Helium effects on Tungsten surface morphology and Deuterium retention

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Introduction

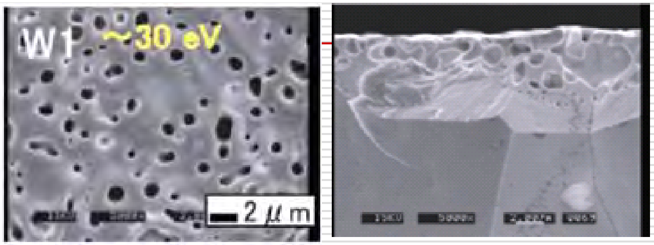
- Recent experimental results on low energy He induced morphologies (nano-structure) and He effect on D retention are reviewed.

Outline of this talk

- Formation of nano-structures in linear plasma devices
- Formation of nano-structures in magnetic confinement devices
- Erosion and arcing of nano-structures
- Simultaneous He irradiation effect on D retention
- Summary

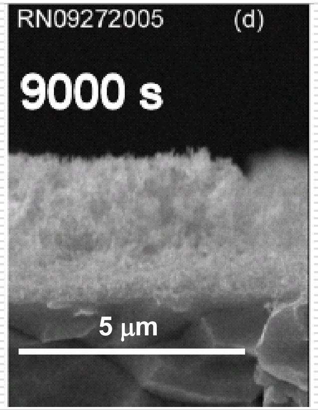
Low energy* He effects on W

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

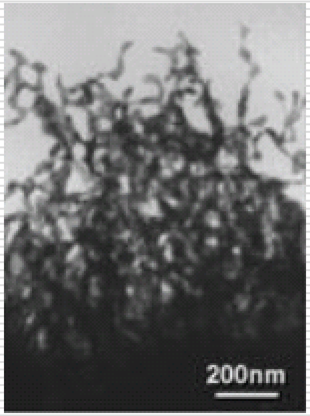


NAGDIS (Nagoya Univ.)
T ~ **2,100 K**

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

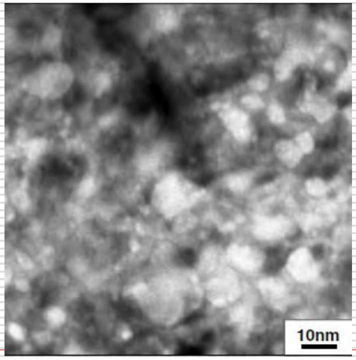


PISCES (UCSD)
T ~ **1,120 K**



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

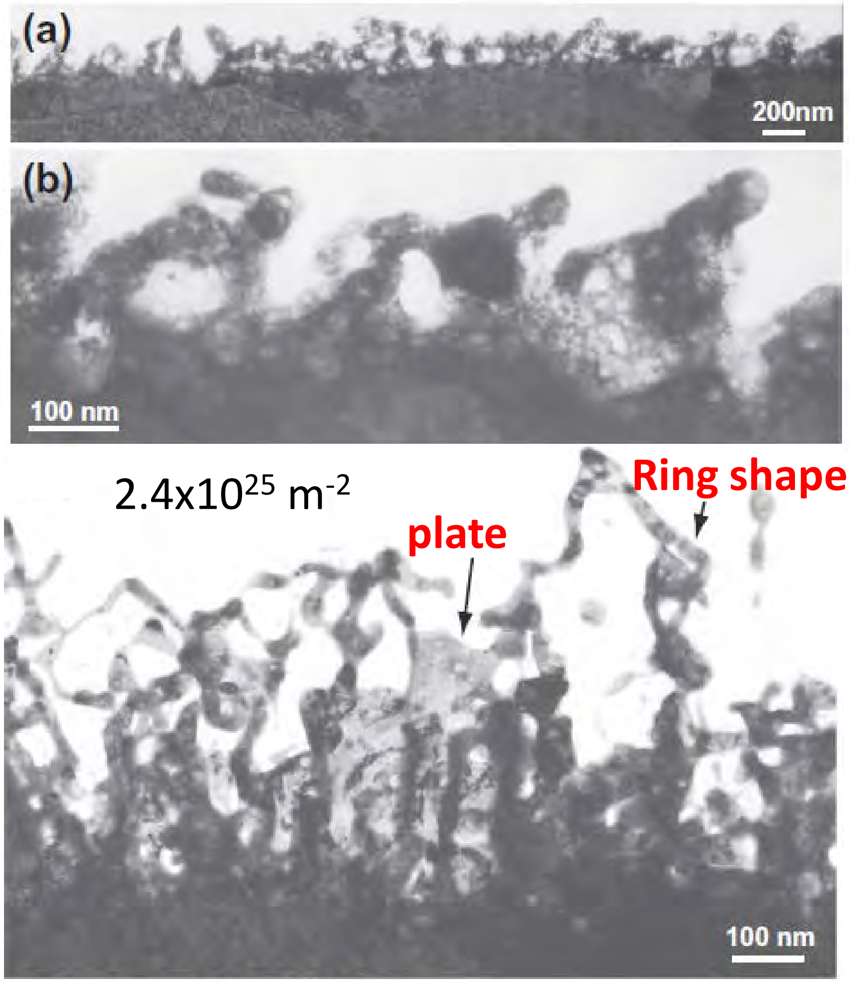
Formation of nano-structures in linear plasma devices

- How are they formed?
  - Formation mechanism
  - Formation Conditions

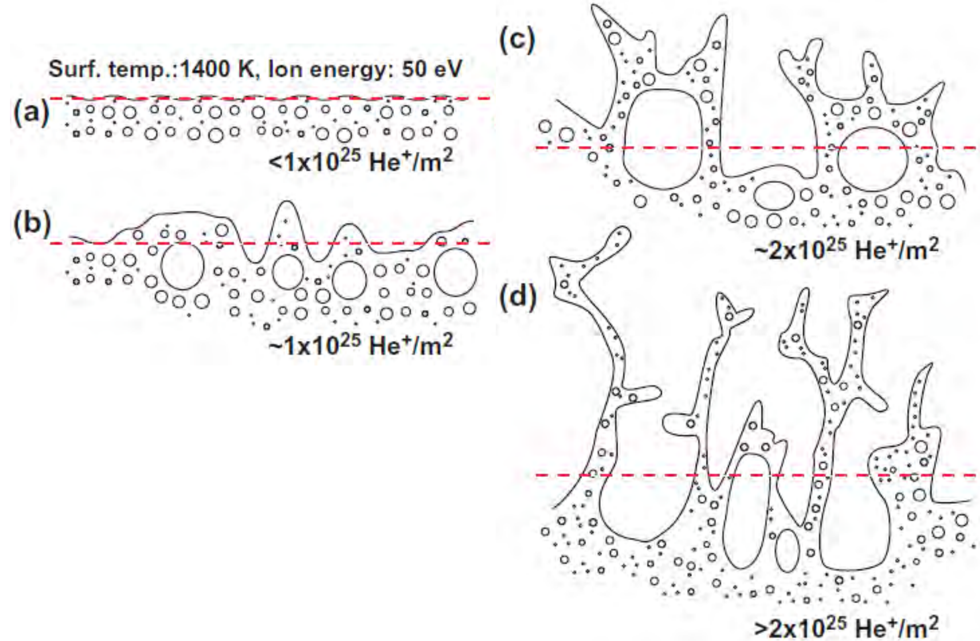
TEM observation of nanostructured tungsten: formation mechanism

NAGDIS

1.1x10^{25} m^{-2}



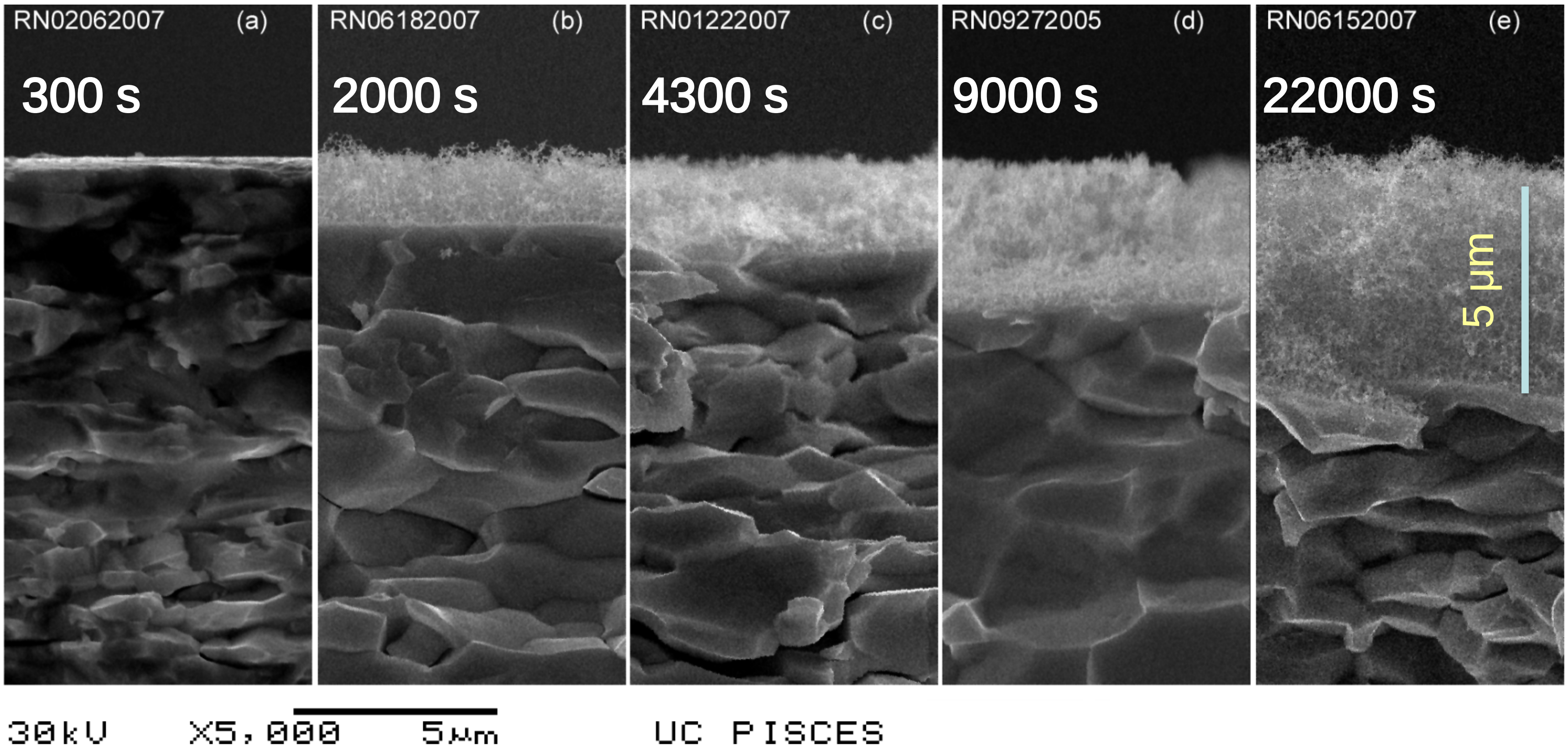
He irradiated W in NAGDIS-II at 1400 K and 50 eV.



