~300 ºC : ~ITER wall
    - ~550 ºC : ~Chemical Sputtering peak
    - ~850 ºC : Thermal diffusion + RES

NRA measurements (IPP Garching)

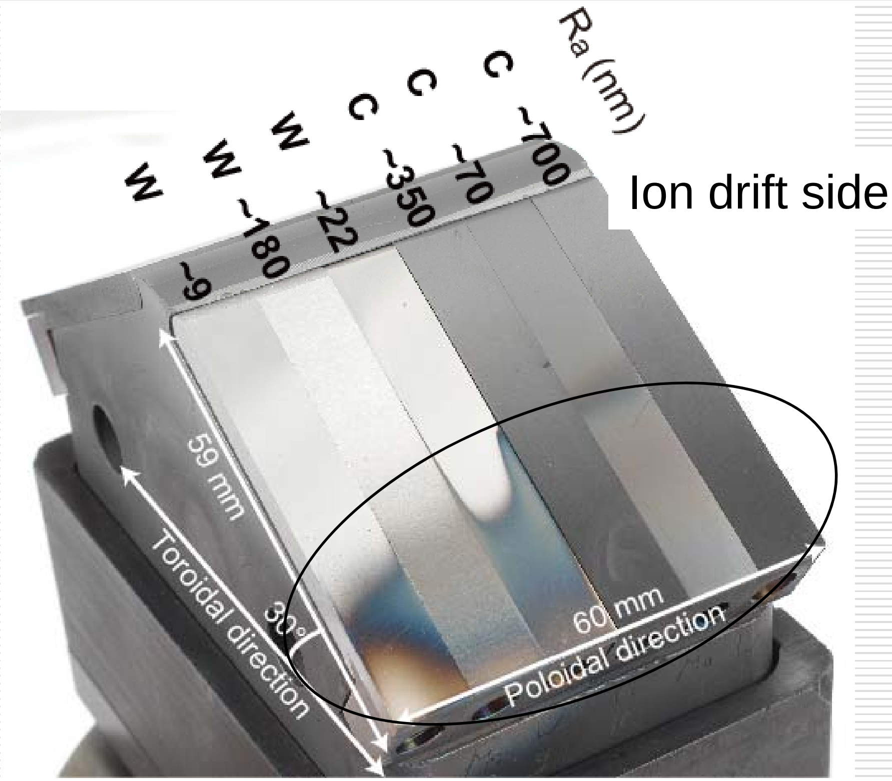
NRA (Nuclear Reaction Analysis)

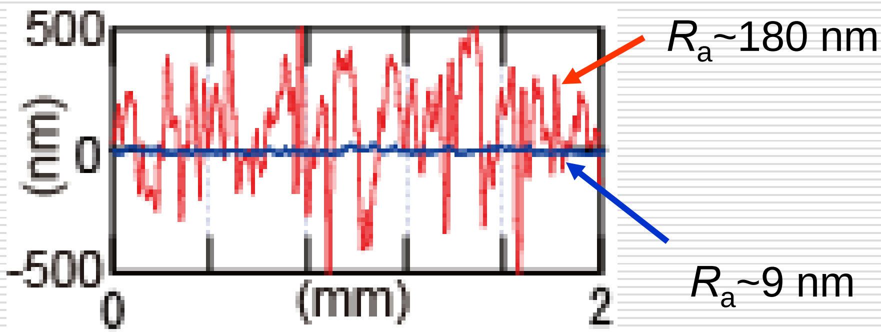
- Analysis beam: 2.5 MeV $^{3}He^{+}$
- Protons produced by D(^{3}He, p)^{4}He & ^{12}C(^{3}He, p)^{14}N nuclear reactions were detected.
- Absolute amounts of D and ^{12}C were determined by each proton yield.



Setup for study on surface roughness effects

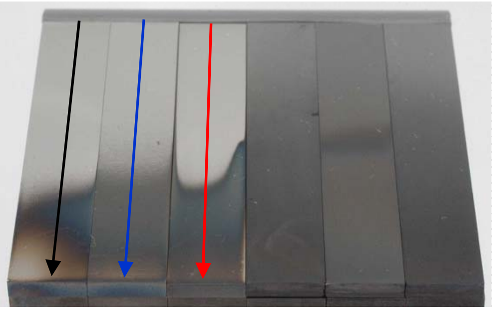
- Pure W samples
  - R_a~9 nm, ~22 nm, ~180 nm
  - Difference in surface polishing
- Graphite (fine grained)
  - R_a~70 nm, ~350 nm, ~700 nm
- Deposition mechanism
  - Lower T_e deeper into SOL
  - Higher carbon density deeper into SOL



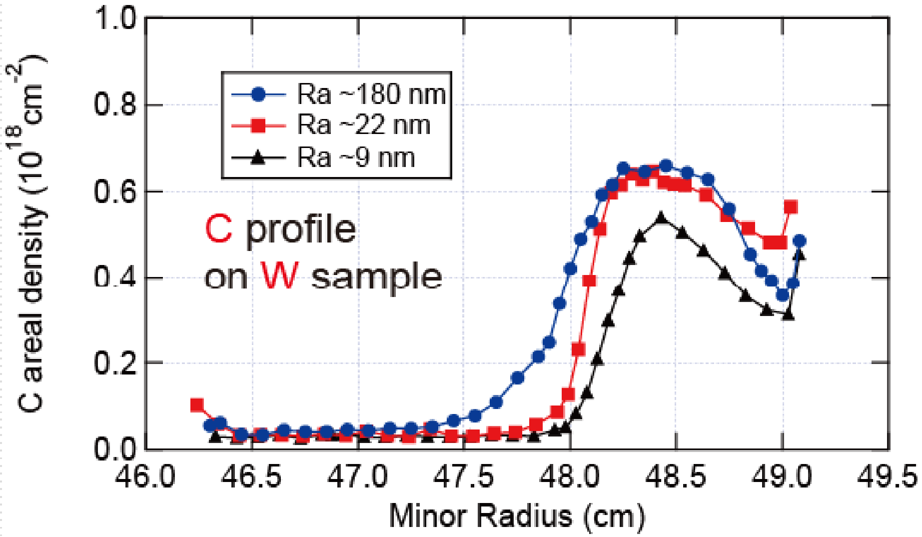


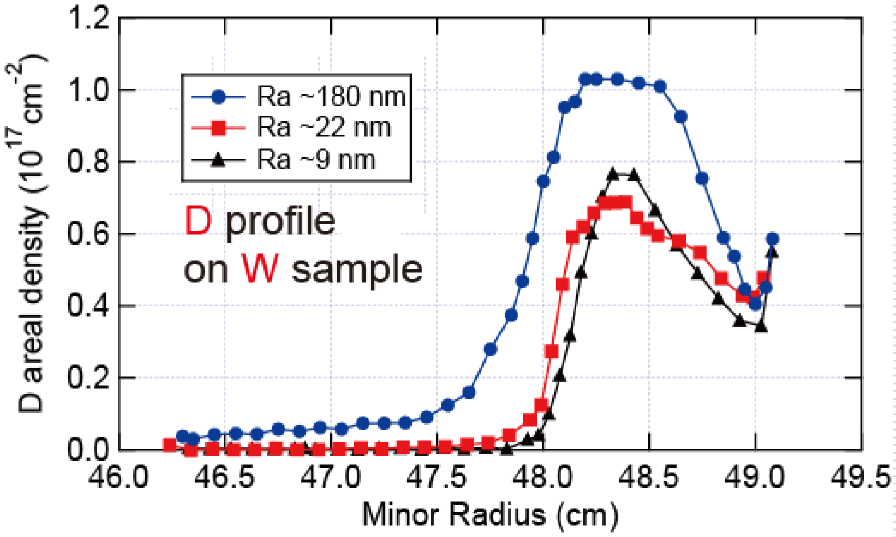
C deposition and D retention on W

- C deposition
  - Roughness enhances C deposition
  - R_a~180 nm : Long tail
  - Sharpe boundary between erosion and deposition
- D retention
  - similar to C deposition
  - no surface retention in erosion zone
  - D/C = 0.1~0.15



W Graphite

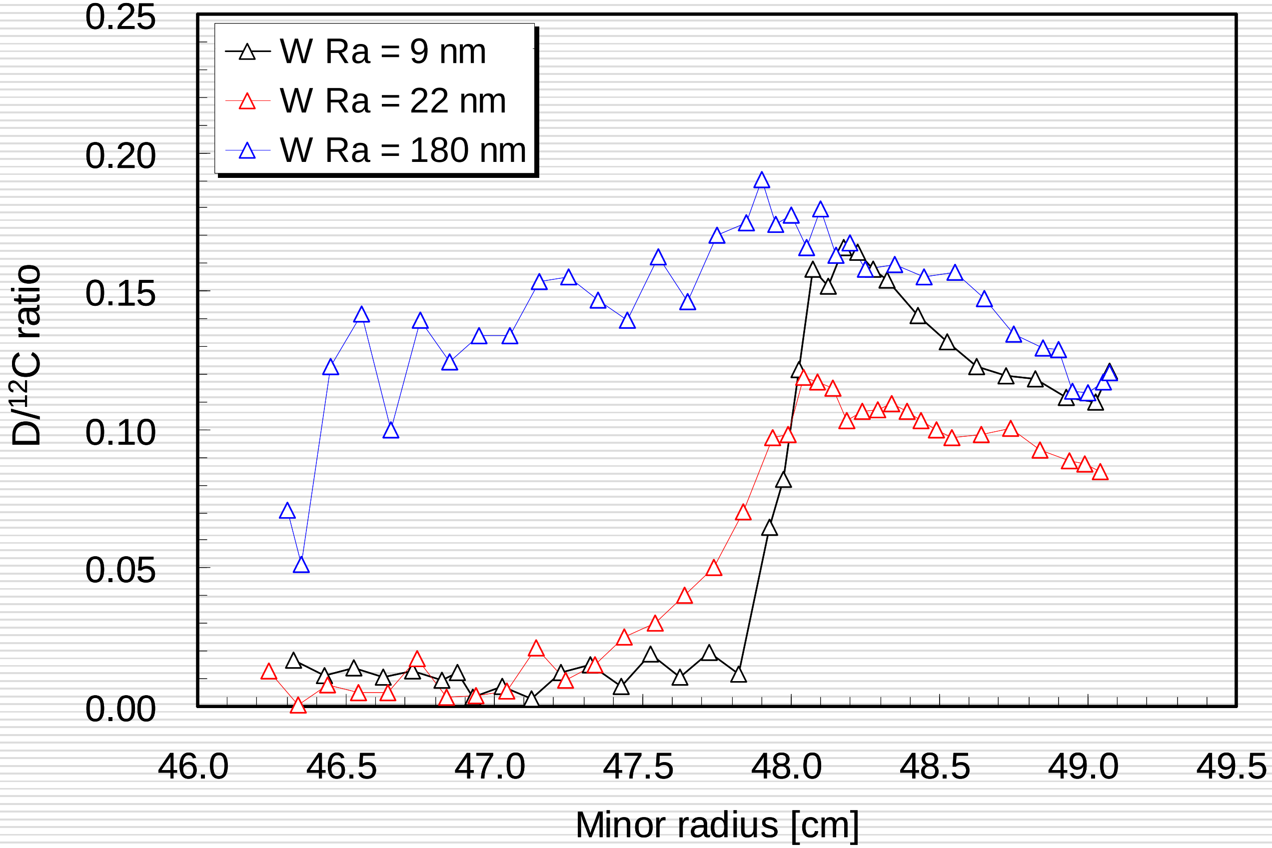




NRA measurement

D/C ratio in C deposition layer

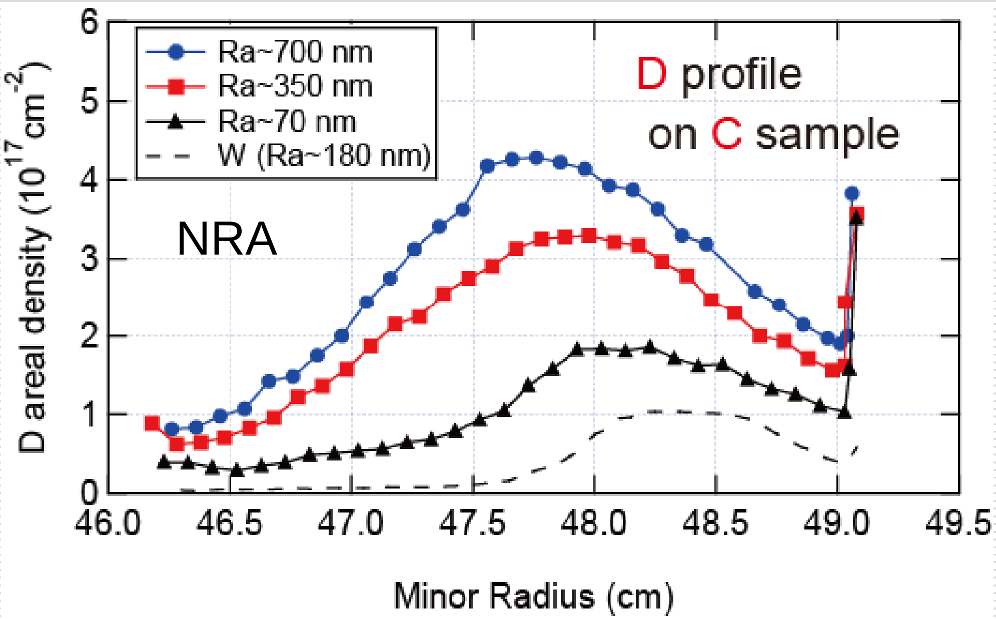
- For the roughest case (R_a = 180 mm), the region of D/C ~ 0.1-0.15 extends to r ~ 46.5 cm, suggesting thin C deposition layer exists over wide area of the sample.

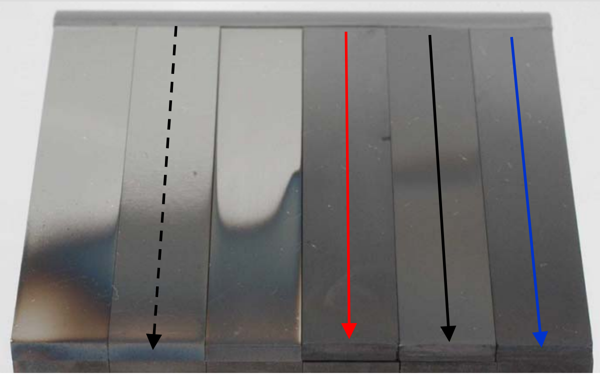


Profiles of D/C ratio in C deposition layers

D retention (C deposition) on graphite

- C deposition on graphite
  - D retention was mainly in C deposition layer
  - D/C ~ const in deposition layer
    - **D retention ~ C deposition**
- Characteristics of C deposition on graphite
  - Roughness enhanced C deposition also on graphite
  - No sharp transition between erosion and deposition

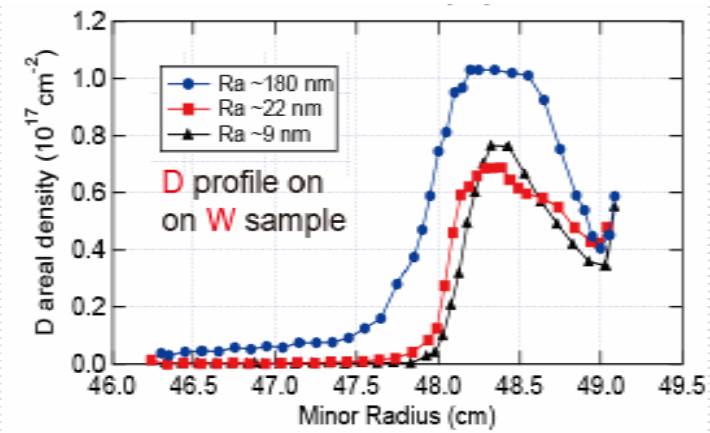


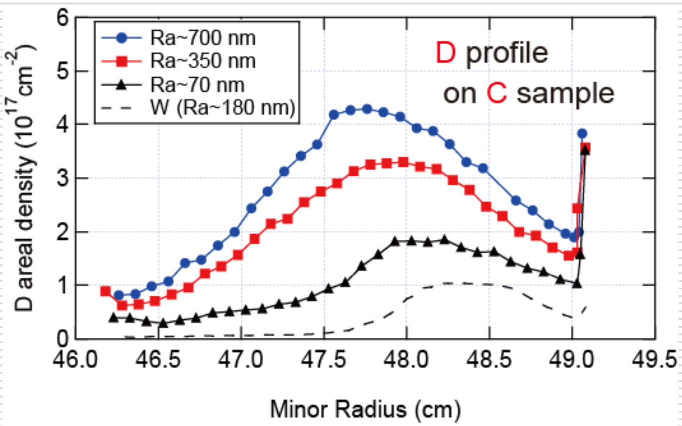


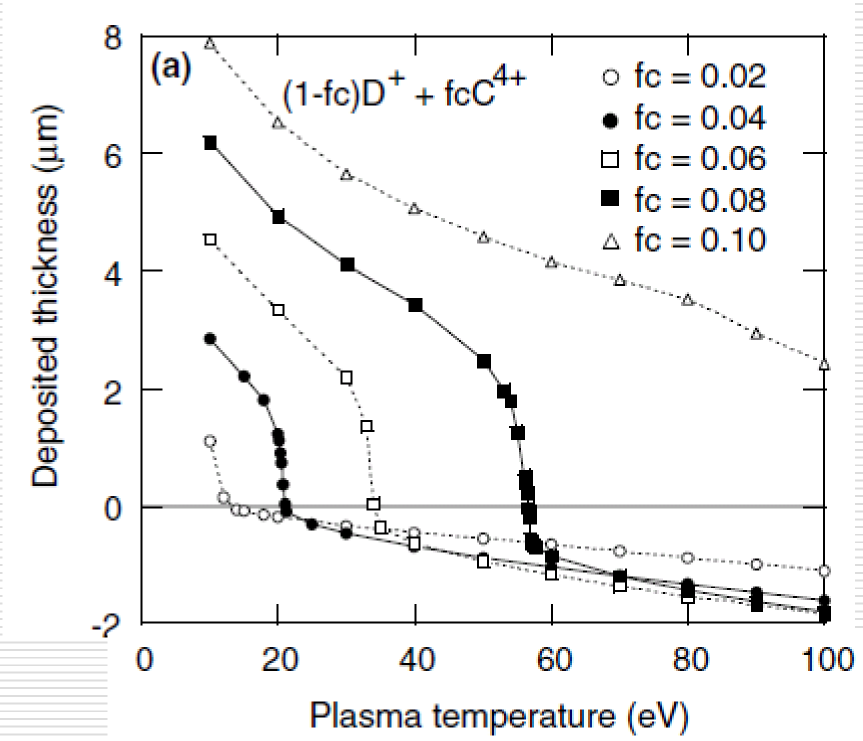
Measured position

Sharp C deposition- erosion boundary on W

- C deposition rate is much higher on C than W.
- Once C deposition layer is formed, the deposition rate increases.
- Sharp boundary is formed.





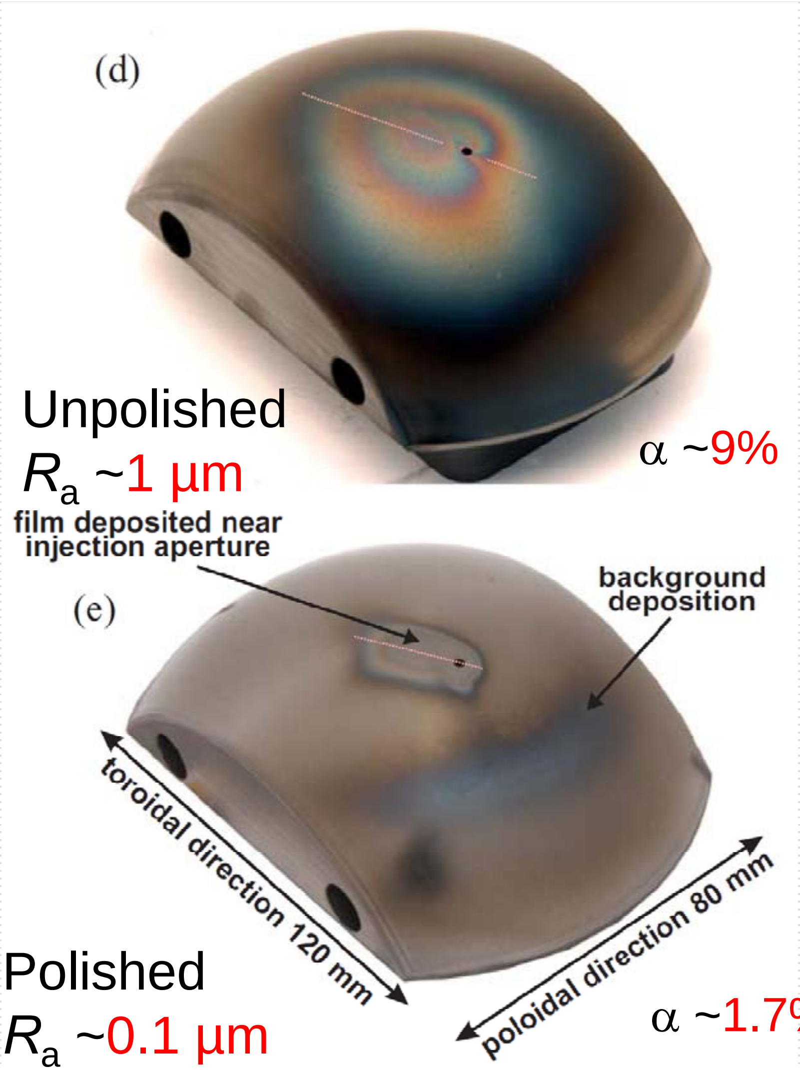


Simulation of C deposition

K. Ohya et al., J. Nucl. Mater. 337–339 (2005) 882

$^{13}CH_4$ puff exp. with graphite limiter (TEXTOR)

- C deposition on graphite test limiter (TEXTOR exp.)
  - Deposition Efficiency α
    - Deposited ^{13}C /injected $^{13}CH_4$
  - C on unpolished C (R_a ~ 1 μm)
    - α ~9%
  - C on polished C (R_a ~ 0.1 μm)
    - α ~1.7%
- <u>Surface roughness seems to affect C deposition</u>
  - Similar or larger than substrate effects (W or graphite)

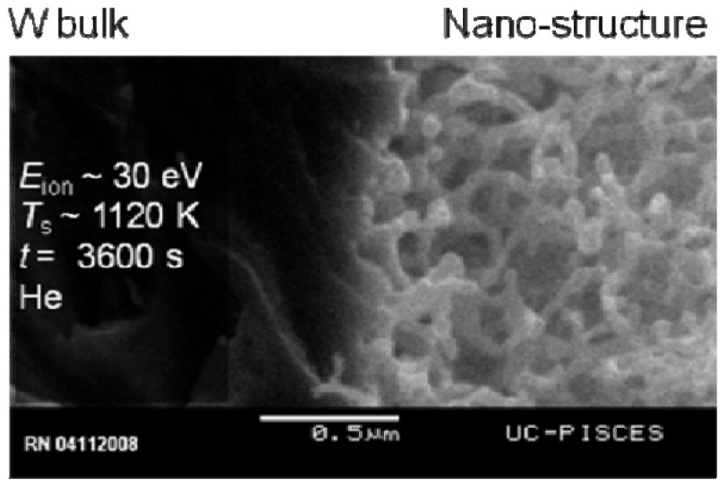


<u>Ohmic discharge</u>

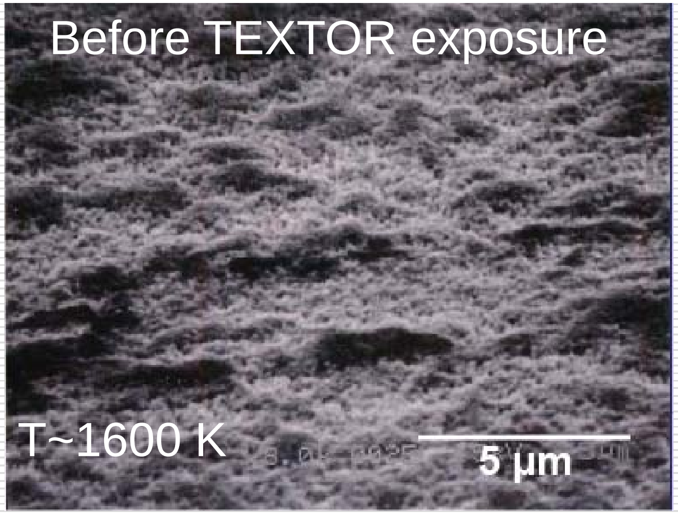
<u>A. Kreter, et al., Plasma Phys. Control. Fusion (2008)</u>

C deposition on He pre-exposed W

- He plasma pre-exposure
  - High density pure He plasma exposure in NAGDIS-II (Nagoya U.)
  - Black surface after ~1h exposure at 1300 ºC (flux ~10^{23} $m^{-2}s^{-1}$)
    - He bubble and nanostructure formation
  - Surface structure removed before TEXTOR plasma exposure
    - Loosely bound nano-structure was wiped out mechanically
- Roughness of He exposed W
  - Roughness ~15 nm (after exp.)
    - Small pits could be missing due to stylus type measurement



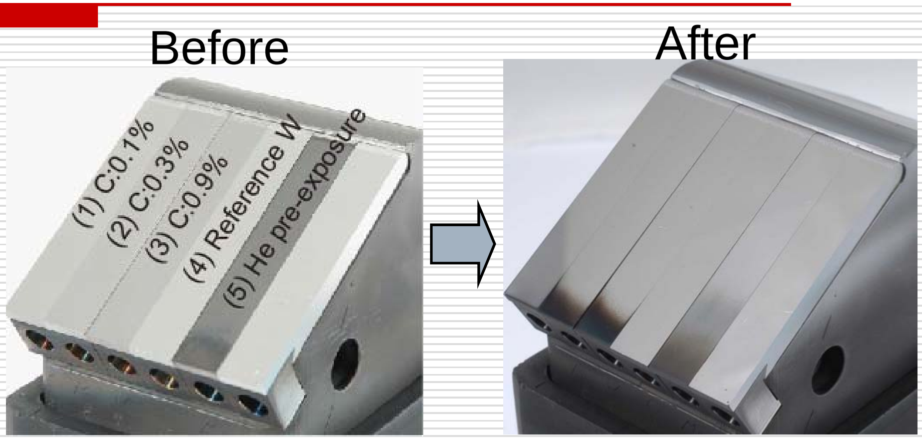
M. Baldwin et al., I-20, PSI18



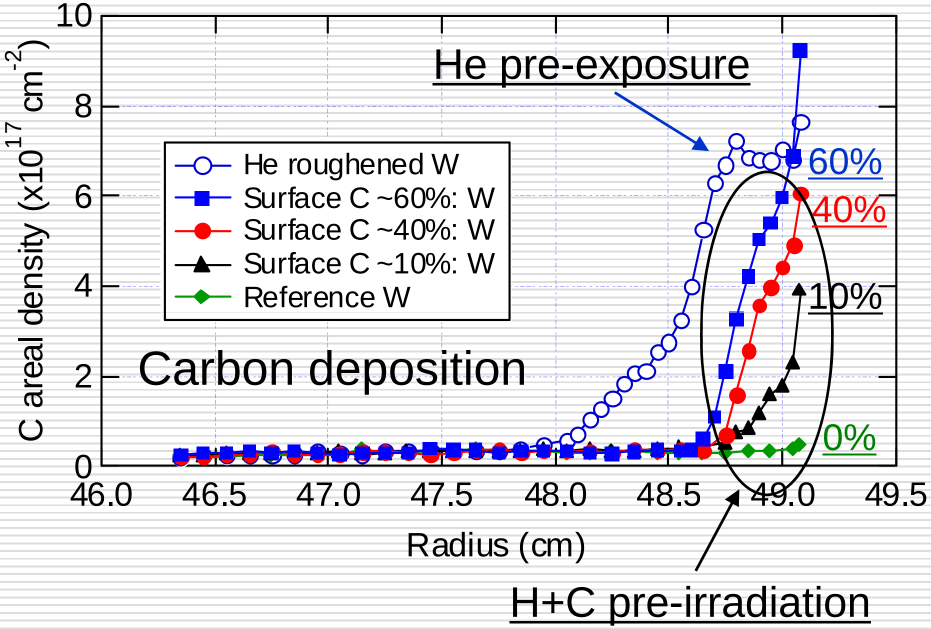
W surface in this work

C deposition on He pre-exposed W

- He pre-exposed W
  - Enhancement of C deposition
  - C profile : long tail
    - increase in deposition area
  - large enhancement of deposition despite small roughness (~15 nm)
- H+C pre-irradiated W
  - C deposition speed relates to surface C concentration
    - only 10% initial C affects deposition
    - No deposition on pure W (0%C)
  - R_a ~ 10 nm for each W

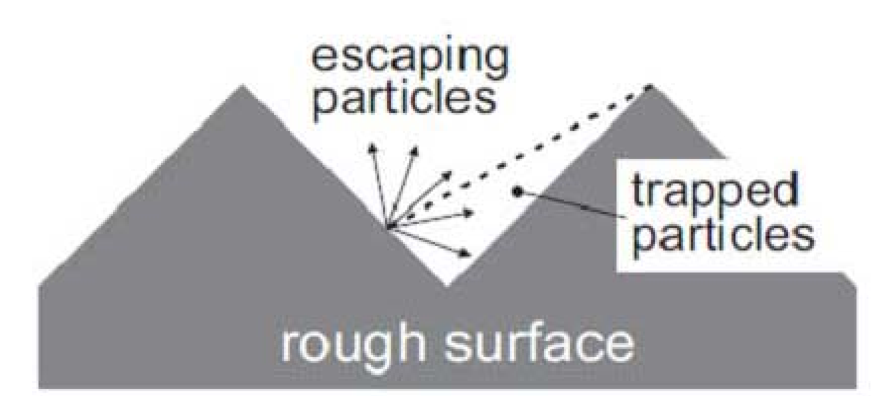


46 shots (Ohmic plasma)
r = 46 cm (same as LCFS)



Explanation of roughness effect on deposition

- Roughness (0.01-1 μm) << Ion Lamor radius (0.1-1mm)
  - D ion flux and C ion flux did not change locally
  - Local shading effect of D ions may not occur
- Some of sputtered or reflected particles redeposited immediately.
  - Trapping rate depends on the morphology
  - He roughened surface was very fine and complicated structure
    - **He induced roughness could have high trapping rate** (C deposition)



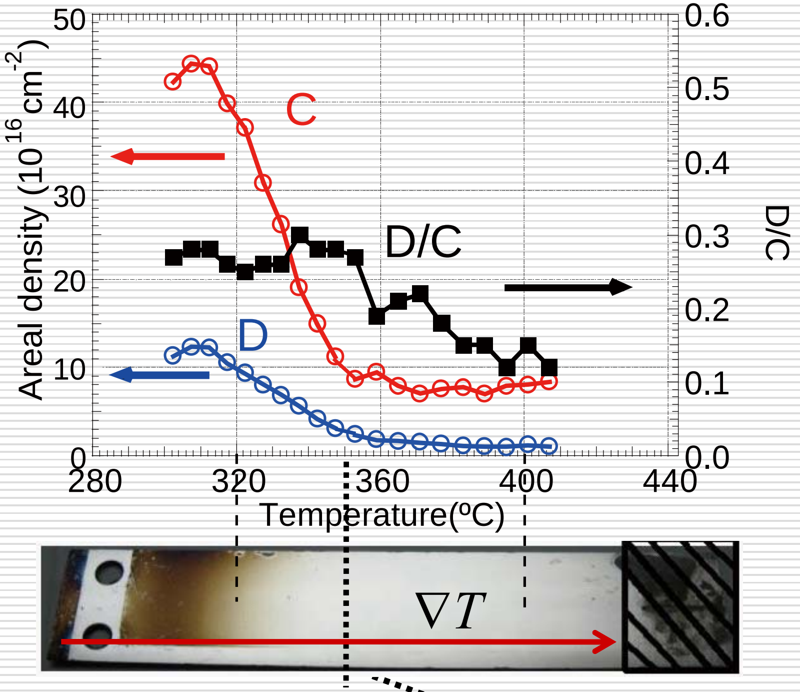
M. Kunster et al., Nucl. Instrum. Meth.B145 (1998)320.