- 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

At 1120 K, nano-structured layer thickness increases with He plasma exposure time.



Consistent He plasma exposures: T_s = 1120 K, Γ_{He+} = 4–6 × 10^{22} $m^{-2}s^{-1}$, E_{ion} ~ 60 eV

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

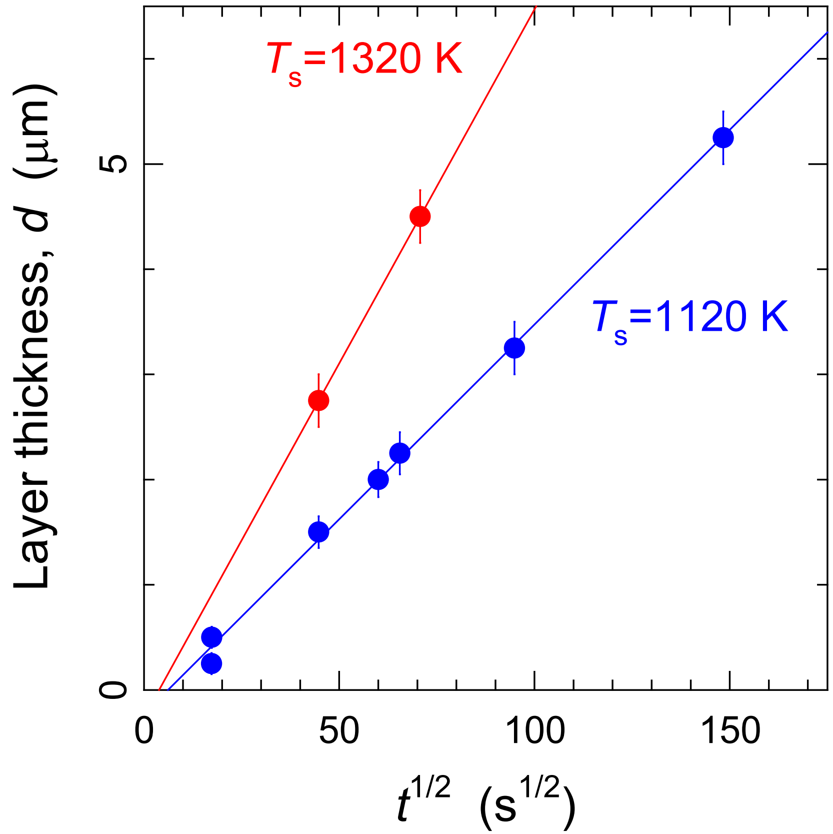
- Observed $t^{1/2}$ proportionality.

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

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

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

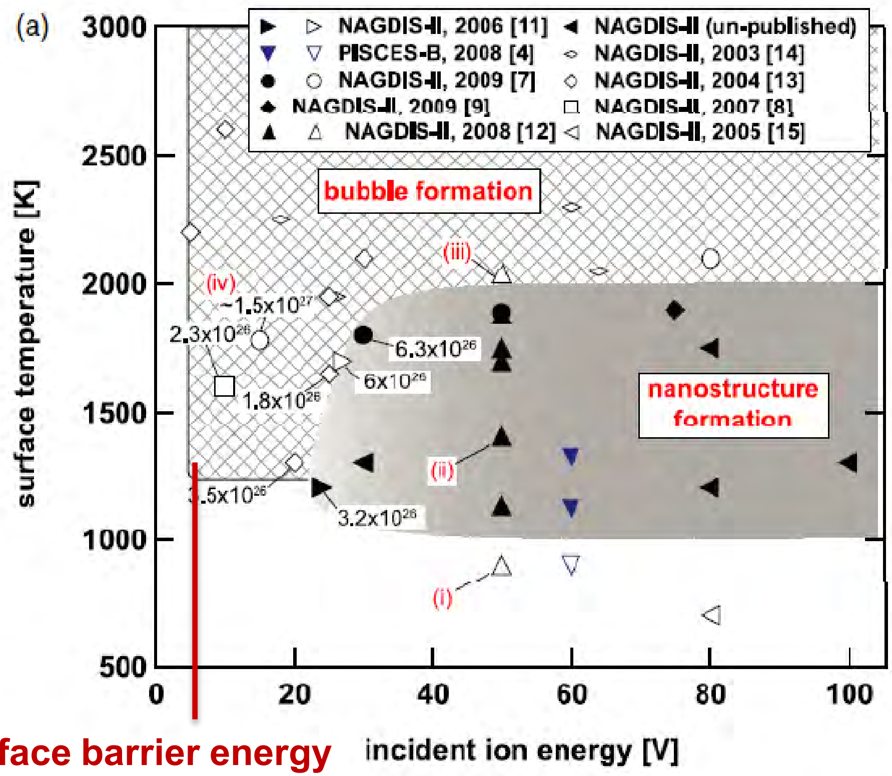
- Overall process is consistent with an activation energy of ~0.7 eV.



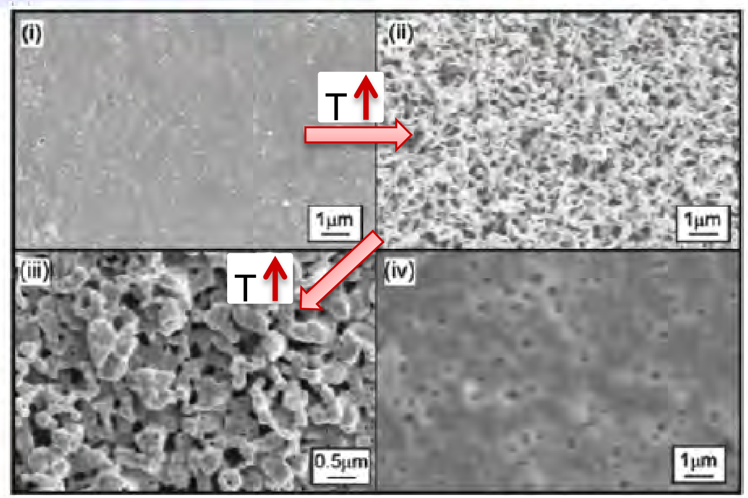
NAGDIS-II and PISCES

Summary of W fuzz formation condition

Flux ≤ 10^{23} $m^{-2}s^{-1}$ **Heat ≤ 1 MWm^{-2}**



Surface barrier energy



- Closed markers with nanostructure
- open markers without nanostructure

[4] M. Baldwin NF (2008).
[7] W. Sakaguchi JNM (2009)
[8] S. Kajita, NF (2007).
[9] S. Kajita, NF (2009).
[11] S. Kajita, J. Appl. Phys. (2006).
[12] W. Sakaguchi, Proc. 18th Int. Toki Conf. (2008).
[13] D. Nishijima, JNM (2004).
[14] D. Nishijima, JNM (2003).
[15] D. Nishijima, NF (2005).

Surface Temp: **1000 K < T < 2000 K**

Ion Incident Energy>**20 eV**

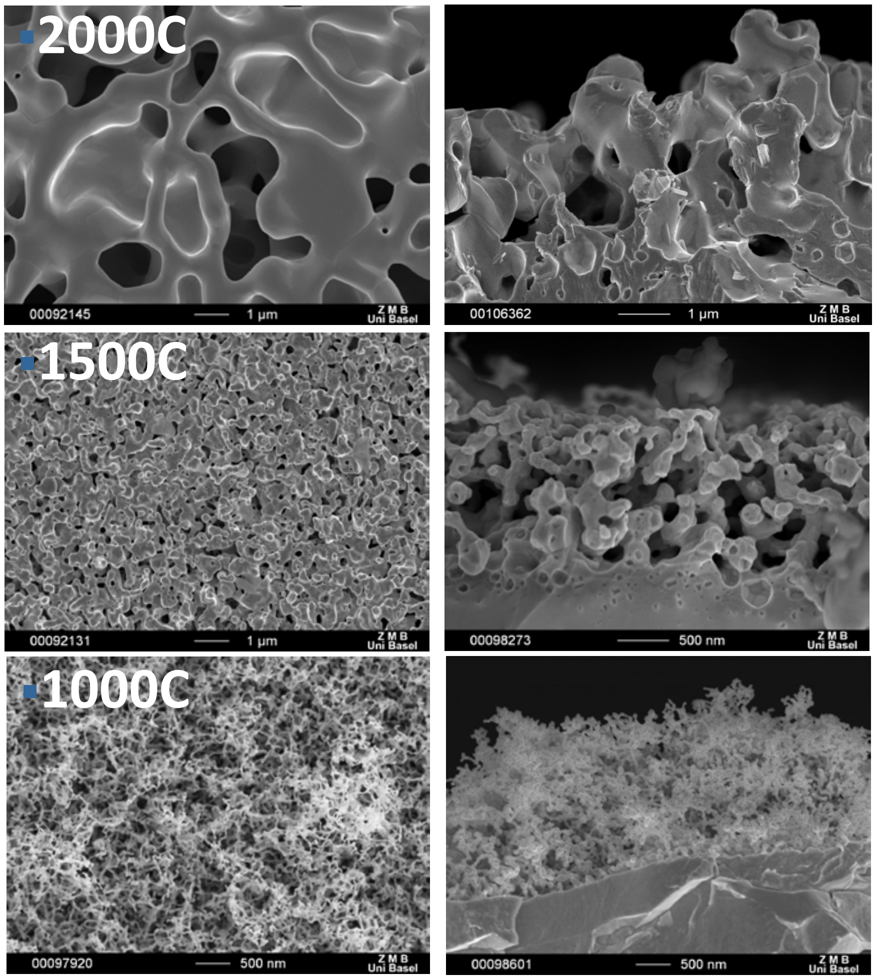
S. Kajita et al., Nucl. Fusion 49 (2009) 095005

Effect of surface temperature

T

W target

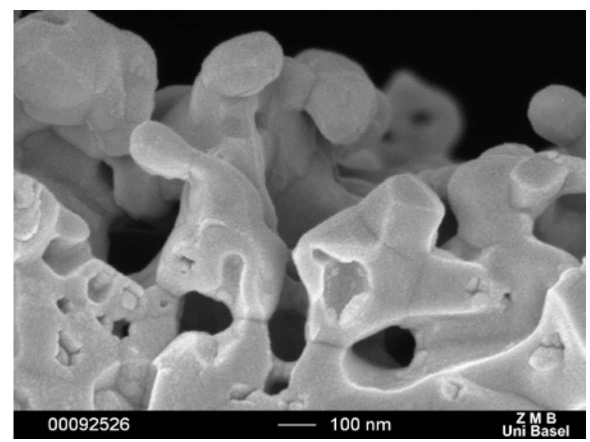
1000 s, 5x10^{26} He$^+$/m^2, 50 eV He$^+$



Pilot-PSI : ~5 x 10^{23} m^{-2}s^{-1} (~4 MW/m^2)

Closer to divertor flux condition

- Low energy helium ion exposure at high surface temperatures induce formation of near surface voids/bubbles
- Correlation between bubble size and helium-induced nanostructure scale
- Coalescence of He bubbles and swelling of tungsten surface