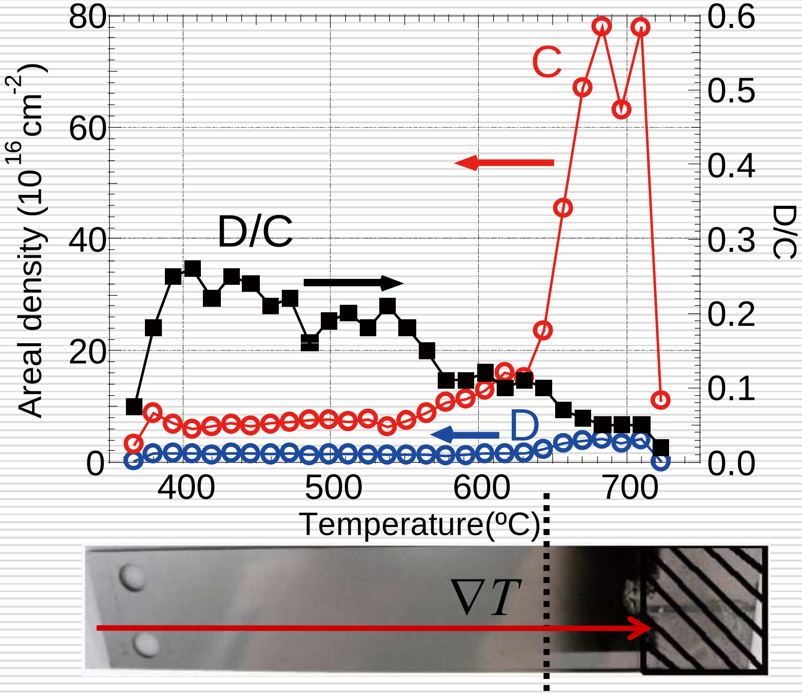
He roughened W surface

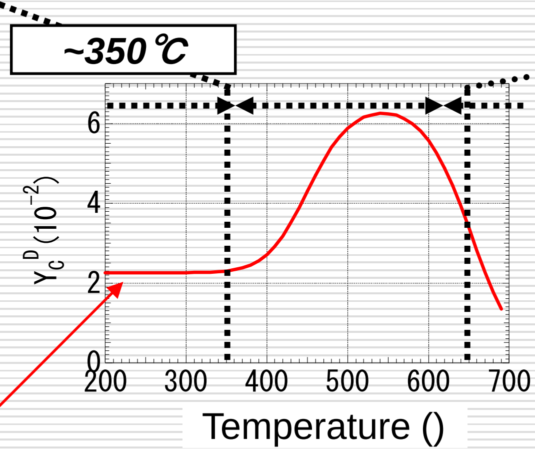
Experimental conditions for TEXTOR experiments

- Effects of surface roughness on C deposition
  - Tungsten
    - Roughness R_a = 9 ~180 nm
  - Graphite (fine grained graphite)
    - Roughness R_a = 70 ~700 nm
  - High density He plasma pre-exposed W
    - Nano-structure formed
- C deposition on tungsten at elevated temperature
  - Temperature range
    - ~300 ºC : ~ITER wall
    - ~550 ºC : ~Chemical Sputtering peak
    - ~850 ºC : Thermal diffusion + RES

Temperature dependence of C deposition





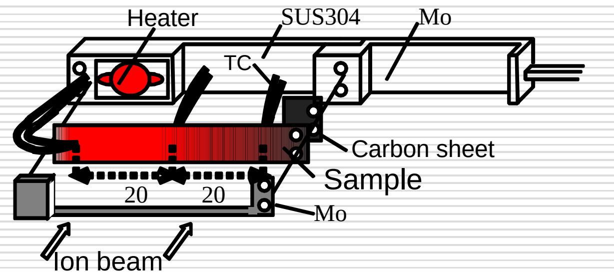


Temperature dependence of C sputtering yield （Roth (1996)) for 150 eV D

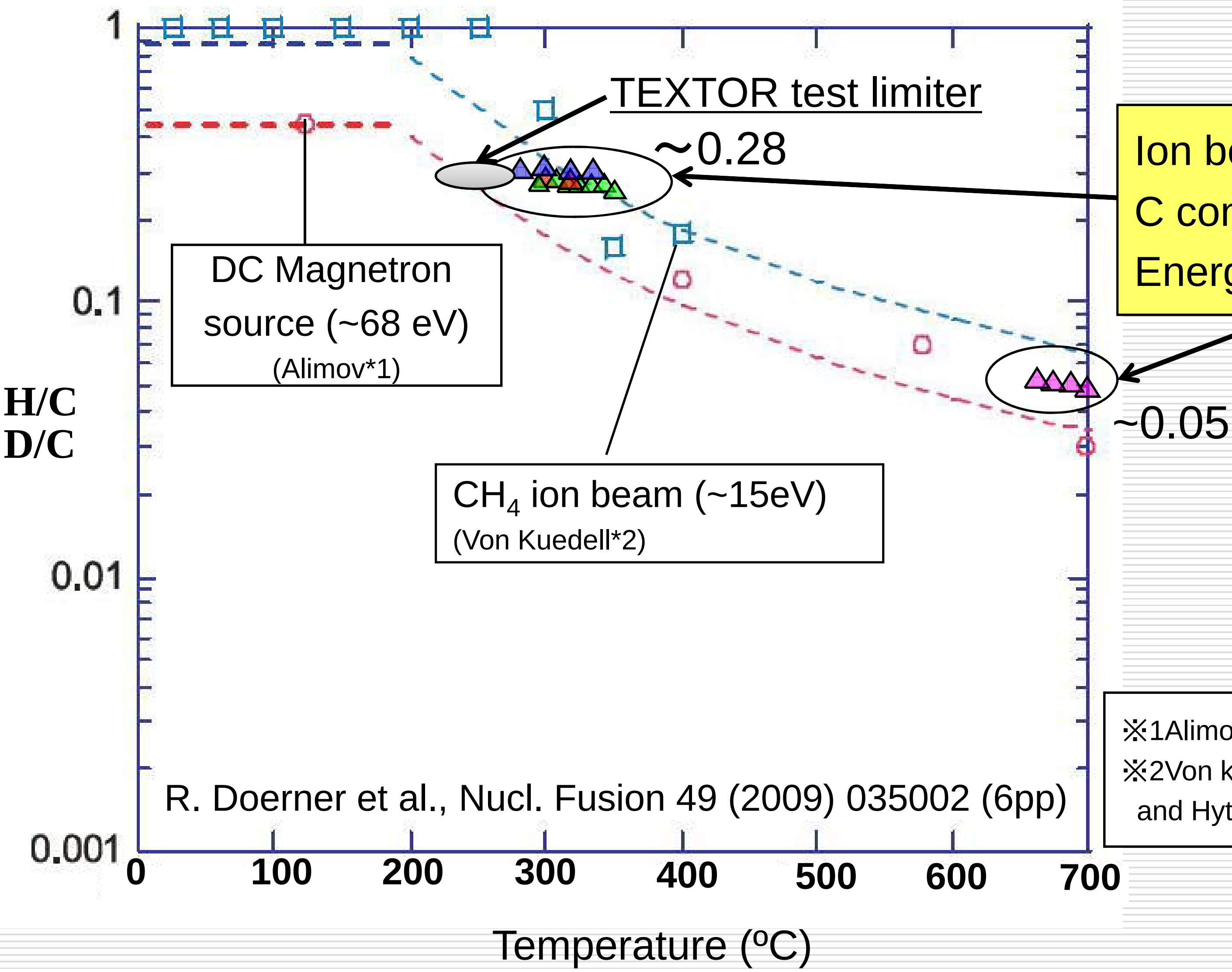
HiFIT experiments

Ion beam energy : 150 eV
Flux : 1.3 × 10^{20}/m^{2}sec
Irradiation time : 6600 sec
C ratio in ion beam : 6.4%

Clear correlation between C deposition and C sputtering



Comparison with previous C deposition data



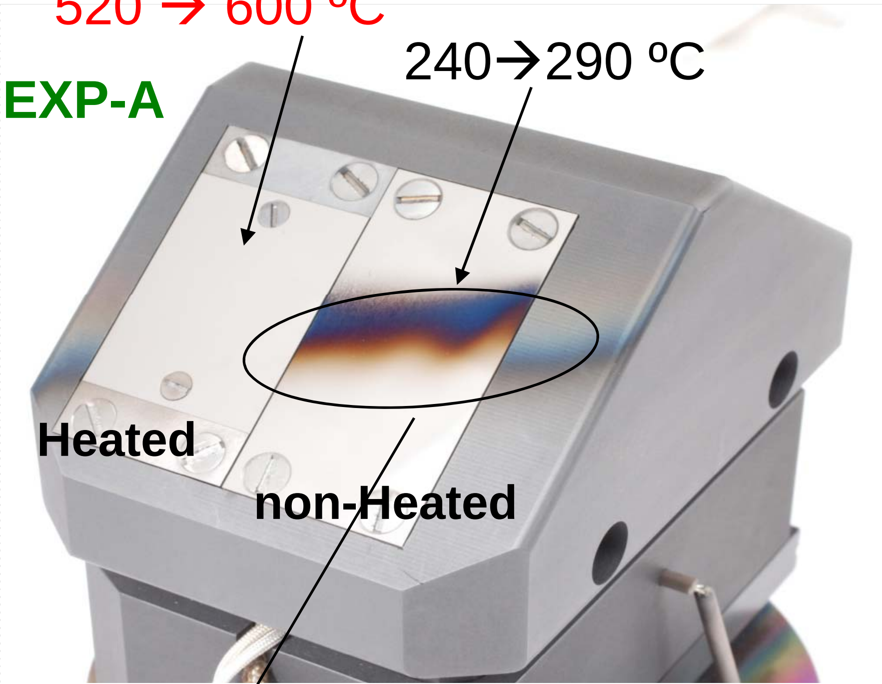
※1Alimov V.Kh. 2004 Phys .Scr.T 108 46
※2Von keudell A./ Moller W. and Hyty R.1993 Appl.Phys 62 937

Partially heated limiter exp. for C deposition on W

520 → 600 ºC

240→290 ºC

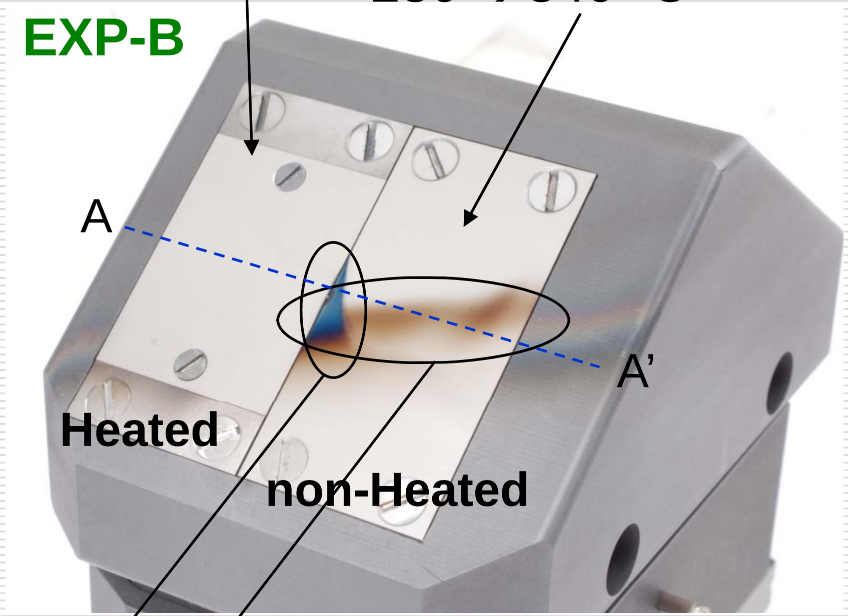
EXP-A



770 → 930 ºC

280 →340 ºC

EXP-B



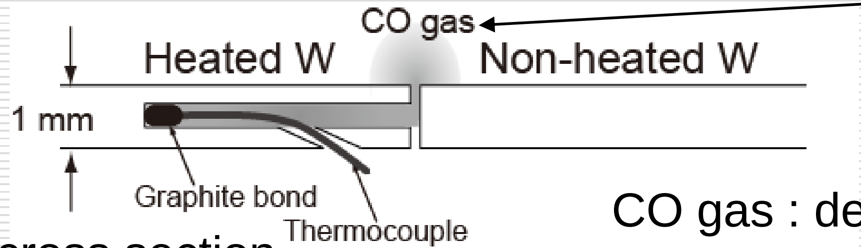
Deposition by edge plasma exposure

No deposition on the heated sample.

Deposition by edge plasma exposure

Deposition due to "gas puff" (CO)

No deposition on the heated sample.



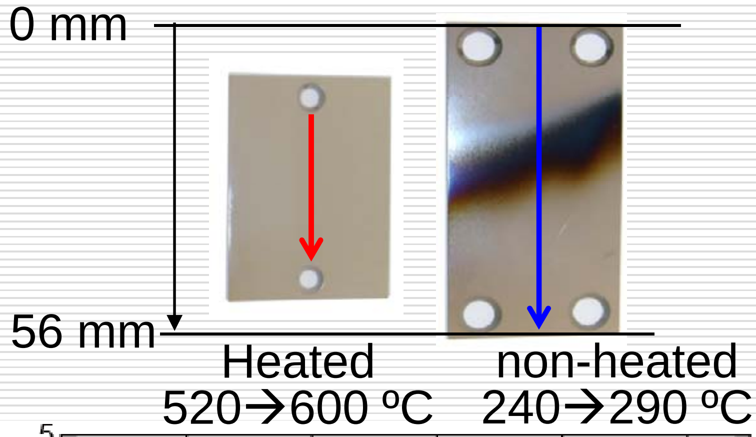
A-A' cross section

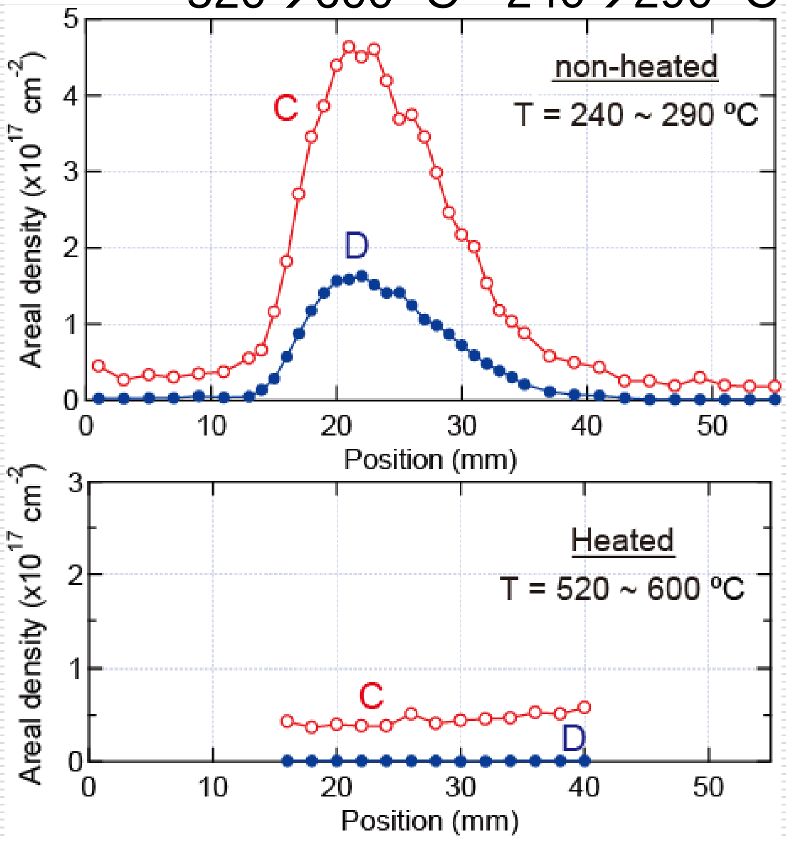
CO gas : desorbed above **~700 ºC**

Partially heated limiter exp. (heated W : 520 ºC)

- non-heated W (240 ºC~280 ºC)
  - Beltlike C deposition (asymmetry)
  - D retention only on C deposition
  - D/C ratio ~ 0.3

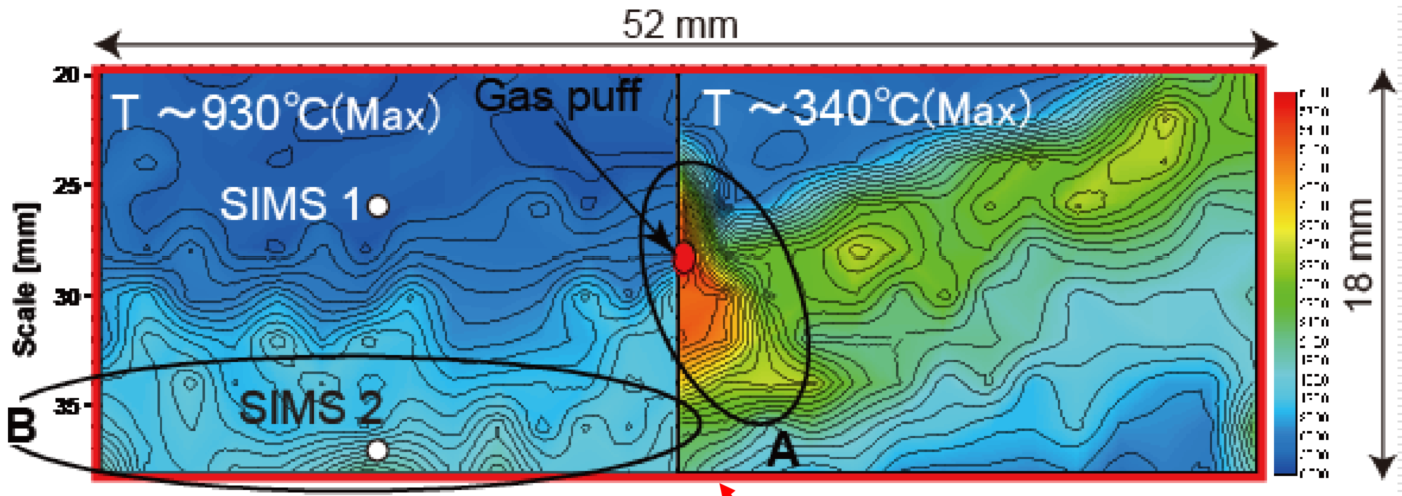
- Heated W (520 ºC~600 ºC)
  - no C deposition
  - no near surface D retention
  - near peak T of chemical sputtering





Partially heated limiter exp. (heated W : ~930 ºC)

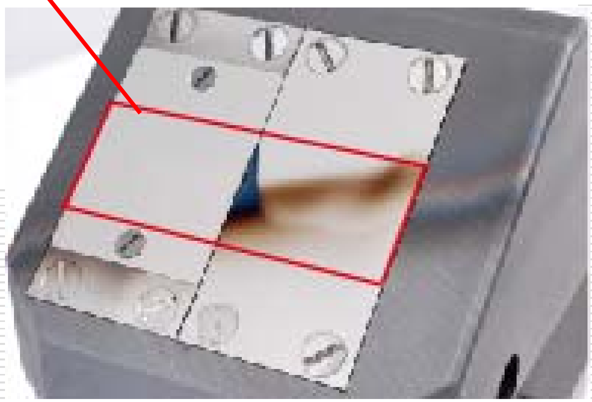
2D Carbon surface density (NRA)



Heated sample

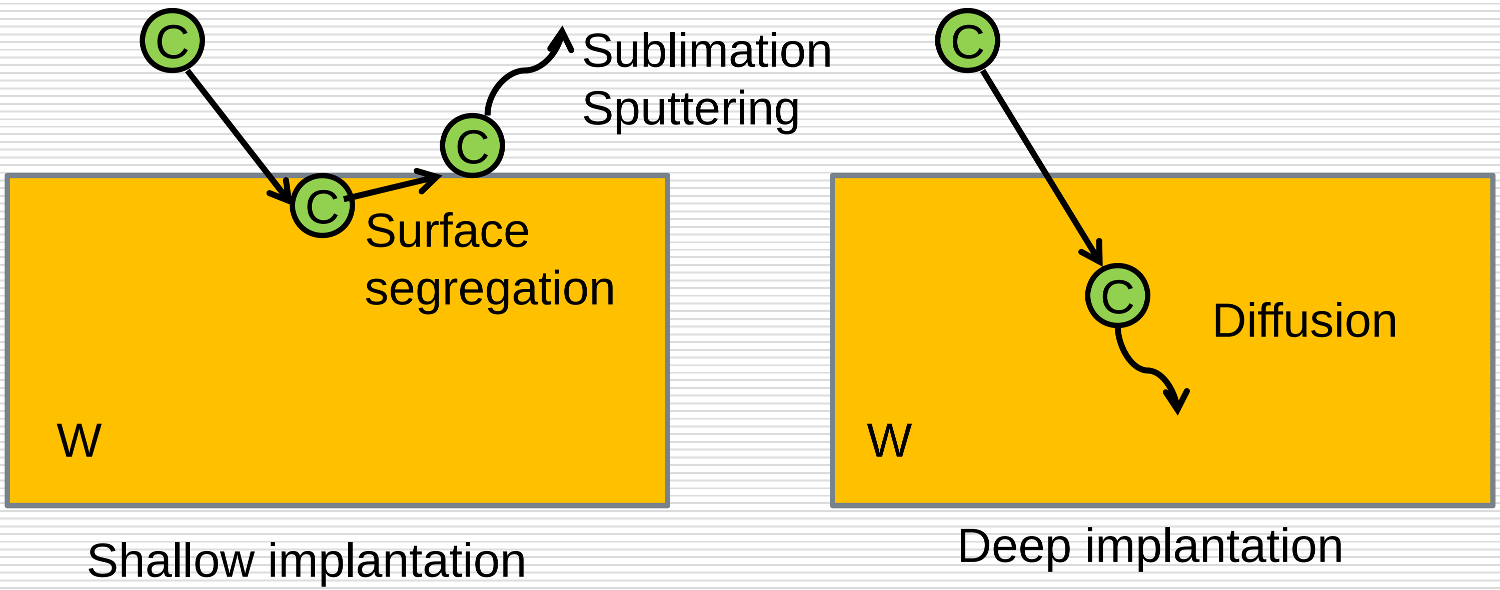
non-heated sample

- In area A (heated W)
  - No C observed near CO gas puff
- In area B (heated W)
  - C diffusion in bulk W



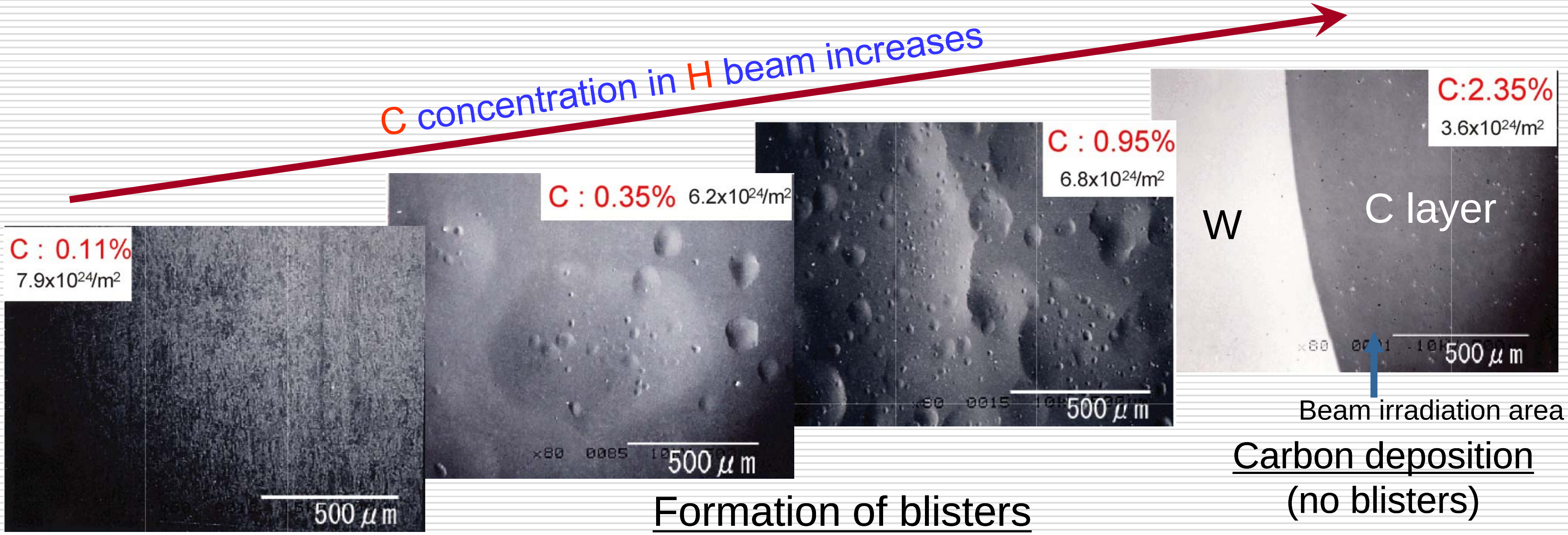
Possible reason for C behavior on high T tungsten

- Difference in Ion energy could be the reason
  - C in plasma : highly charged (~ +4), thermalized
    - impact energy E ~ 580 eV (T_e~T_i~40 eV)
  - C^+ or CO^+ from CO gas : singly charged, not thermalized
    - impact energy E ~120 eV (T_e~40 eV, T_i~0 eV)
    - Ion range ~ less than a few ML
    - **Implantation → Surface segregation → sputtering, sublimation**



Retention/blistering by simultaneous C/He/D exposure

Enhancement of blistering by carbon impurity



No blisters

Formation of blisters

Carbon deposition
(no blisters)

Small amount of carbon (less than 1%) in ion beam can enhance blister formation on W.

Experimental conditions

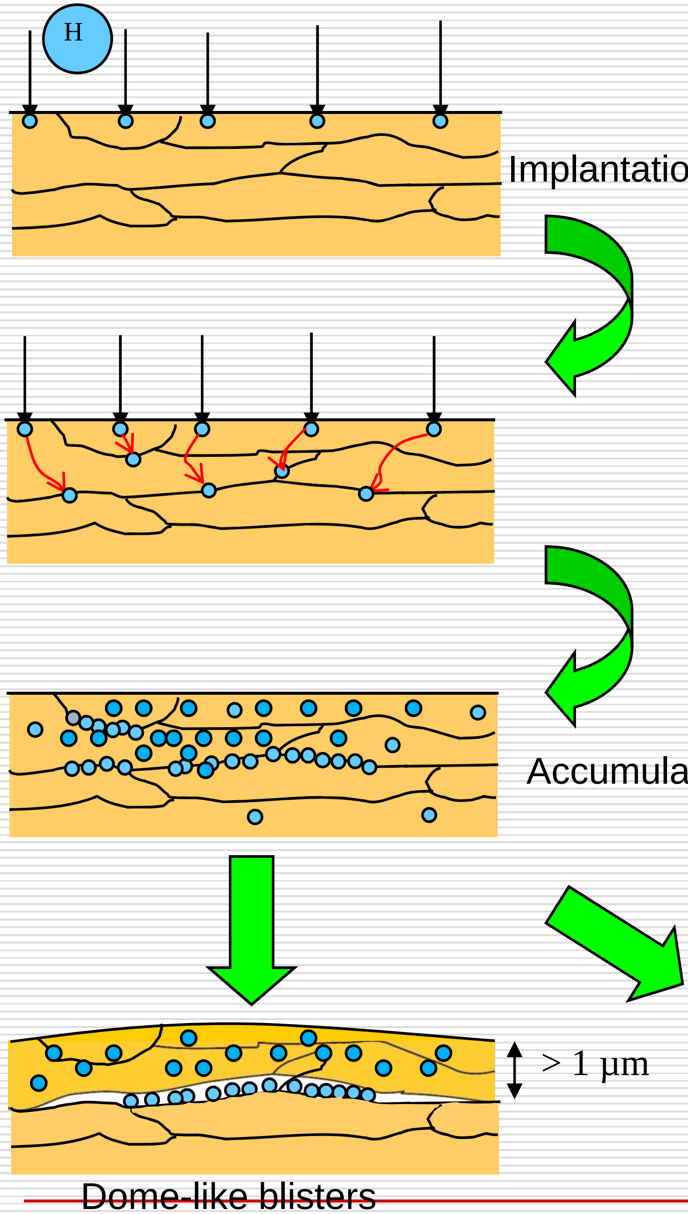
Beam Energy: 1keV H_3^+, Flux : (3-4)x10^{20} $Hm^{-2}s^{-1}$

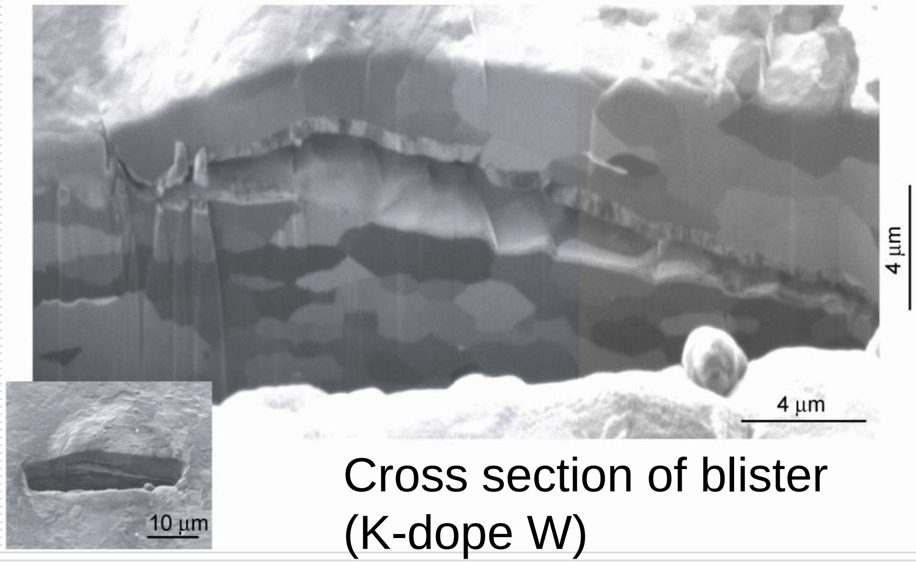
Temperature : 653 K

Sample : pure W with mirror polished

Osaka University

Mechanism for blistering (K-doped Poly-W)

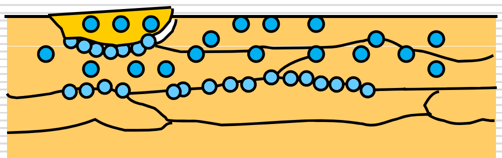




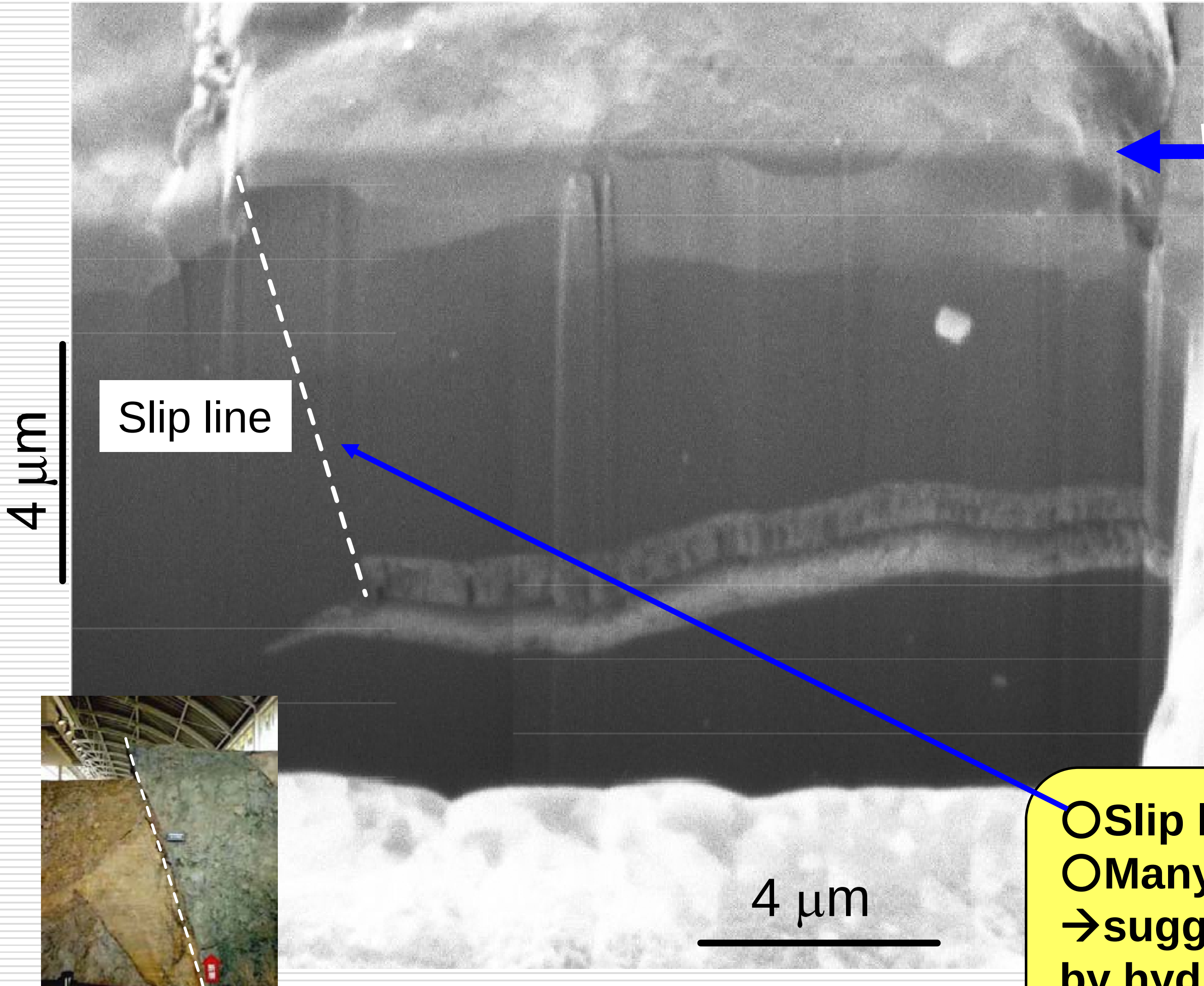
Cross section of blister (K-dope W)

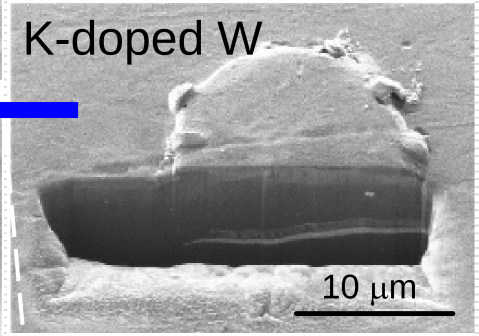
What is a driving force for plastic deformation?