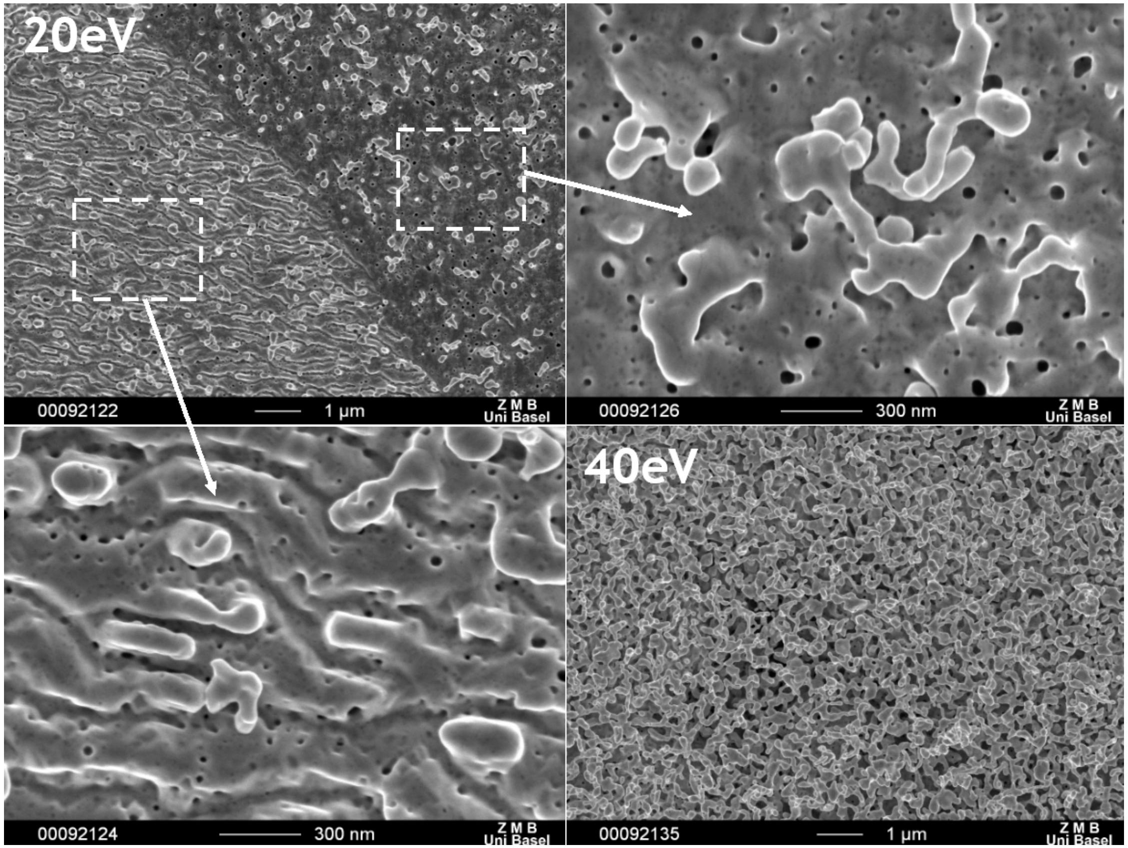


Similar mechanism for Mo and W

Effect of ion energy for W

W target, low flux region

1000 C, 500 s, 2×10^{26} He^+/m^2

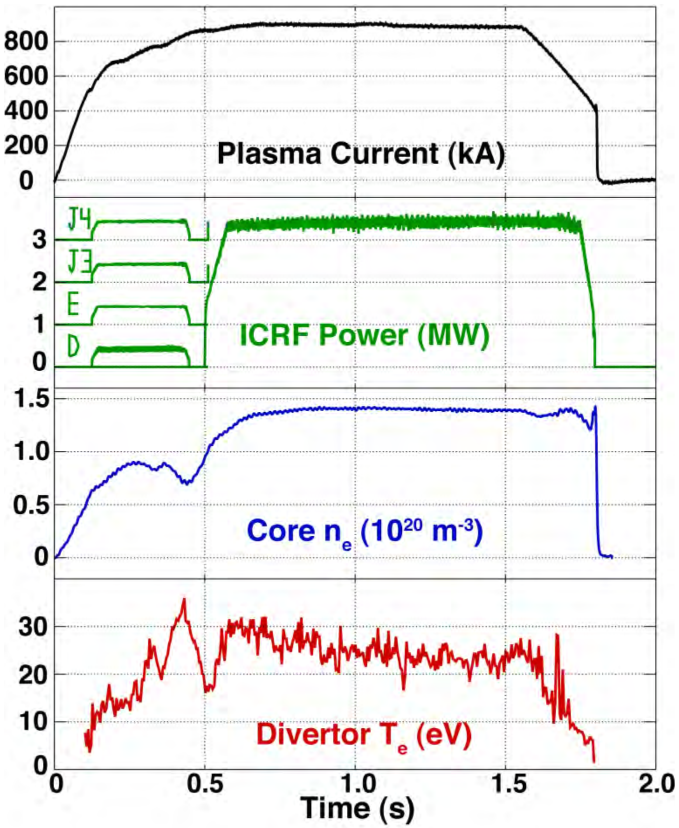


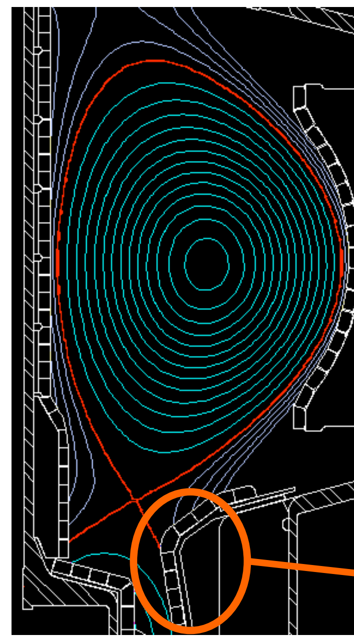
- Ion energy has a strong effect on the nano-structure formation kinetics
- Surface modification is strongly dependent on the grain orientation at the beginning of the process
- Once the structure has developed, there is no trace of these initial differences

Formation of nano-structures in magnetic confinement devices

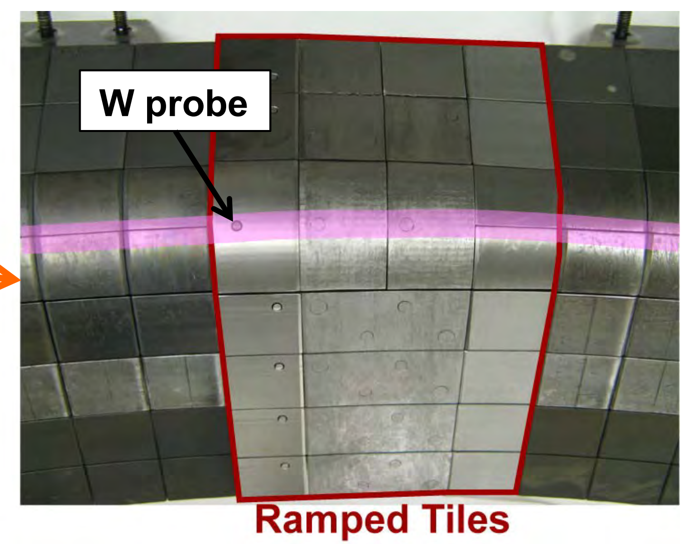
- **Are nano-structures formed in magnetic confinement devices?**
  - Different ion irradiation conditions from linear plasmas
    - Oblique incidence of impinging ions
    - Ion energy distribution
  - Mixed ion effects (enhanced erosion, deposition, etc.)
    - D/T, He, wall materials, cooling gas etc.
  - Reactor relevant high heat flux condition (~10 MW/m^2 or more)

Alcator C-Mod Helium plasmas produced necessary plasma conditions for nano-tendril growth at the outer strikepoint





Strike point run on the nose tiles to reduce flux expansion allowing for higher local surface temperatures.

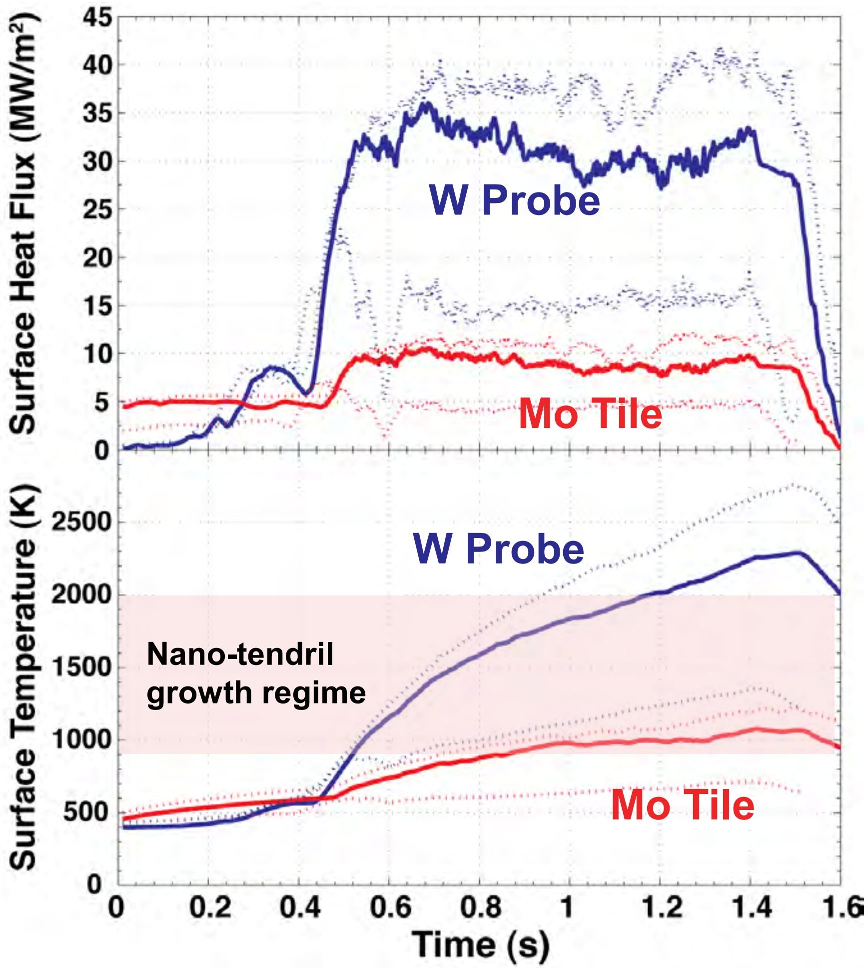


- **14 repeated L-mode discharges**
- $T_{e,divertor}$ 20-25 eV, $q_{||}$ > 0.2 GW/m^2

→13-15 s of total exposure at appropriate growth conditions

Prepared by : G. Wright (MIT)

Both the tungsten probe and surrounding Mo tile surfaces reached temperatures required for nano-tendril growth



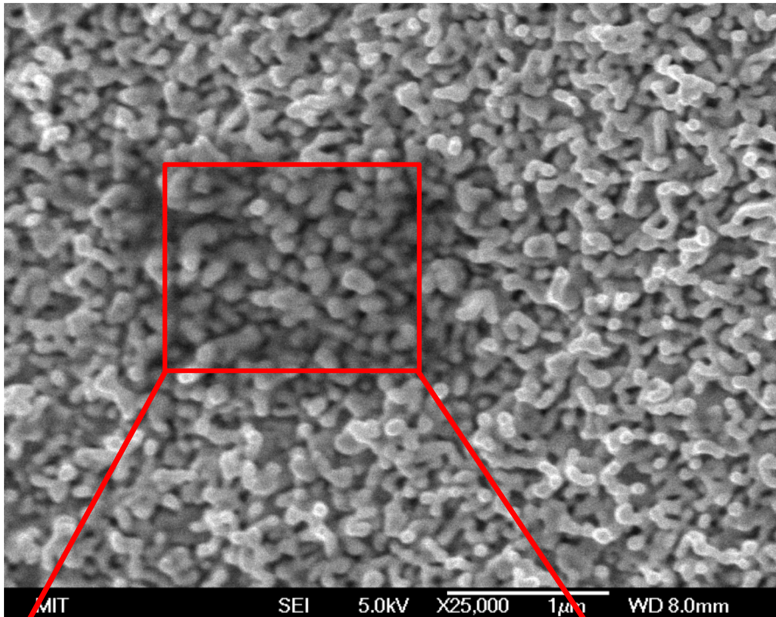
W probe ramped ~11° into parallel heat flux and is electrically/thermally isolated.