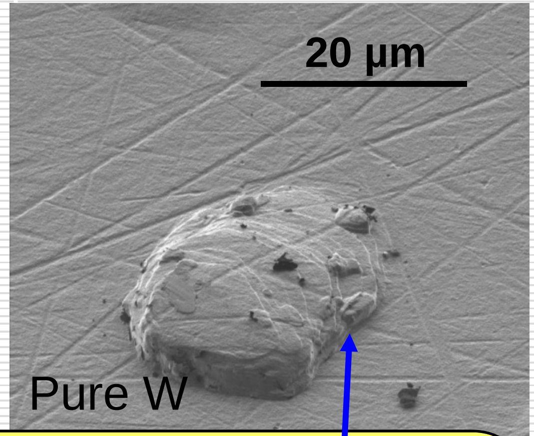
Pressure inside cracks or internal stress?



Blistering of Recrystallized W





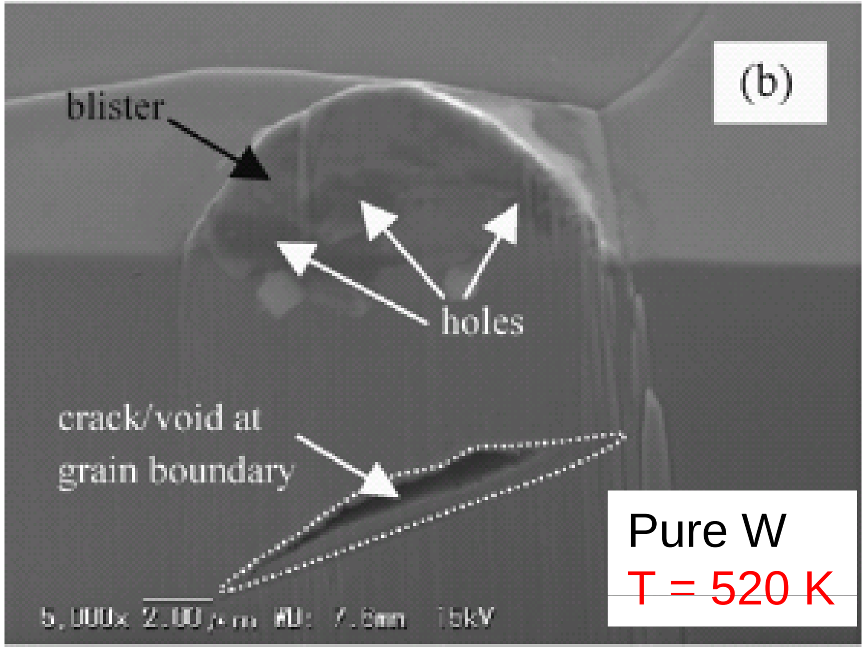


Reverse Fault

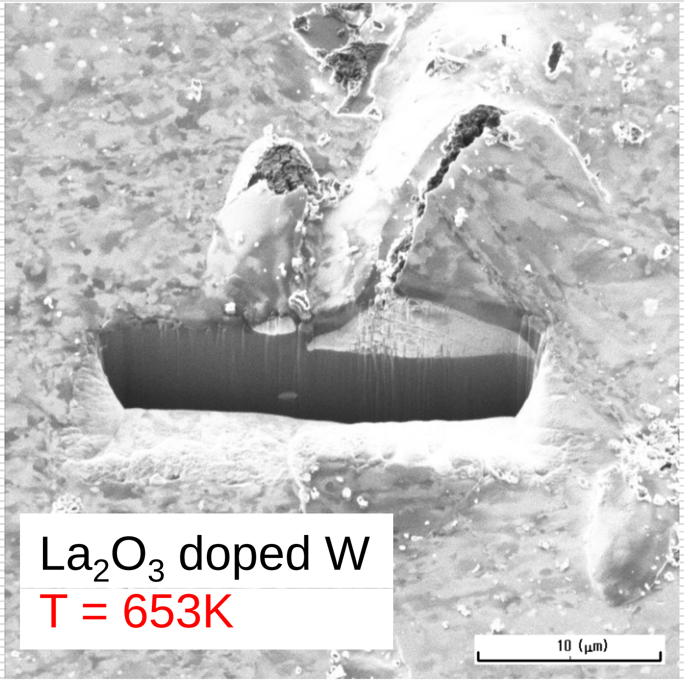
○Slip line like reverse fault
○Many step elevation
→suggesting <u>internal stress</u> by hydrogen implantation played a dominant role.

Blisters without gaps

- Blisters without gaps (or small gaps) are reported lately.
- Formation mechanism is not known.
  - Abnormal diffusion of W?
  - Giant swelling due to high flux D/H irradiation?



W.M. Shu, et al., Nucl. Fusion 47 (2007) 201–209

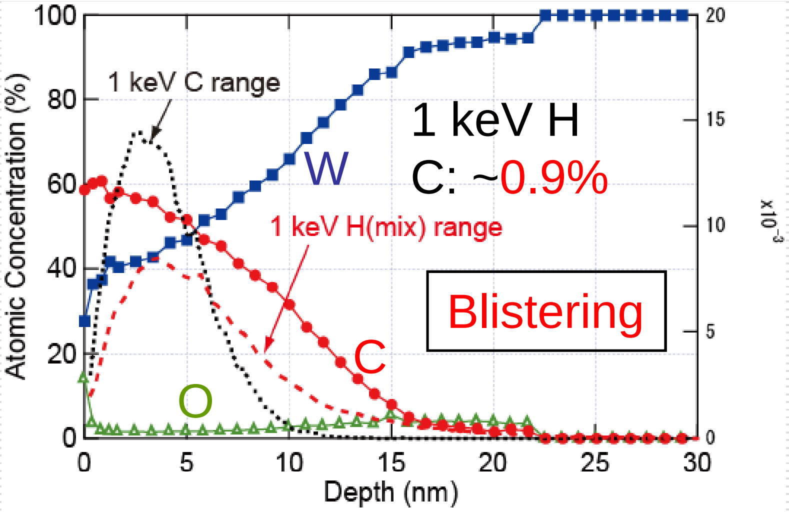


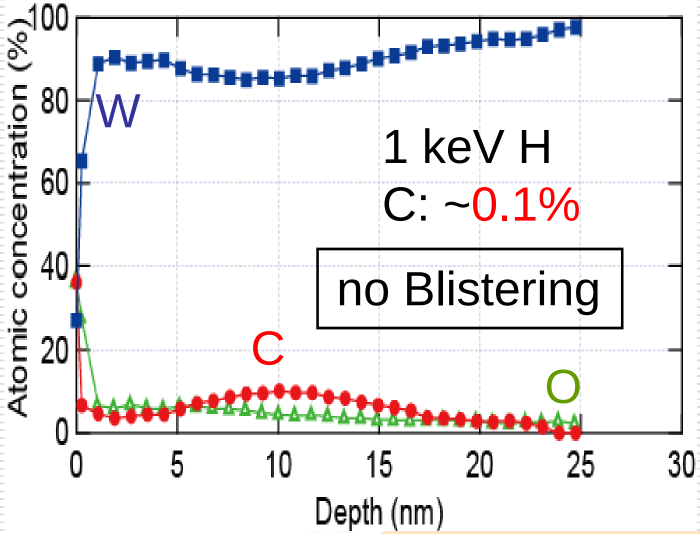
Osaka Univ.

W and C mixing layer reduced desorption

- C depth distribution
  - Absolutely calibrated by NRA
  - broader than ion implantation range
  - Recoil implantation by H
- High C (~0.9% in the beam) case
  - WC layer reduced desorption of H
  - Enhance bulk diffusion of H
  - Enhance blister formation
- Low C (~0.1% in the beam) case
  - Low surface C concentration
  - no significant reduction of recombination

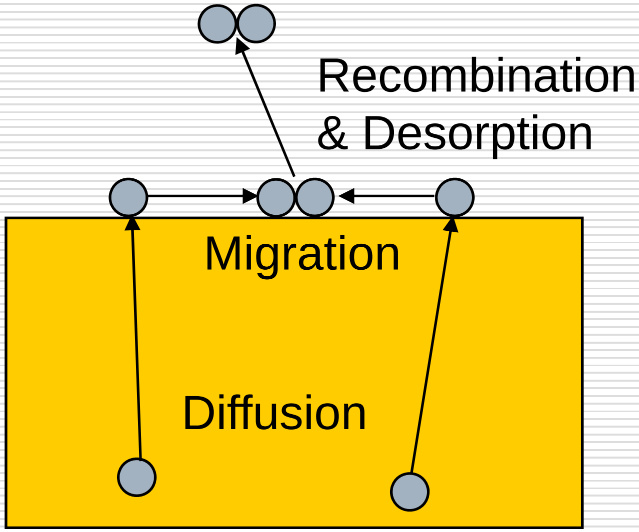
Atomic composition in tungsten



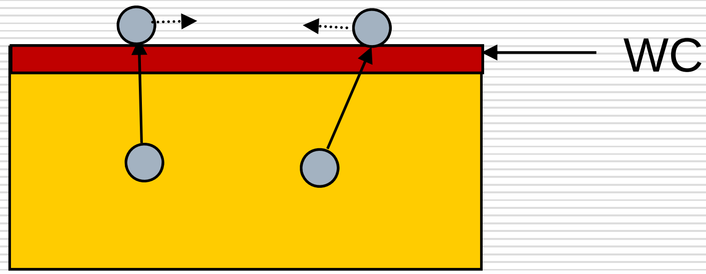


How does WC layer affect H behavior?

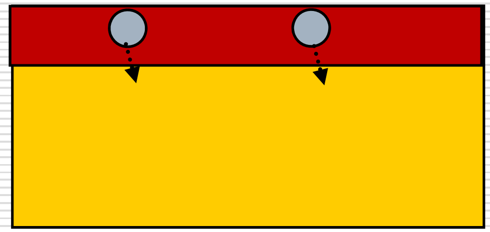
- Low H-recombination rate on WC surface
  - Suppress surface migration of H atoms
- Low H-diffusion coefficient in WC



Hydrogen Desorption (<1000 °C)



Surface WC-rich layer suppresses hydrogen recombination and desorption

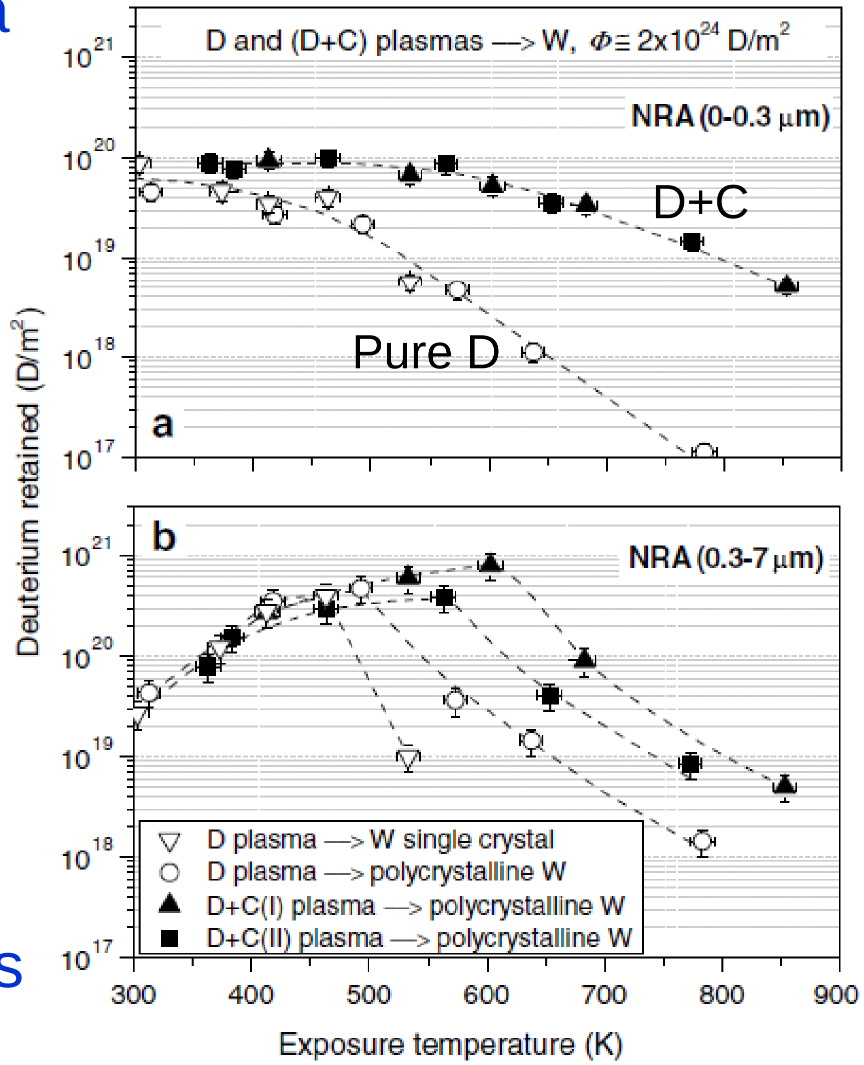


Bulk WC layer reduces hydrogen diffusion

D & C mixed plasma exposure to W

V. Alimov et al., J. Nucl. Mater. 375 (2008) 192.

- Planar DC magnetron plasma
  - Energy : ~200 eV (D_2^+ mainly)
  - Flux : 1 x 10^{21} $m^{-2}s^{-1}$
  - C plate on cathode surface to provides C into plasma
- For D+C, D retention near surface (a) and bulk (b) increased at elevated temp.
- For D+C, fraction of C on W surface is higher.
- Possibly, surface C+W mixed layer (C existed as carbidic and graphitic phases) reduces release of D from surface.



D retention in W exposed to pure D plasma (□▽) and D+C plasma (▲■)

From 300-700 K, thin and thick layers of Be suppresses blister formation.

M. Baldwin et al.
PSI 18(2008)

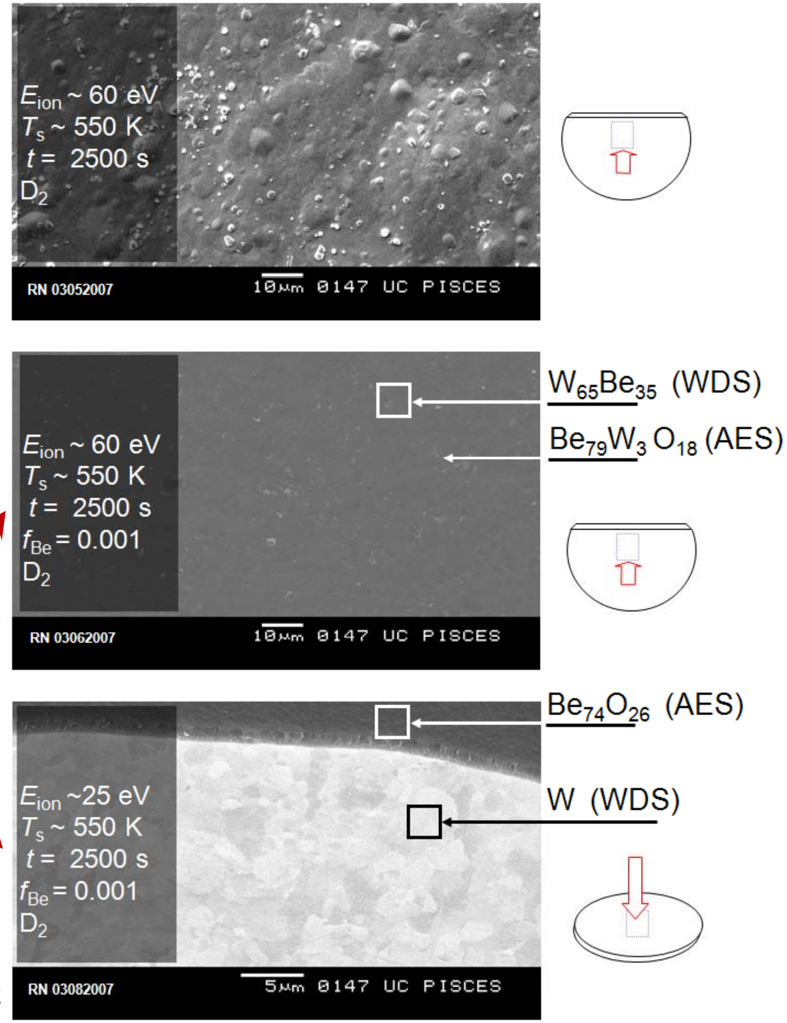
PISCES

- Blistering & exfoliation of blister caps is a concern for certain varieties of W.

- Increased retention is associated with the trapping of hydrogen in blisters.
  E.g. *K Tokunaga et al. J. Nucl. Mater. (2004)* <u>*337–339*</u>*, 887.*

- At 550 K a blistered surface is prevalent after exposure to D_2 plasma.

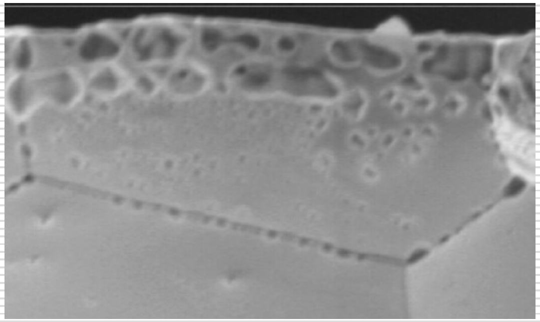
- A thin layer of Be as little as a few 10's of nm, or thicker, is found to suppress blister formation.



D^+ ion fluence ~1×10^{26} m^{-2}

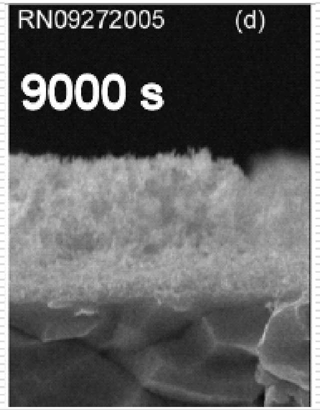
He effects on W

- High temperature (> ~1,600 K)
  - Large He bubbles formation with recrystallization
  - Degradation of mechanical and thermal properties
  - Dust formation (enhanced erosion)
- Medium temperature (> ~1,100 K)
  - Nano-structure formation
  - Dust formation (enhanced erosion)
  - Initiation of arcing
- Low temperature (< ~900 K)
  - Small He bubble formation (a few nm)
  - Significantly affects D/T retention and diffusion



NAGDIS (Nagoya Univ.)

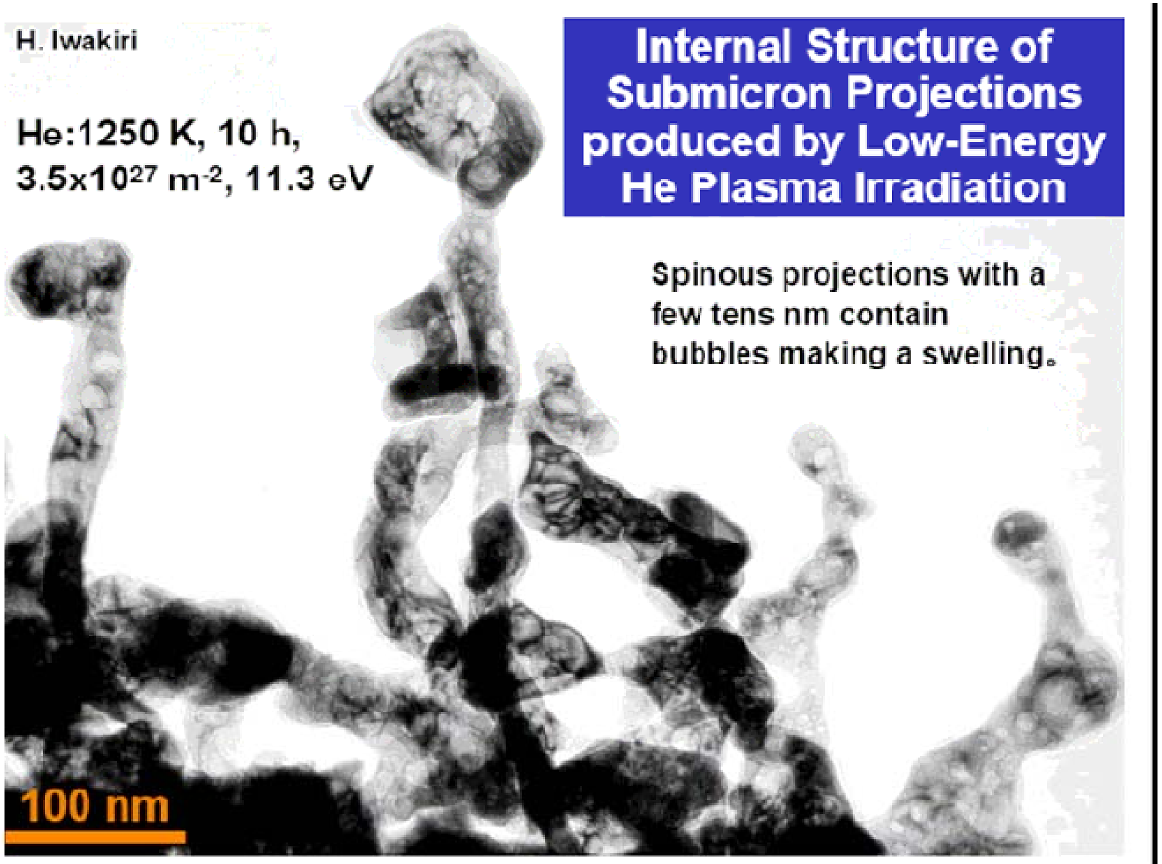
T ~ 1,600 K



PISCES (UCSD)

T ~ 1,120 K

Submicron structure on W (T~1250 K)

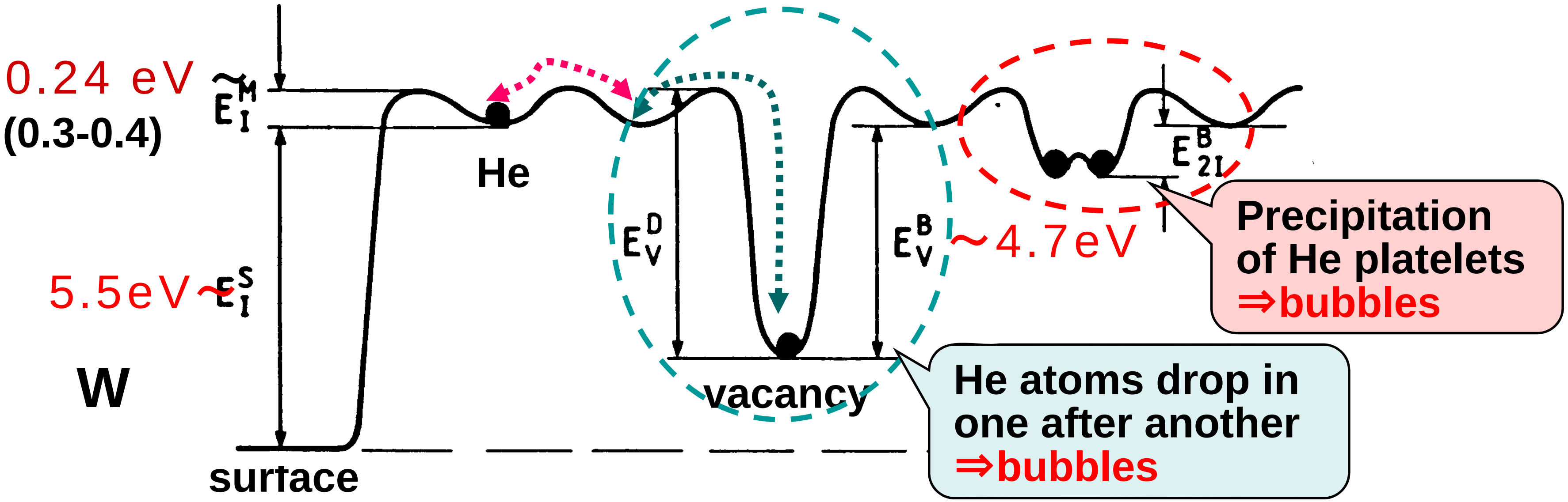


From Prof. Takamura presentation at ITPA sol./div meeting, Toronto, Nov. 2006.

Basic Behavior of He in W

Y. Yoshida (Kyushu U)
18th PSI (2008)

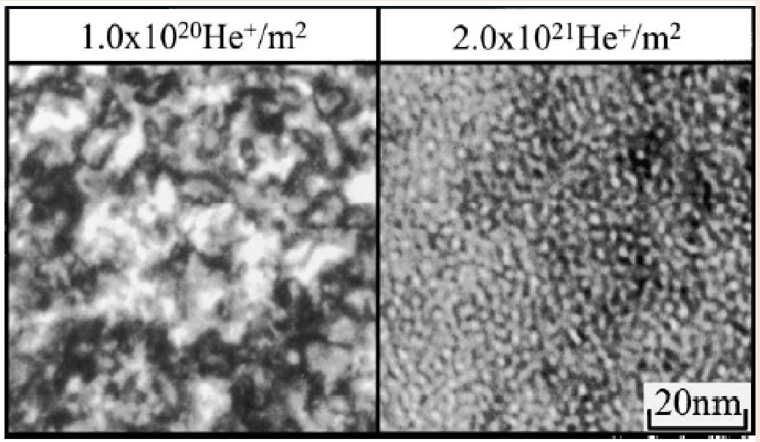
- Very low solubility.
- Very fast thermal migration via interstitial sites (very high mobility even at R. Temp.)
- Very deep trapping in a vacancy (Large E_V^B)
- Comfortable positions of He in W lattice:
  empty sites such as vacancy, bubble, grain boundaries, dislocations etc. ⇚ *closed electron shell 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

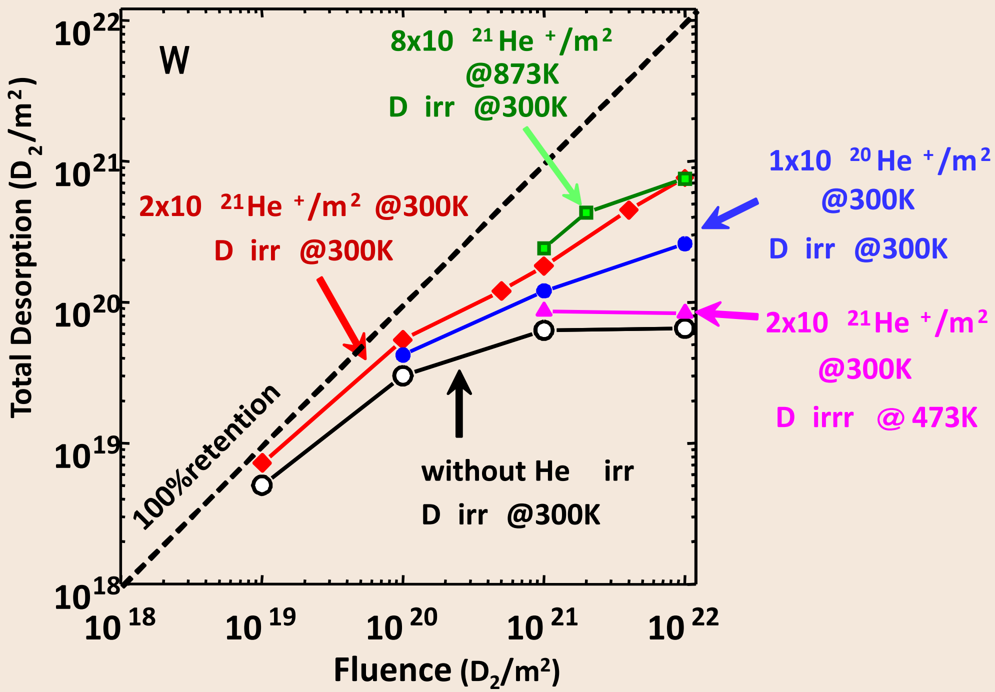


He effect on retention

- Sequential irradiation of He and D.
- Formation of He bubbles enhances D retention very much.
- He bubbles become traps of D.
  - *(H. Iwakiri et al., J. Nucl. Mater. 307-311 (2002) 135-138)*

8keV He^+ → W (300K)

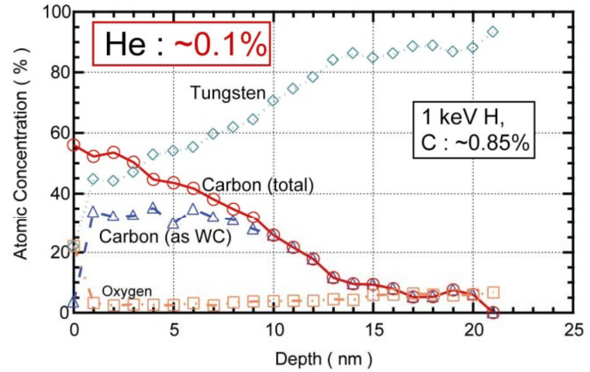


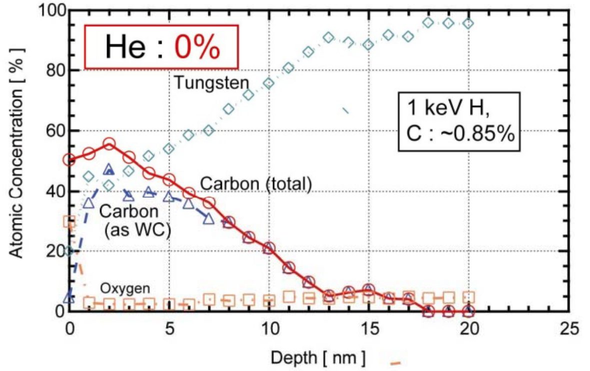


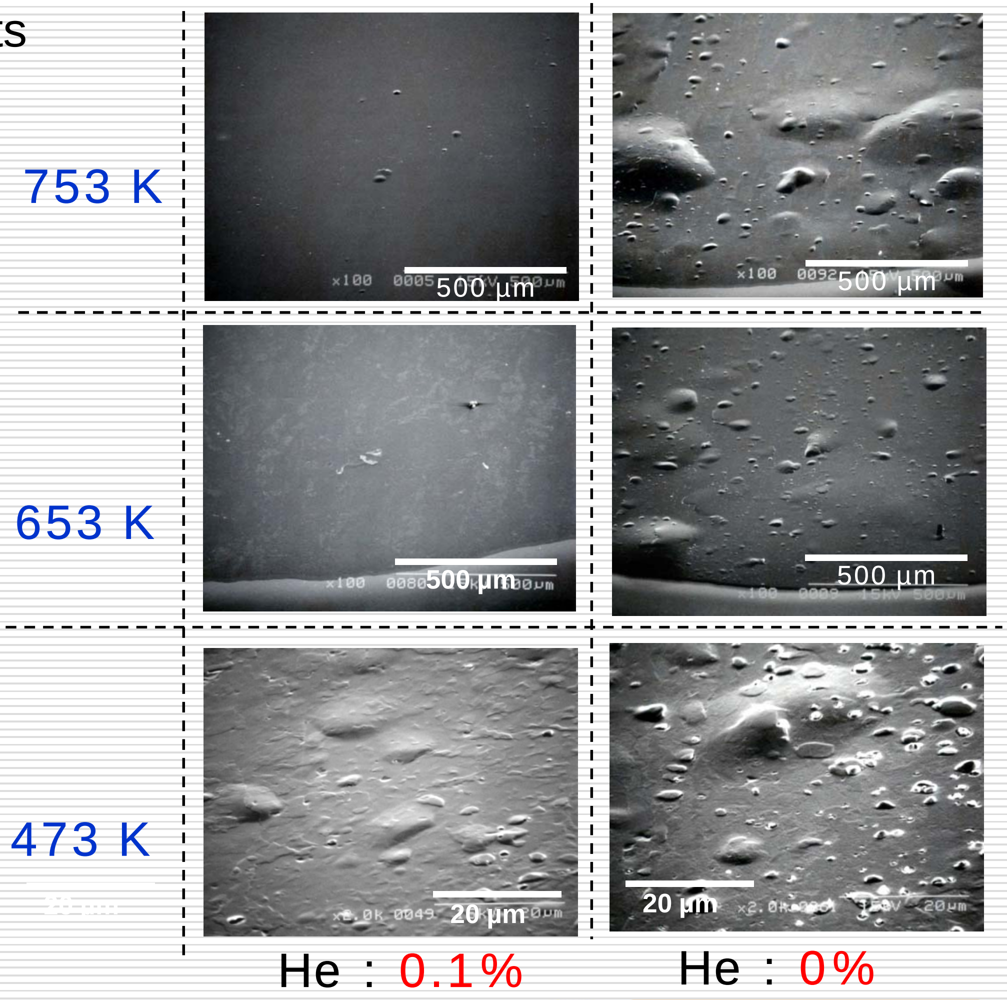
Blister formation under H & He (&C) irradiation

- Small amount of He affected blistering
  - He : ~0.1% has strong effects
- Suppression of blisters at T>653 K
  - 0.1% He did not change surface mixing layer much.