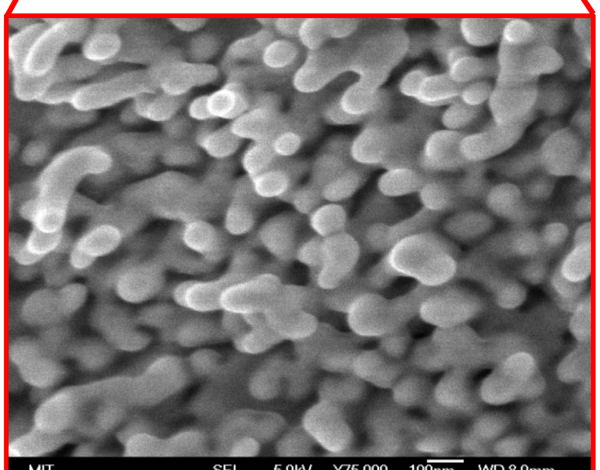
Mo tiles are ramped ~2° into parallel heat flux and grounded.

➔ W probe intercepts more parallel heat flux and reaches ***much higher surface temperatures*** than the surrounding Mo surfaces.

Solid lines = Heat flux (or temperature) for discharge which is the 14-shot median
Dotted lines = Heat flux (or temperature) for discharges having the 14-shot maximum or minimum

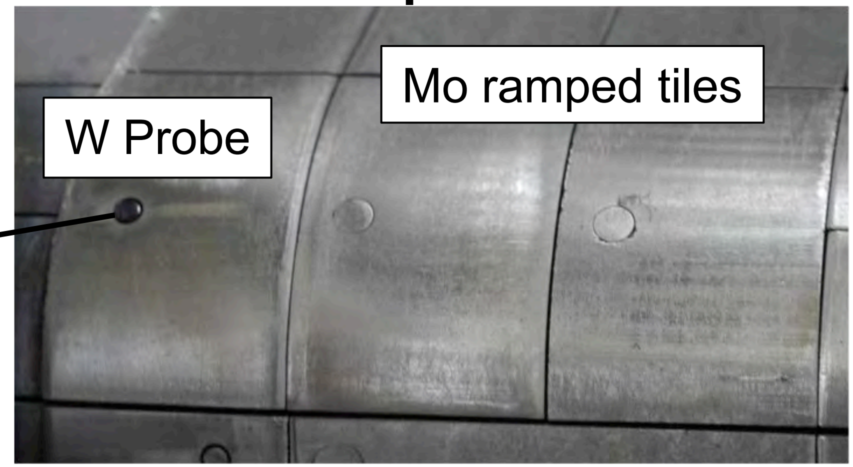
Nano-tendrils are fully formed on surface of the tungsten probe exposed to heat fluxes of 30-40 MW/m^2





Thickness of individual tendril is 50-100 nm, which is thicker than tendrils grown in linear devices (20-30 nm)

After exposure

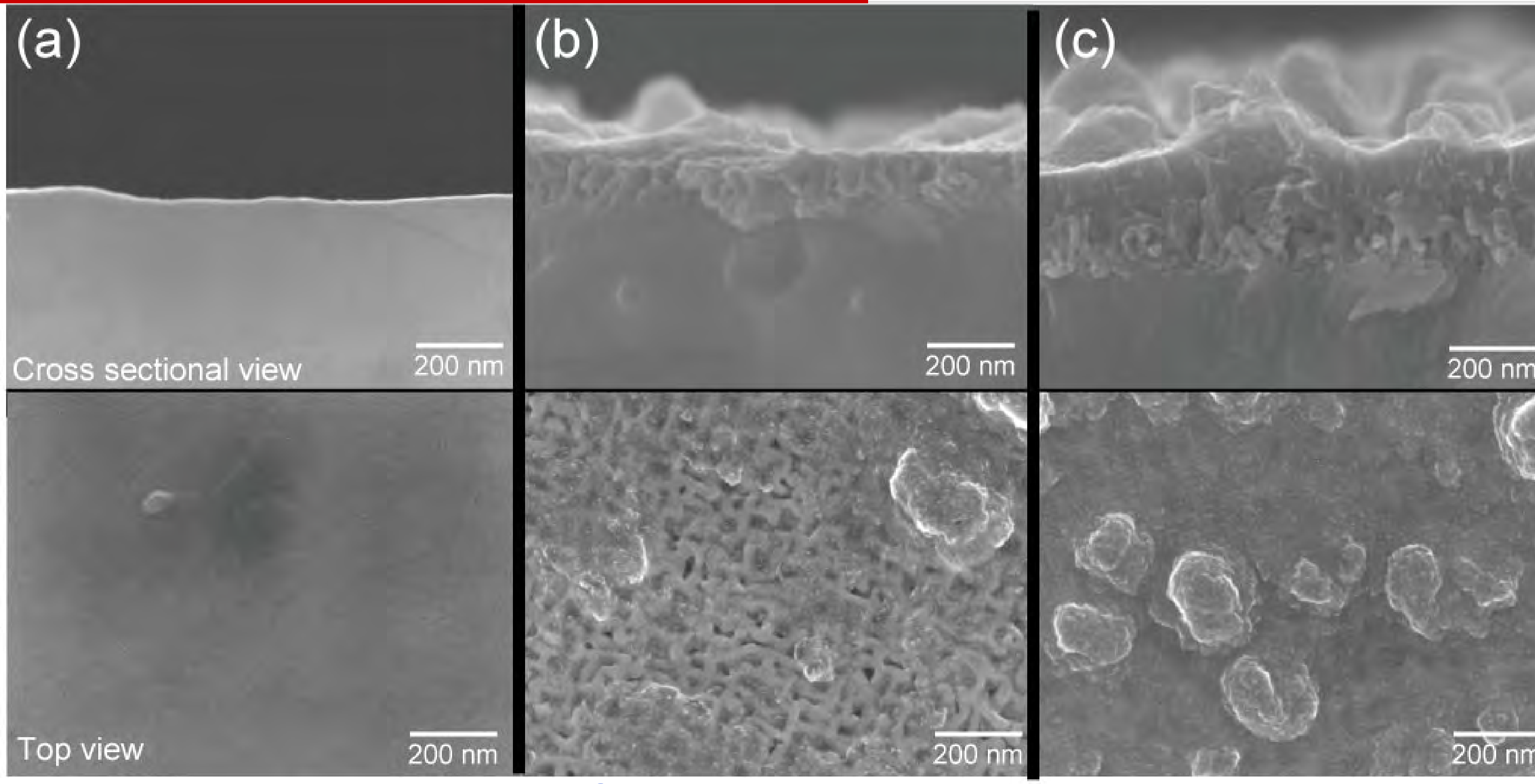


Lack of nano-tendrils on Mo surfaces (still under investigation):

- Different sputtering thresholds
- Different temperature evolution
- Possible impurity coating (boron?) on ramped Mo tiles

Prepared by : G. Wright (MIT)

Pre-made fuzz exposure to D/He TEXTOR plasma



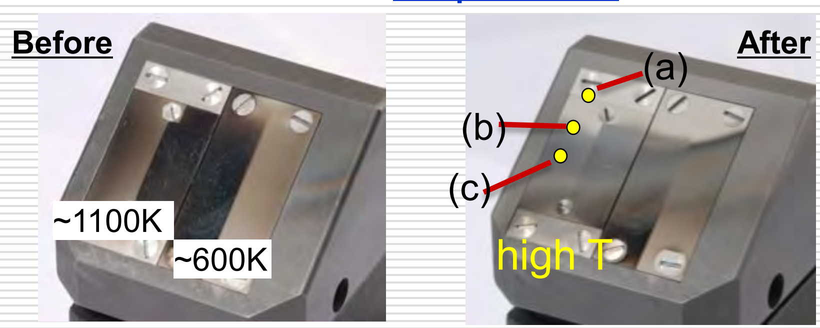
Erosion — Slight deposition — Deposition

Under TEXTOR D/He mixed plasma:

Only erosion and C deposition area

No evidence of fuzz growth

Probably due to high C concentration



Y. Ueda et al., J. Nucl. Mater. (2011) in print.

Erosion and arcing of nano-structures

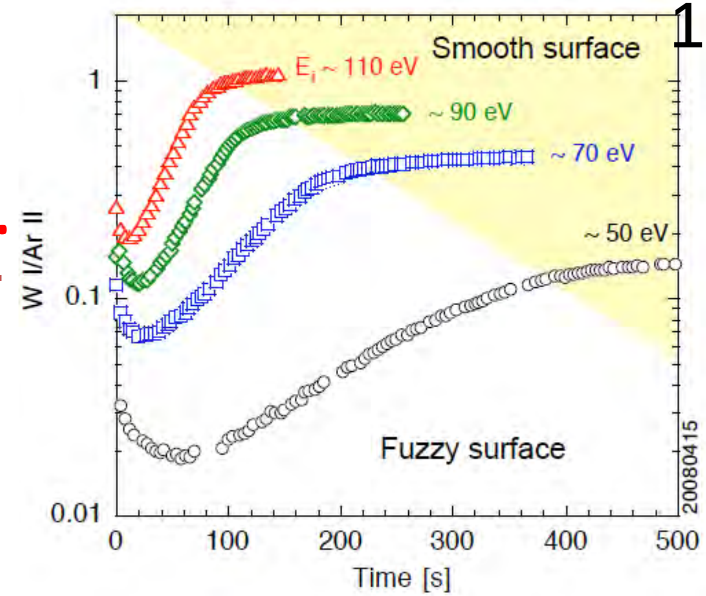
- **How do they behave in edge plasmas?**
  - **Sputtering erosion**
  - **Thermal annealing without He irradiation**
  - **Response to pulsed heat/particles**
  - **Unipolar arcing (enhanced erosion)**

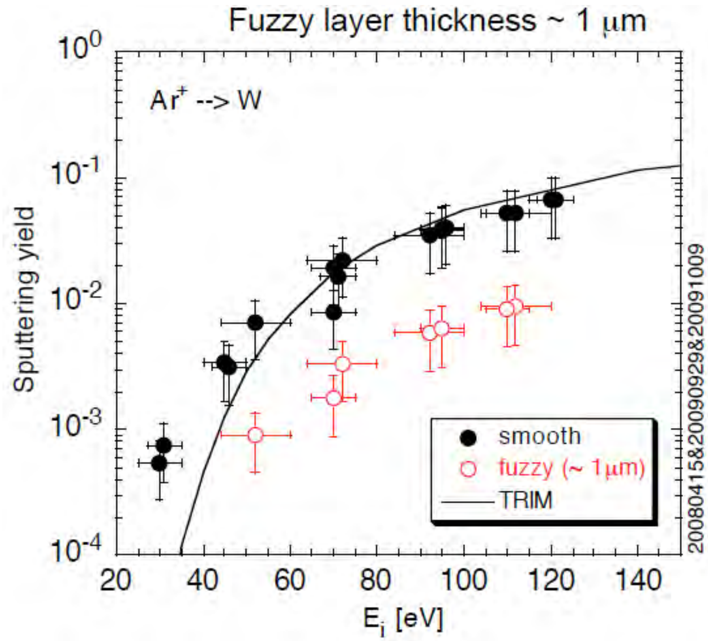
W fuzz has lower physical sputtering yield than smooth W.

PISCES

- Fuzz produced on W by He plasma exposure over 800 s at 1150 K, E_i ~ 90 eV.
- Switch to He/Ar plasma at t = 0 s, & measure time evolution of W I emission in front of W target.

- $Y_{smooth}(Ar^+ \rightarrow W)$ ~0.05 @ E_i ~ 110 eV, by mass loss. (Agrees w/ TRIM).
- Y_{fuzzy}= (0.05 / $WI/ArII_{110\ eV,\ smooth}$) x WI/ArII
- Why is the sputtering yield reduced?
    - Porosity? Internal bubble?
    - Not well understood.

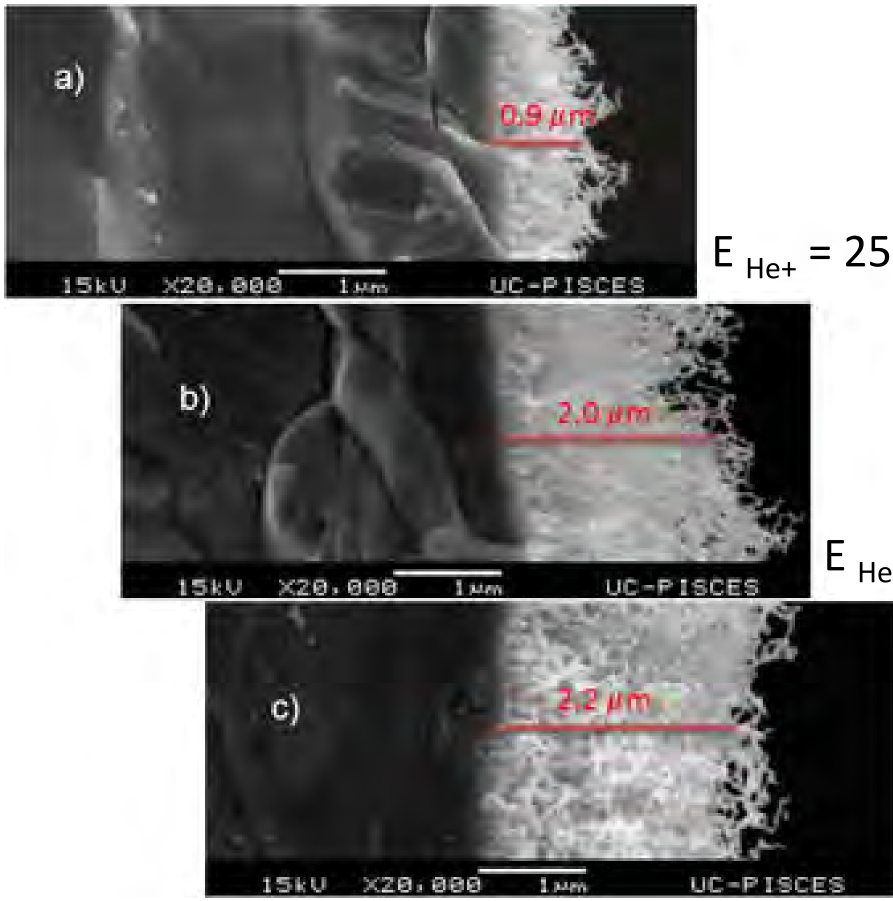




From D. Nishijima et al., PSI-19 in press JNM.

Erosion of fuzzy surface leads to an equilibrium layer thickness where erosion = growth rate

PISCES

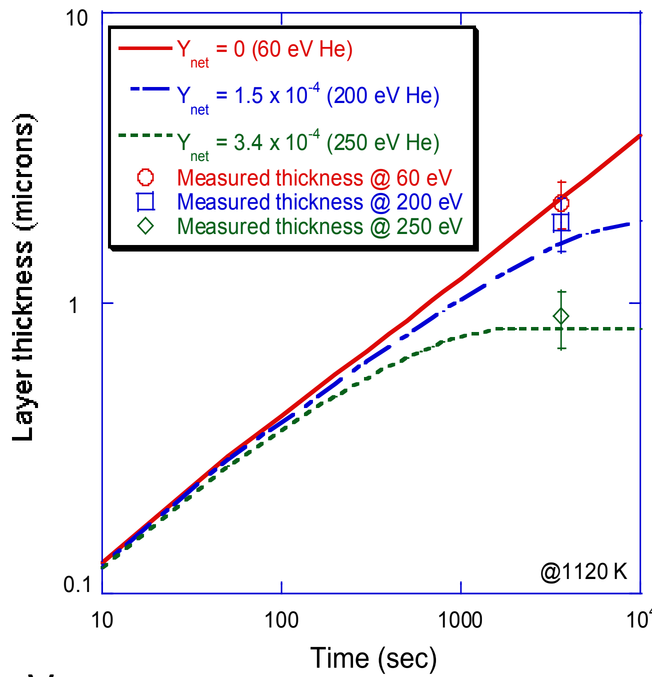


E_{He+} = 250 eV

E_{He+} = 200 eV

E_{He+} = 60 eV

Measured fuzz thickness in PISCES-A agrees with model of competition between growth and erosion rates

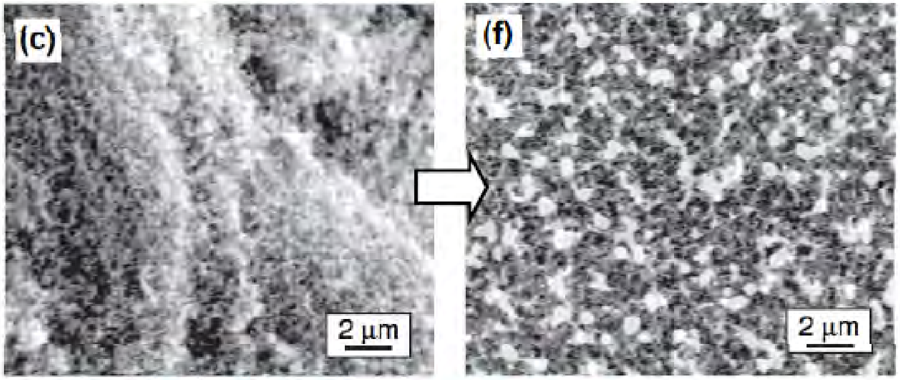


From R. Doerner et al. Nucl. Fus. 51(2011)043001

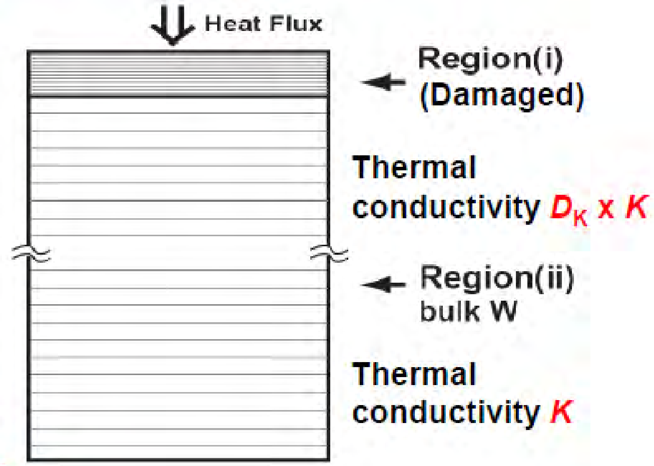
ELM-like pulsed heat effect

Nanostructure melts even if the power is very low

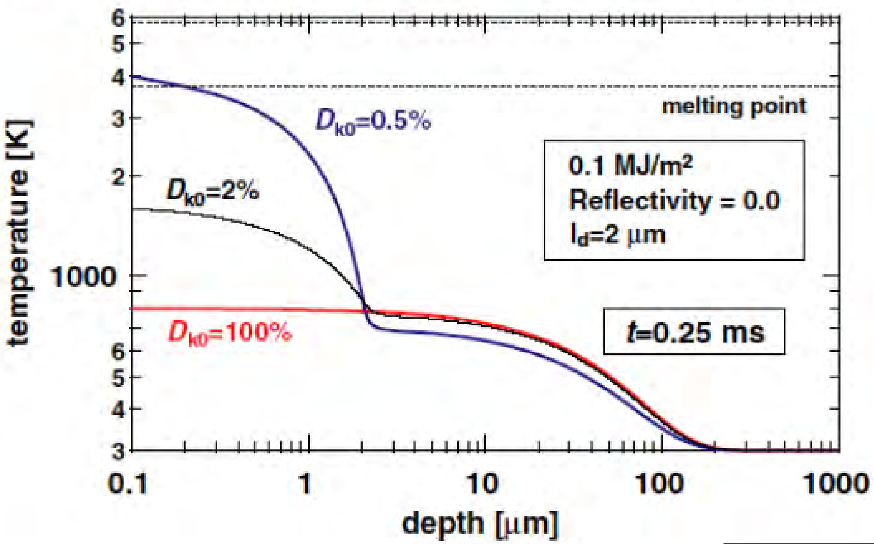
NAGDIS



Δt=0.6 ms, Laser:0.1 MJm^{-2} Melting traces



Even though the laser power is significantly weak, melting traces are formed by laser pulse irradiation.



- Thermal conductivity decreases effectively by more than two orders of magnitude.
- Fiberform nanostructure is considerably weak for pulsed heat load, though the material has durability to continuous heat load.