Energy : 1 keV (H_3^+, H_2^+ , H^+)
Carbon : ~0.8 %
Fluence : ~7.5 x 10^{24} m^{-2}

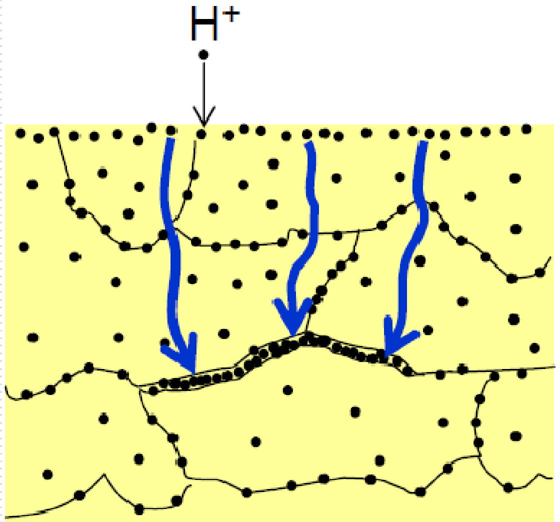


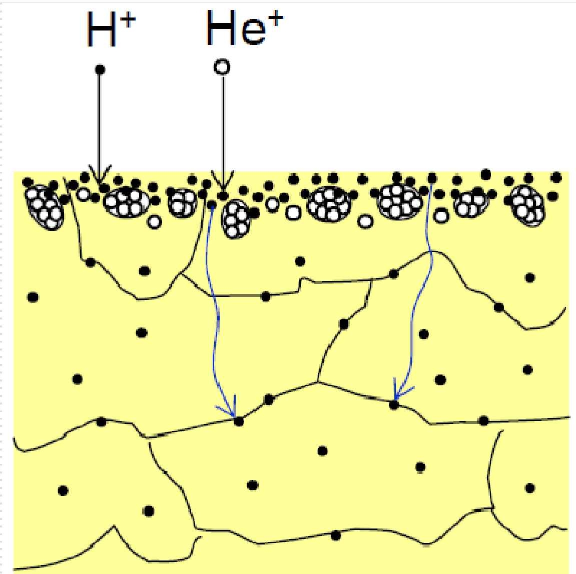




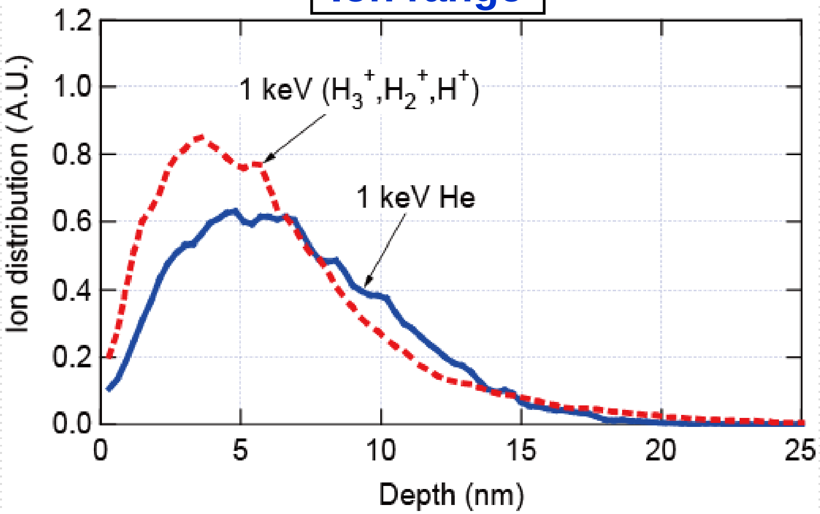
He bubble could affect H diffusion

- 1 keV He has slightly longer range than1 keV H (mixed).
  - He bubbles could be formed around the end of ion ranges.
    - He bubbles in W and C mixed layer.
- He bubbles could block H diffusion into the bulk.





Ion range



Effects of He energy on blistering

Main Ion Beam(1.5 keV : H+C:0.8%)

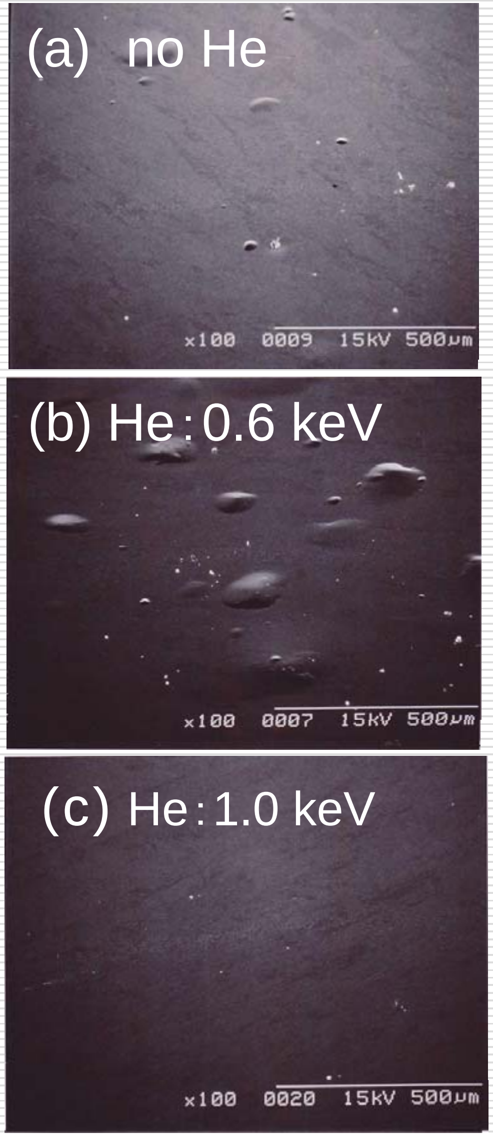
(a) no He ion beam → Blistering

(b) 2nd He beam :0.05%（0.6 keV）→ Blistering

(c) 2nd He beam :0.05%（1.0 keV）* → no Blistering

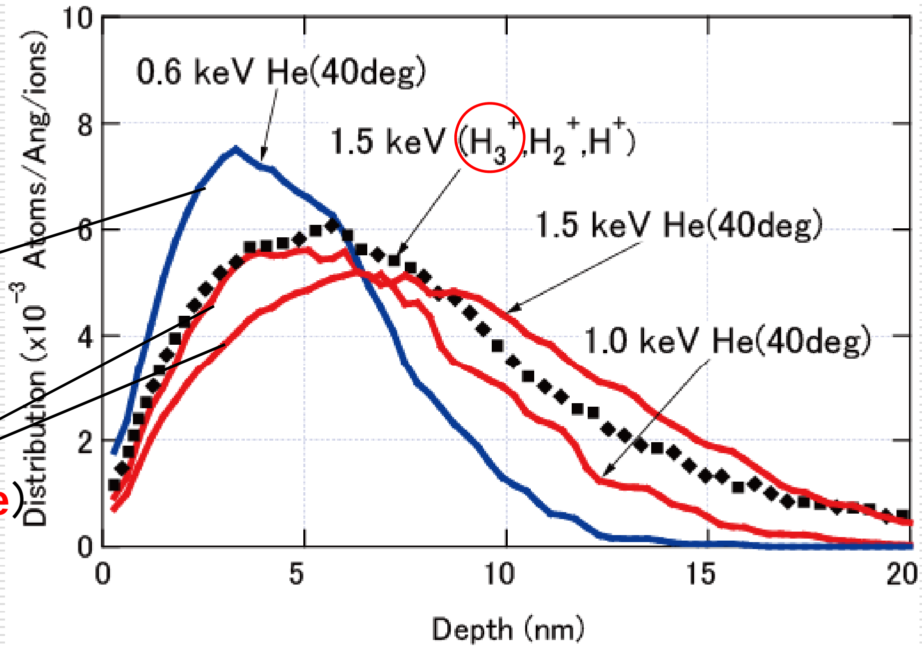
2nd He beam :0.05%（1.5 keV） * → no Blistering

***angle of incidence ~ 40 deg**



Blistering
（0.6 keV He）

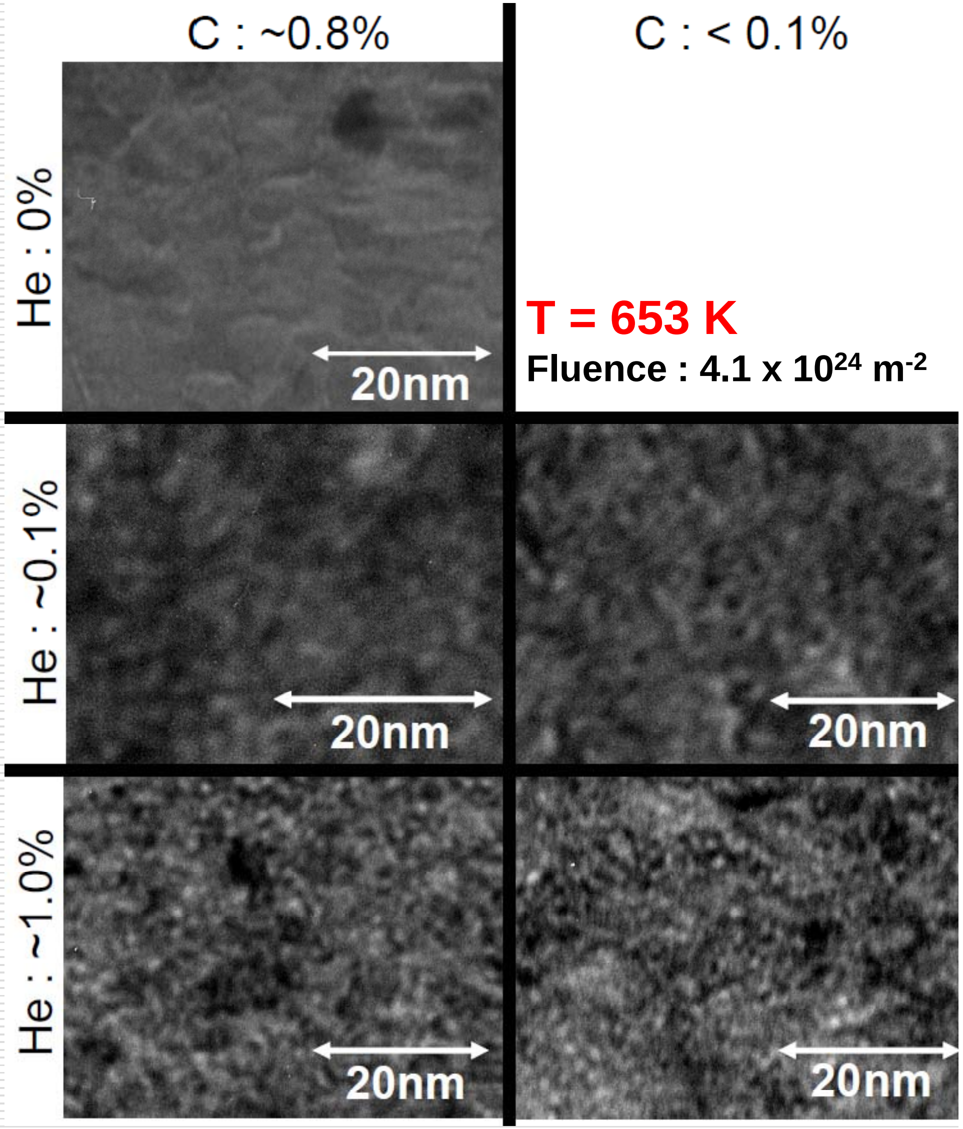
No blistering
(1keV He, 1.5keV He)



Ion range in tungsten

TEM observation of He bubbles

- He:1.0%, ~2 nm$^{\phi}$ He bubbles
- He:0.1%, 1~2 nm$^{\phi}$ He bubbles
  - He fluence : 4.1 x 10^{21}m^{-2}.
- Bubble size and bubble number density had weak dependence on He% and C%.
- He bubbles were formed in WC layer for C:~0.8%.



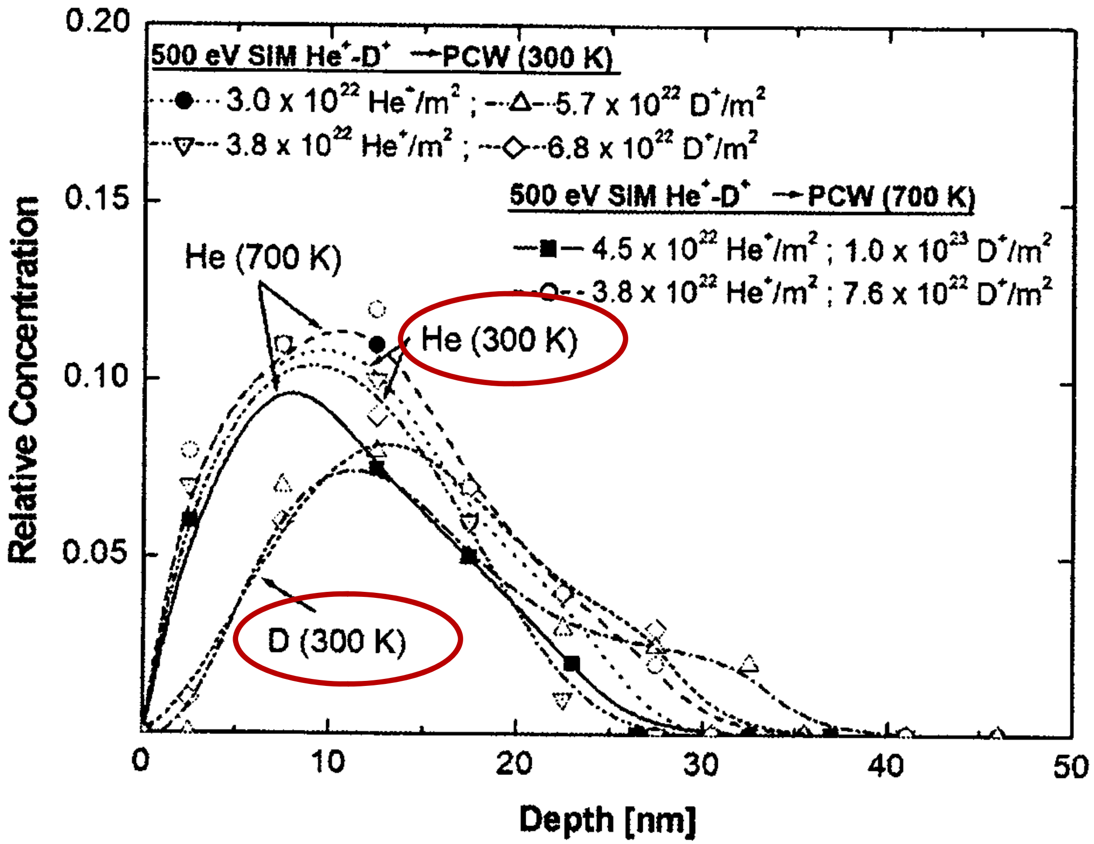
TEM observation of near surface structure

Simultaneous He/D (Toronto)

- 500 eV D & 500 eV He

H. Lee, J. Nucl. Mater. 363-365 (2007) 898

- At 300 K, D did not diffuse into the bulk.
  - For pure D irradiation, D diffused much deeper at 300 K.



Depth distribution of D and He

Suppression of Blistering by He

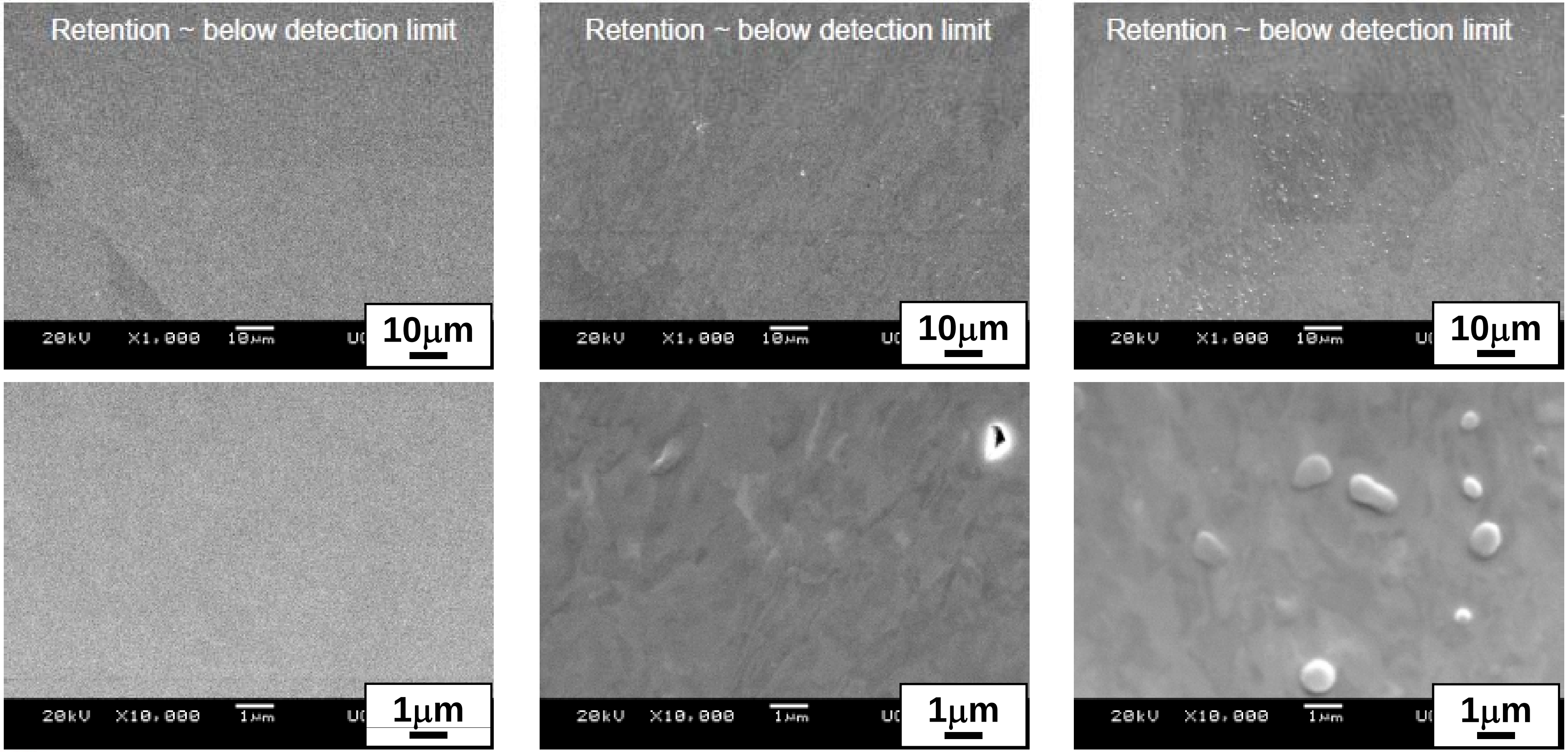
PISCES (UCSD)

$E_i \sim$ 55±15 eV

$\Gamma_i \sim 10^{22}$ ions/m^2

- ***W (SR), $5x10^{25}$ D/m^2, 573K***

D + He(20%)	D + He(5%)	D + He(1-2%)



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

Blisters disappeared above 5% He.

D retention

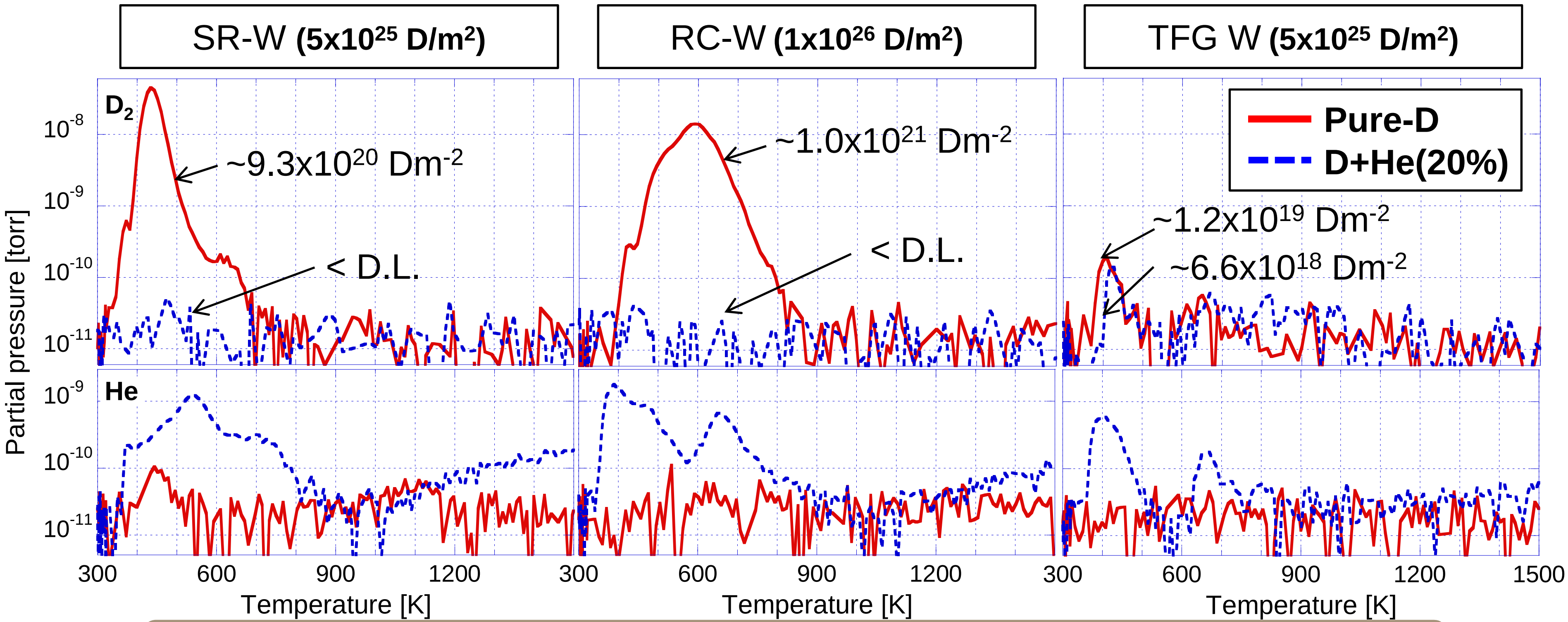
TDS

TDS after plasma exposure

✓High resolution Q-Mass (D_2 and He can be separated).

✓Heating rate : 0.59 K/s

D.L. (Detection Limit) ~10^{18} m^{-2}



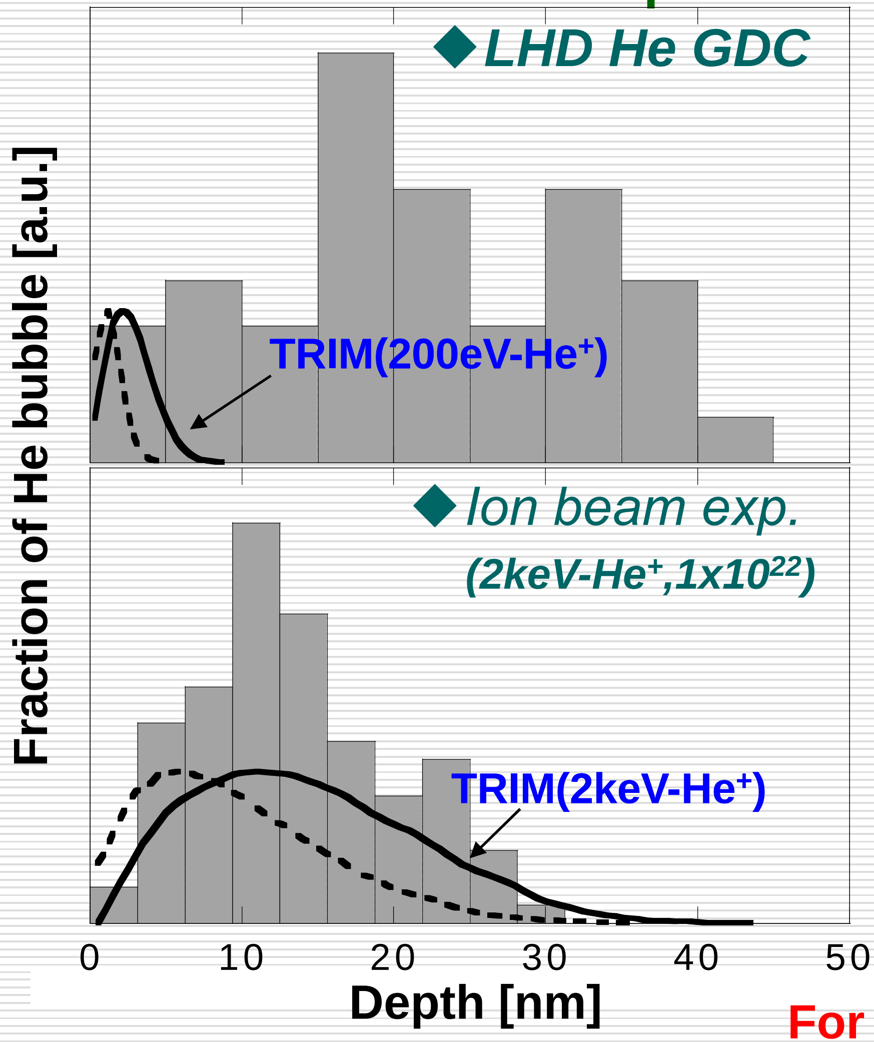
No D retention from W exposed to D+He mixed plasma

Similar results have been obtained in other research group (V. Alimov et al., 12th ITPA (SOL/DIV) meeting (2009)

Depth distribution of He bubbles in SUS.

- LHD, He GDC(200eV), SUS304, 65 hours

He bubble depth distribution measured by TEM



- *LHD-He GDC (~200 eV)*
  - Much broader distribution than ion range.
- *Ion beam exp. (2keV-He$^+$)*
  - Distribution around ion range.

This difference could be due to displacement damage by He ions.
For **low energy He (few damage)*****:*** He atoms diffuse far from ion range to find intrinsic traps.
For **high energy He (damage)*****:*** He atoms are trapped at self-produced traps within ion range.

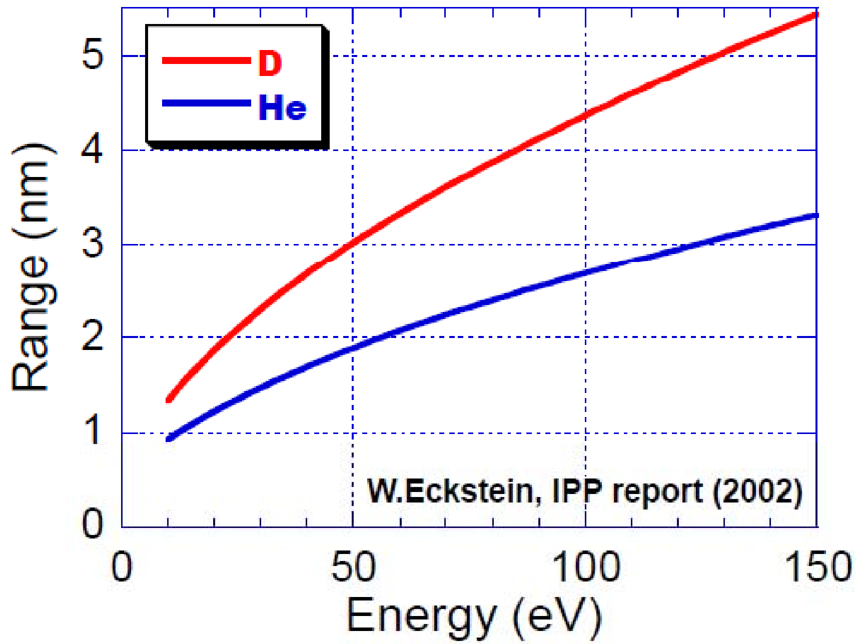
For W, similar phenomena could take place.

Needs experimental results

M. Miyamoto et al., J.N.M. 329-333 (2004) 742

Is He bubble layer a diffusion barrier?

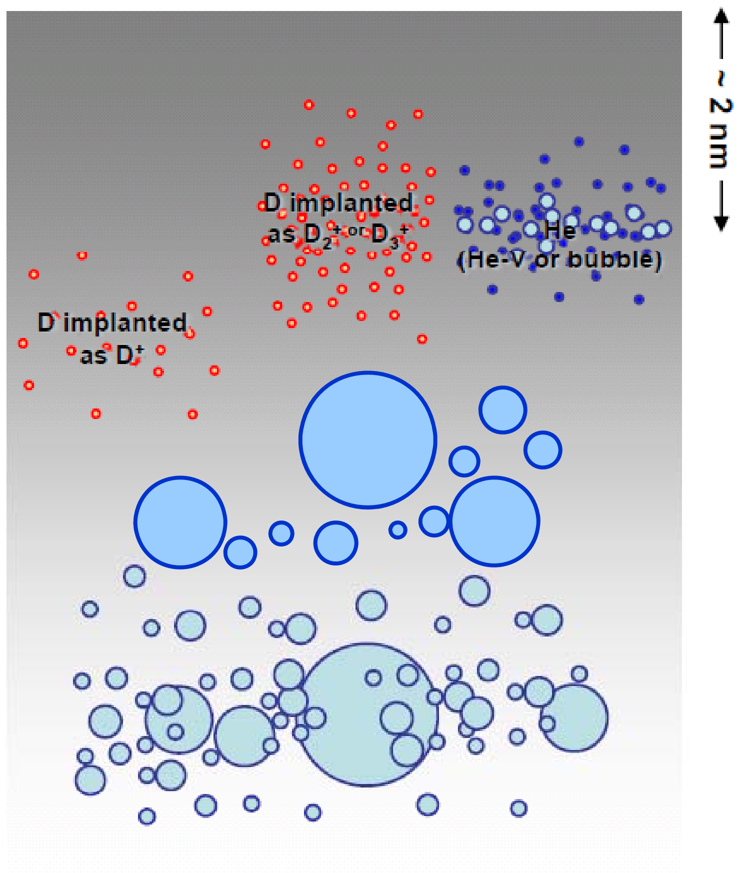
- For low energy He implantation (less than recoil threshold), He bubble layer could extend deeper and become the barrier.



◆Ion range (@70eV)

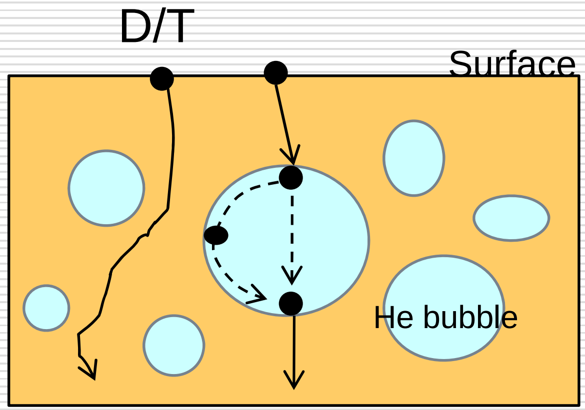
Ion	He^+	D^+	D_2^+	D_3^+
Range	2.2nm	3.6nm	2.5nm	2.2nm

By M. Miyamoto

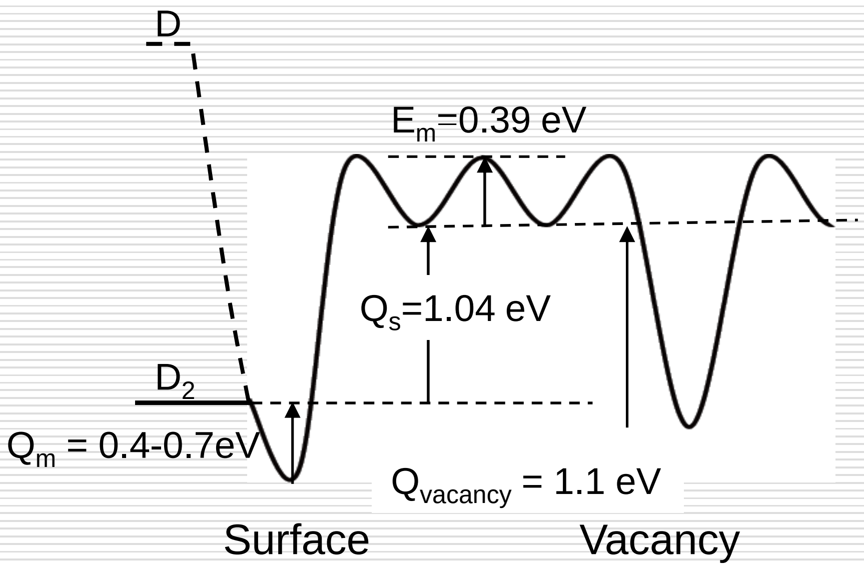


Possible mechanisms

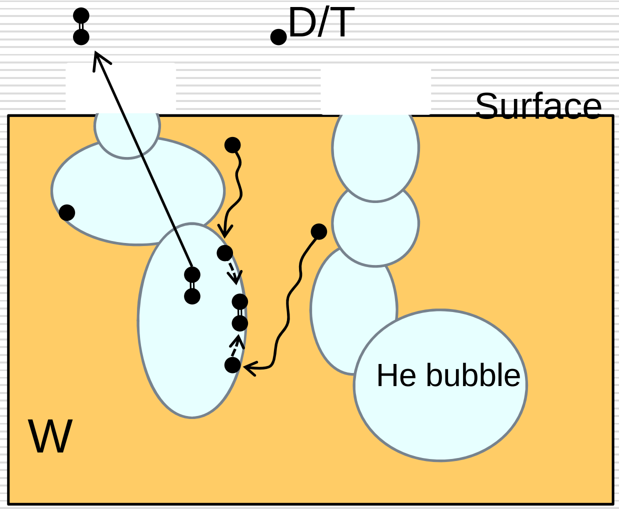
- Narrowing diffusion channels by He bubbles
- Release of D^2 through He created pores
- Reduction of diffusion through stress-induced W



Diffusion of D/T in W



Energy diagram of D in W



Desorption of D_2 through pores

Summary

- There still remain unsolved problems in C & W mixing.
  - C erosion from C&W mixed layer and C deposition layer
  - Effects of surface morphology (roughness) on C deposition
  - C atom behavior at elevated temperatures (> 800 ºC)
- C & W mixed layer strongly affects D behavior
  - W&C mixed surface layer reduces recombination of D atoms
  - Diffusion of D in W&C mixed layer is reduced compared to pure W
- He bubble layer strongly affects D retention
  - Initially increase retention by increasing trapping sites
  - But, under high fluence condition, He bubbles greatly reduce retention as they work as diffusion barrier.
- We do not have enough knowledge on material mixing to correctly evaluate T retention in ITER.