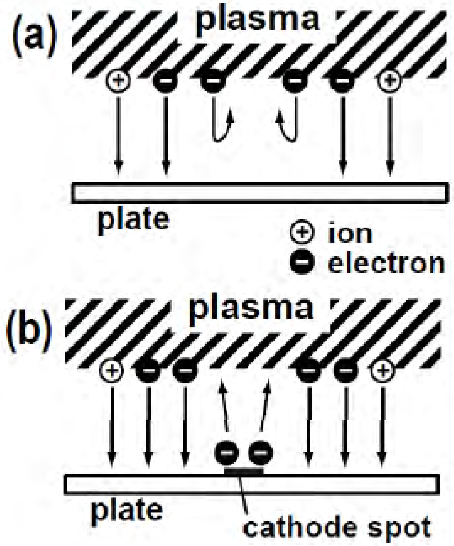
S. Kajita, NF(2007)

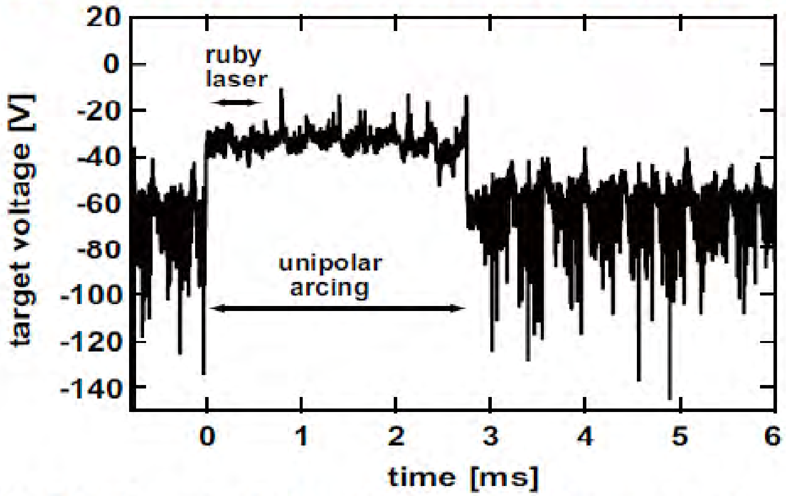
W is released over certain pulse energy

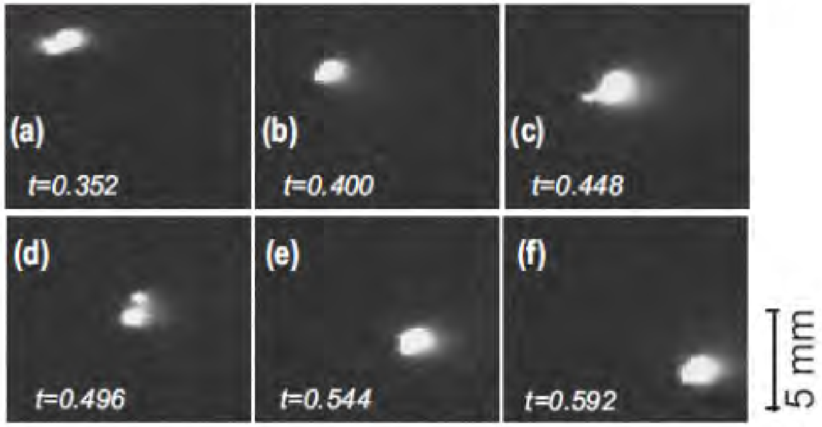
Prompt ignition of unipolar arc: Revival of arcing issue in fusion?!

NAGDIS

- Arcing ignited at the floating potential. Unipolar arcing is the mechanism of the arcing in fusion devices; however, there is no report in steady state plasma in laboratory experiments.
- ELMs could trigger the unipolar arcing with ease for helium irradiated W.







S. Kajita et al., Nucl. Fusion 49 (2009) 032002 (4pp)

Premade W fuzz samples survive plasma gun heat and particle loads

PISCES

He exposure at 300 ˚C

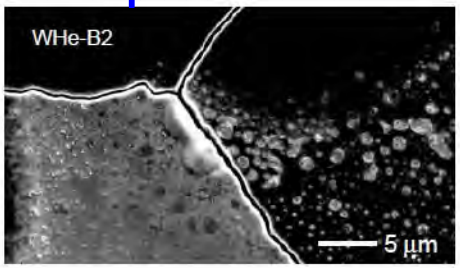


Fig. 3. W surface cracking on WHe-B2 after 10 shots with ~ 0.5 MJ/m^2 per shot.

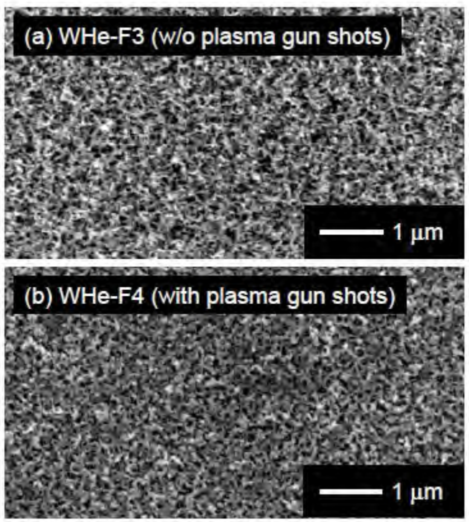
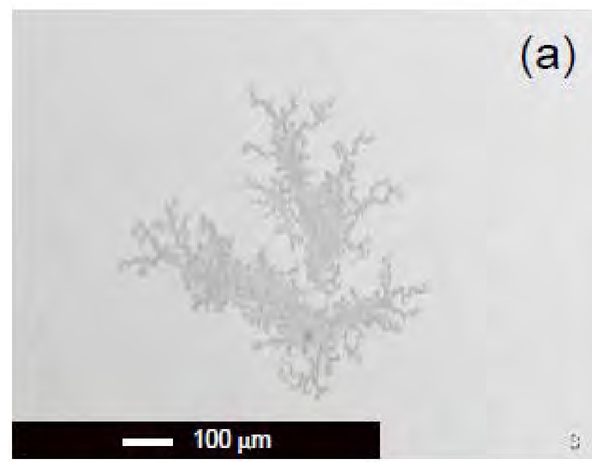


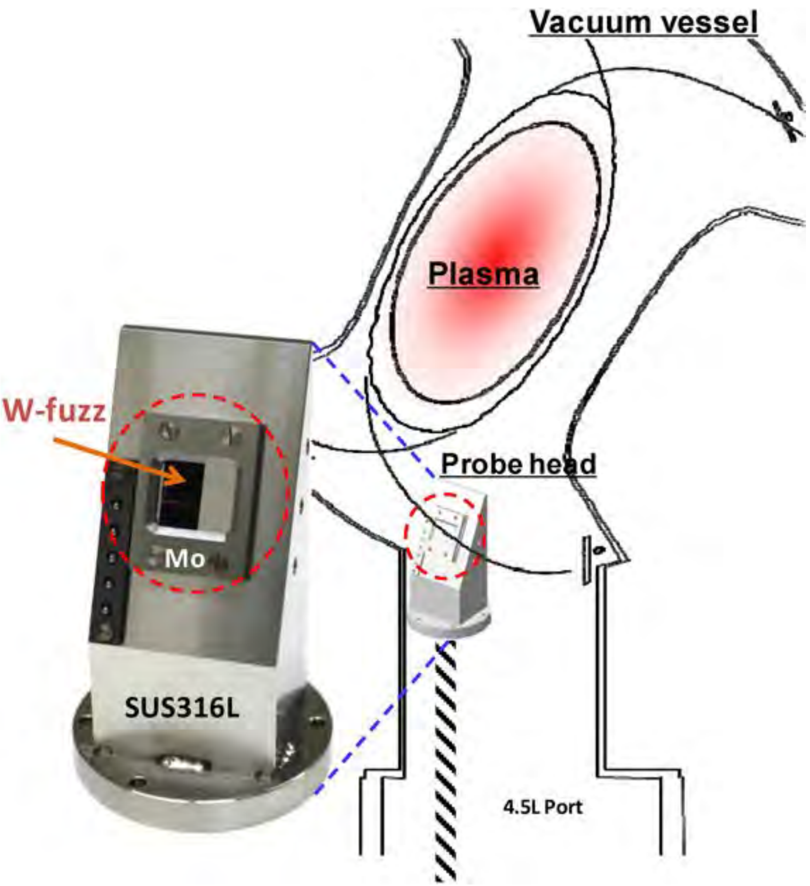
Fig. 4. SEM images of fuzzy W surfaces (L ~ 3 μm). (a) WHe-F3: without plasma gun shots. (b) WHe-F4: after 10 plasma gun shots with ~ 0.7 MJ/m^2 per shot.

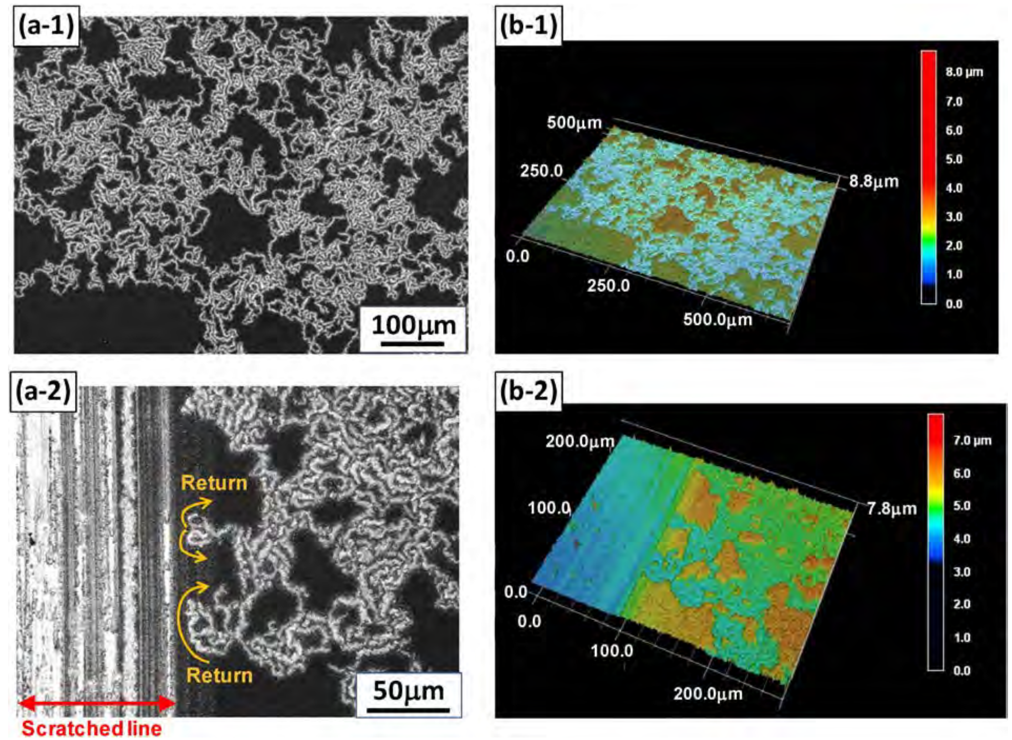
- Fuzzy W samples do not crack after repeated ~0.7 MJ/m^2 shots
- Larger surface area may dissipate heat load or nano-castelation effect
- However, arc tracks are observed only on fuzzy W samples



D. Nishijima et al., Fus. Sci. & Tech. 60(2011)1447

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.

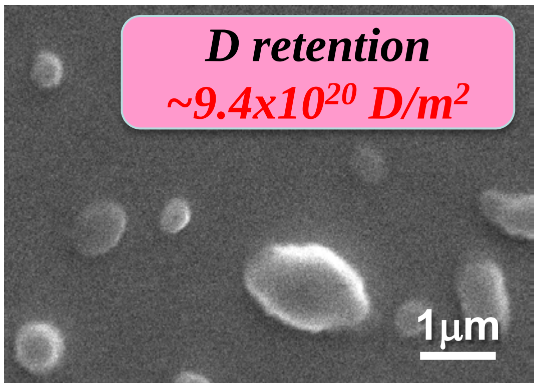
Simultaneous He irradiation effect on D retention

- How do He ions affect D/T retention in tungsten?

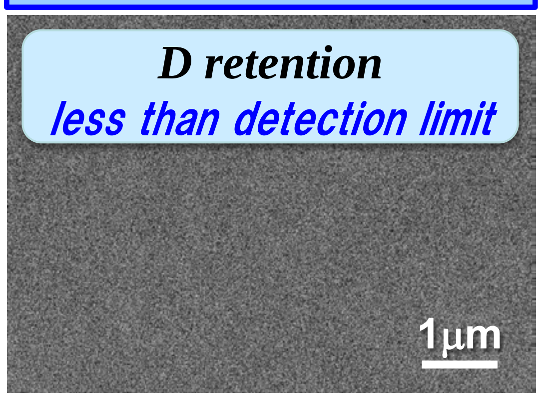
Suppression of D retention by He

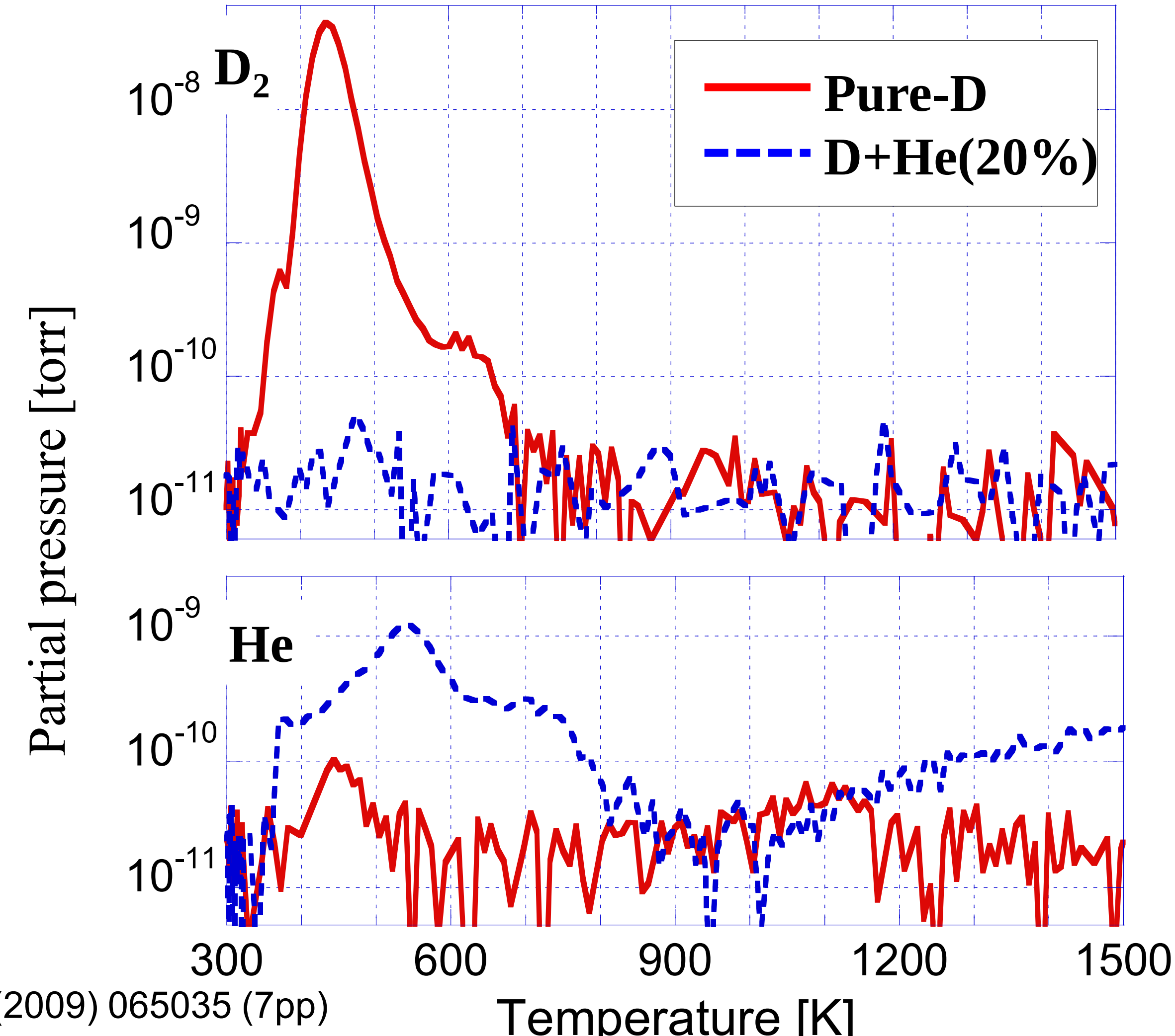
SR-W, $5x10^{25}$ D/m^2, @573K

Pure-D



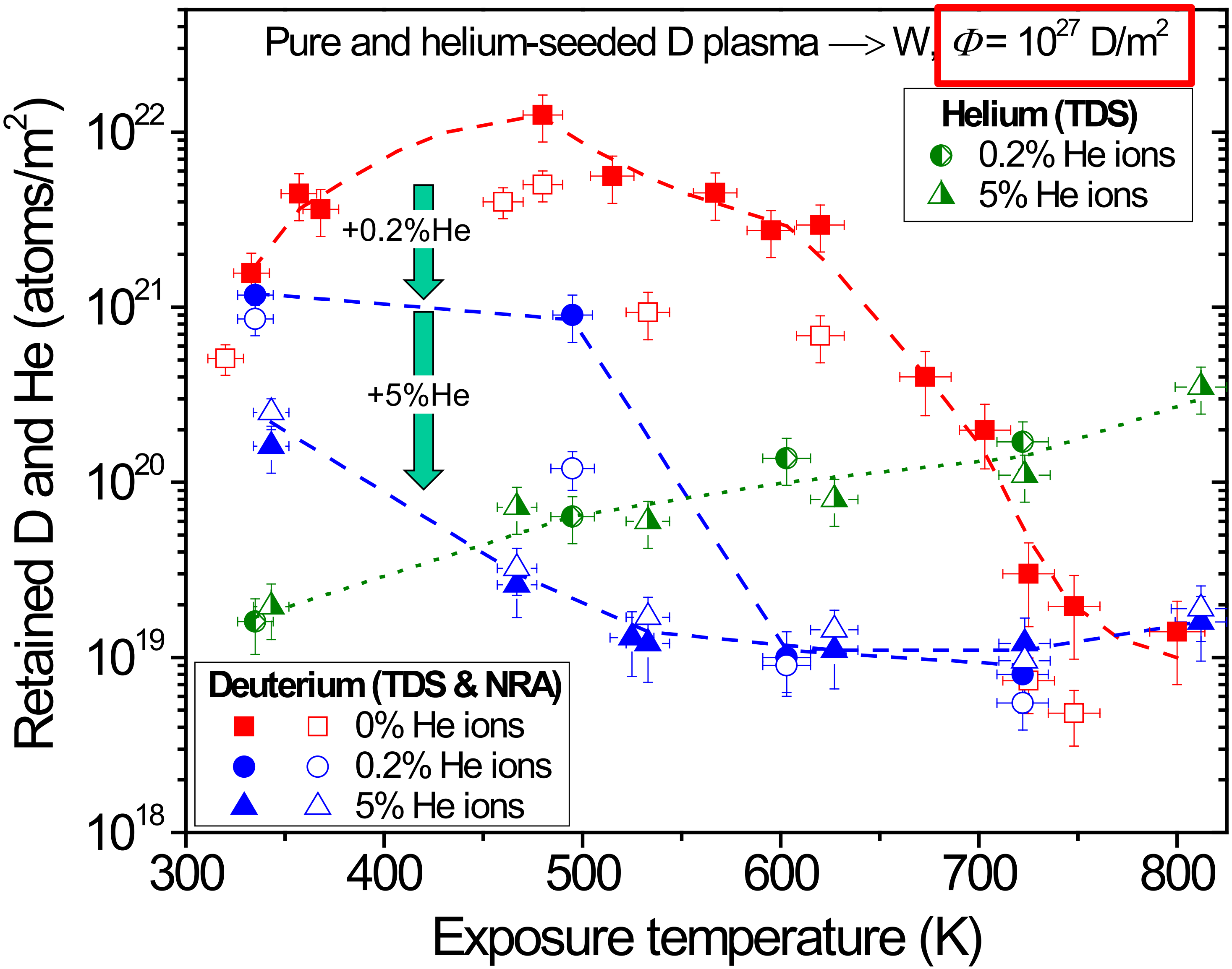
D+He(20%)





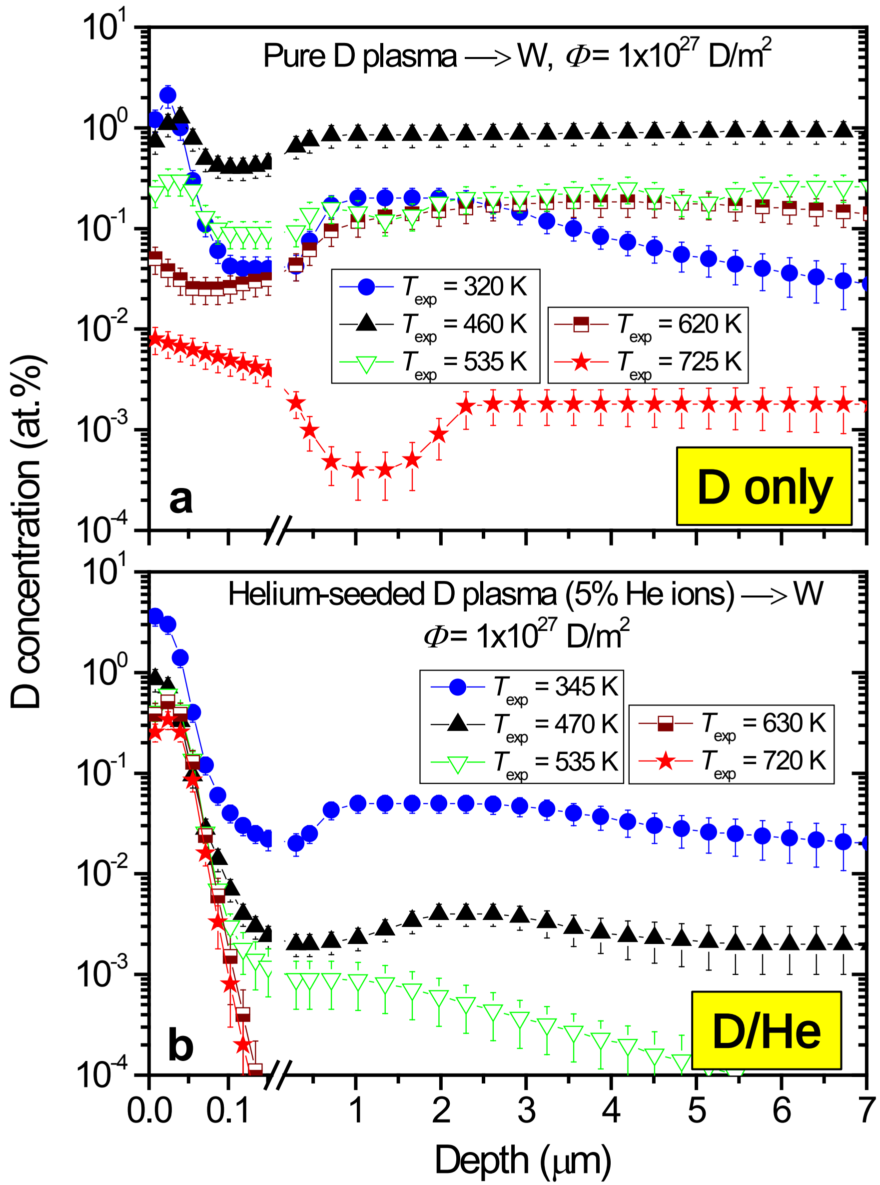
M. Miyamoto et al., Nucl. Fusion 49 (2009) 065035 (7pp)

Deuterium retention in re-crystallized W exposed to pure and helium-seeded D plasmas, $\Phi = 10^{27}$ D/m^2



Prepared by V. Alimov

Deuterium depth profiles in re-crystallized W exposed to pure and helium-seeded D plasmas, $\Phi = 10^{27}$ D/m^2



After exposure to pure D plasma at T_{exp} = 320-620 K, deuterium depth profiles are characterized by high D concentration (0.1-1 at.%) at depths of up to several micrometers.

Seeding of helium into the D plasma significantly reduces the D concentration in the sub-surface layer (1-7 micrometers).

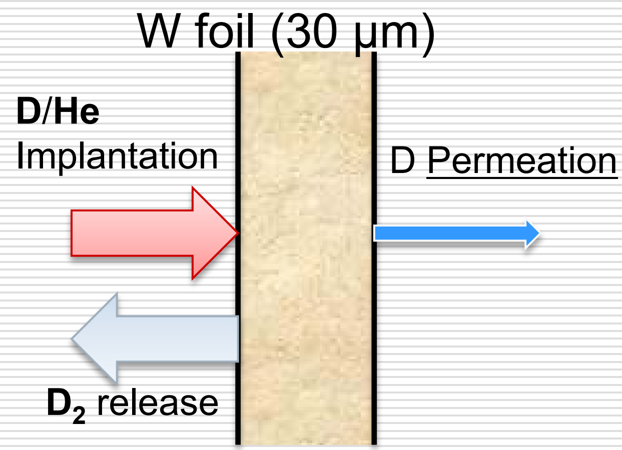
The D concentration in the near-surface layer is higher than that for pure D plasma exposure.

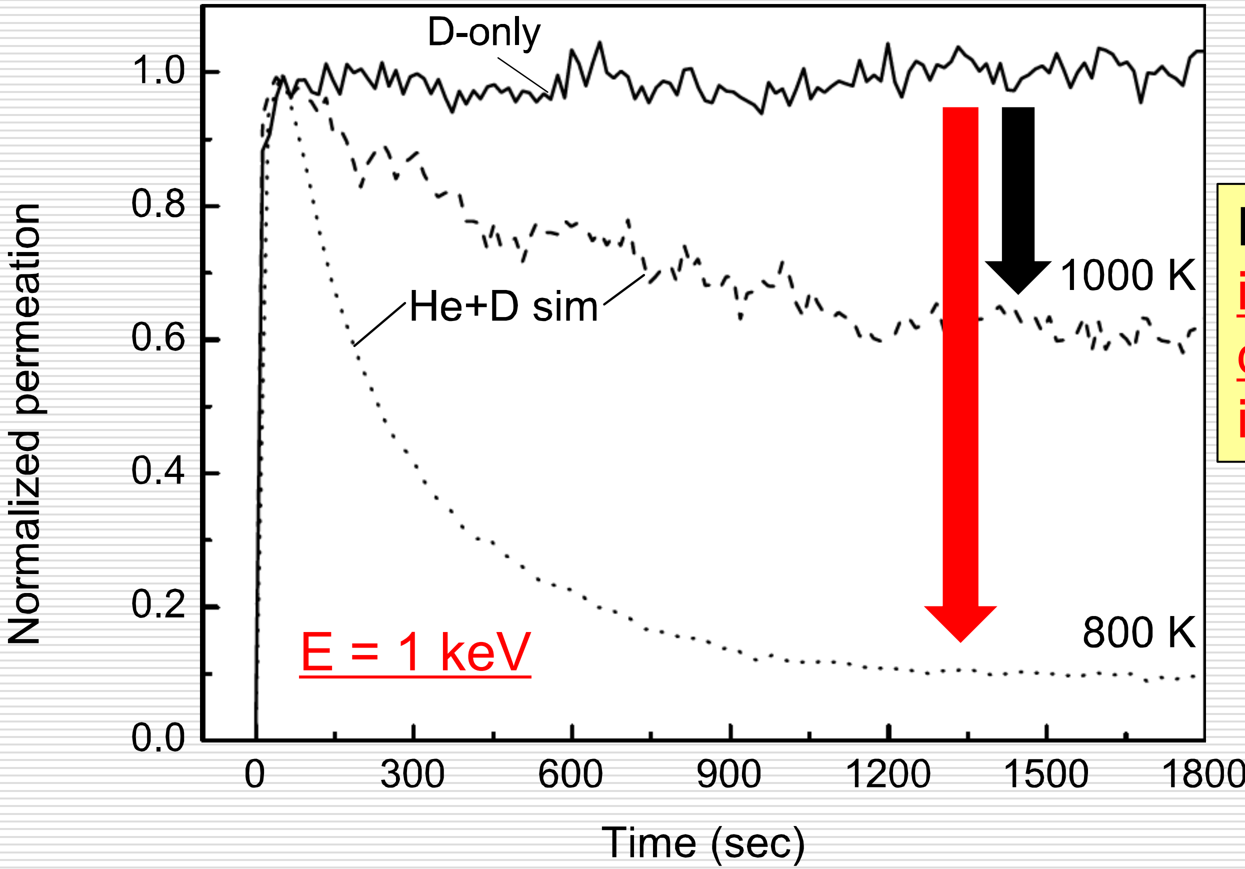
Prepared by V. Alimov

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.

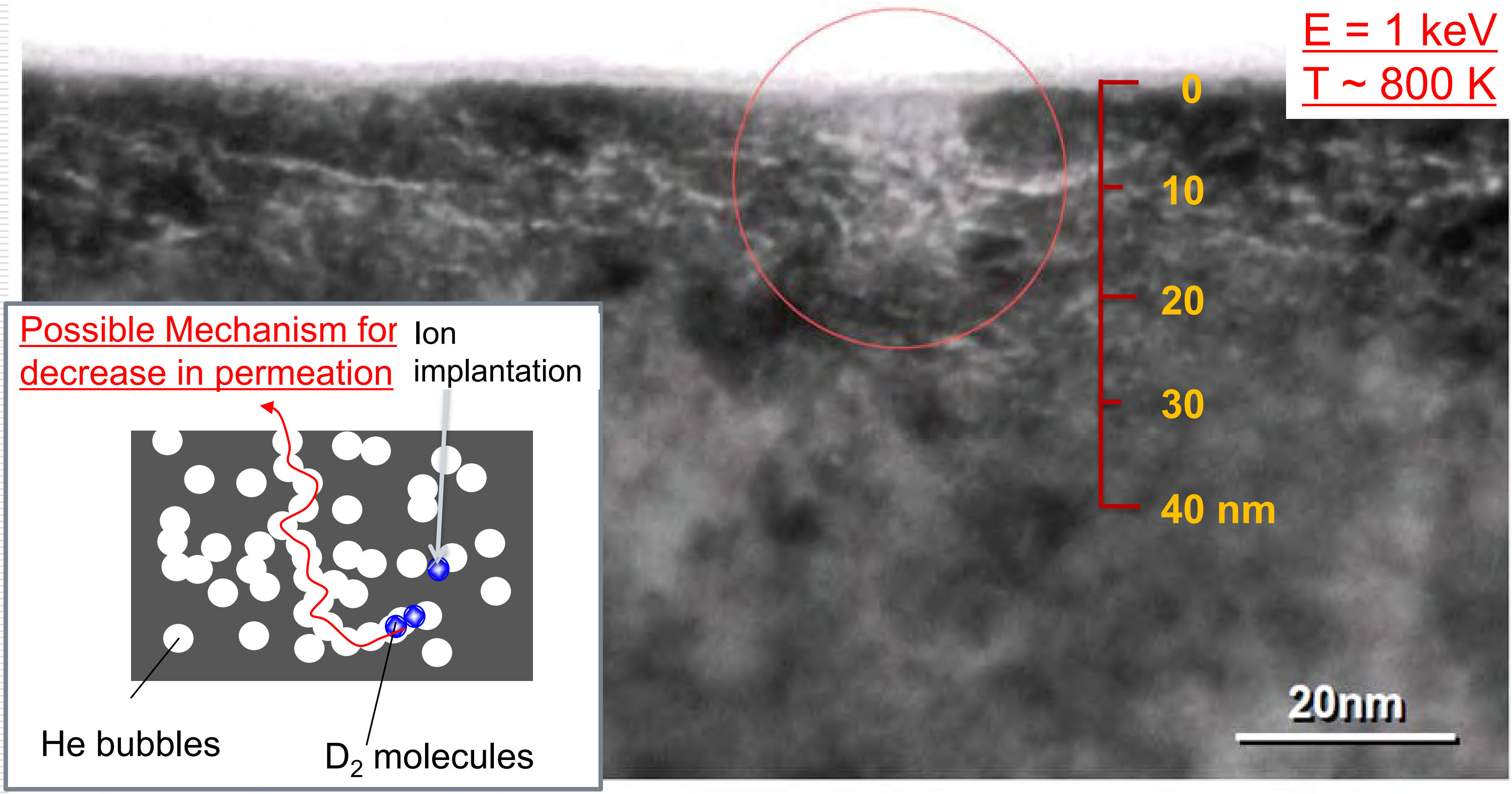
< 800 K
more reduction
(less than detection limit)

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

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 are interconnected to form pores connected to the surface.



Summary

- **Formation of nano-structures**
  - Role of He bubbles on initial formation is understood.
  - Diffusion-like growth is observed.
  - Formation conditions (ion energy, temperature) are clarified.
  - Formation in a confinement device (Alcator C-Mod) was observed on W (but not on Mo).
- **Erosion and arcing of nano-structure**
  - Physical sputtering is lower than smooth surface.
  - Unipolar arcing is liable to occur in any high density plasmas.
  - Eases a pulsed heat effect such as cracking.
  - Thermally annealed at ~1400 K or more without He irradiation.
- **He effects on D retention**
  - Simultaneous He/D irradiation greatly reduces D retention and D influx.

More information is necessary to fully understand characteristics of nano-structure and He/D retention, but we already have a lot of knowledge to evaluate their impacts on fusion plasmas and lifetime of tungsten.