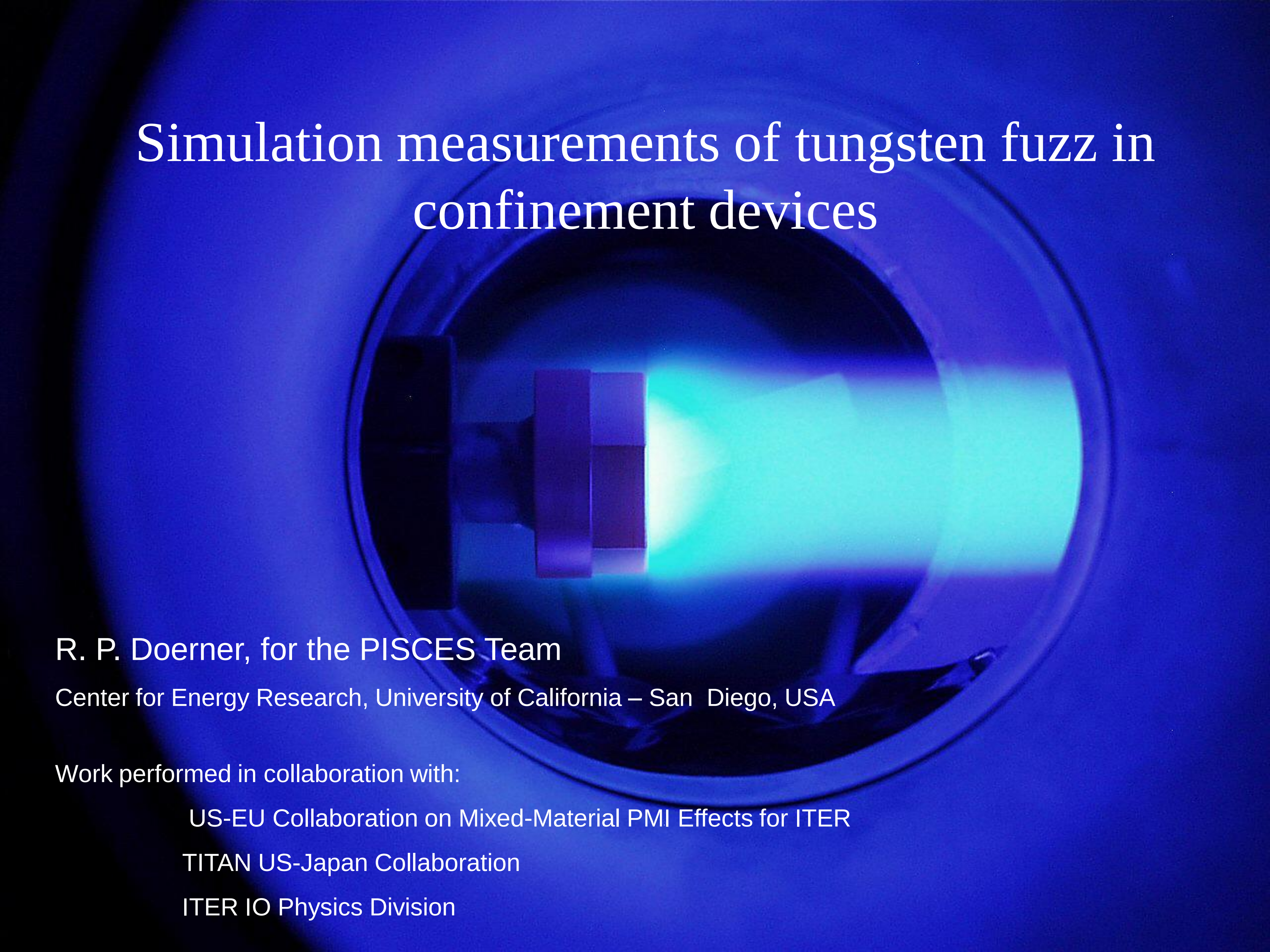
Simulation measurements of tungsten fuzz in confinement devices



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Work performed in collaboration with:

US-EU Collaboration on Mixed-Material PMI Effects for ITER

TITAN US-Japan Collaboration

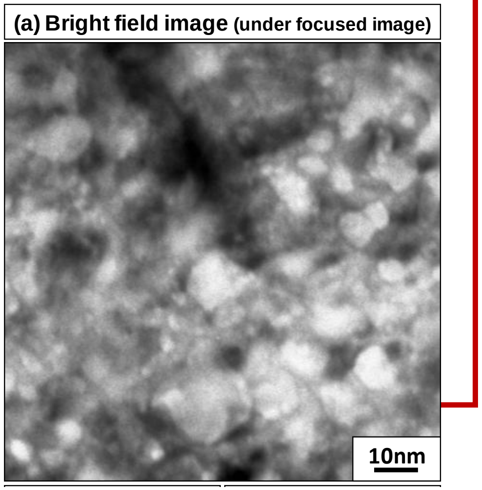
ITER IO Physics Division

W Temperature & PMI are coupled

~ 600 - 700 K

~ 900 – 1900 K

> 2000 K



PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

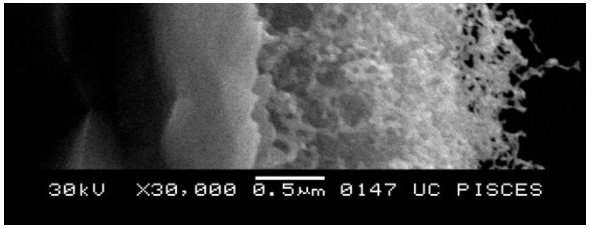
600 K, 1000 s, $2.0\text{x}10^{24}$ He^+/m^2, 55 eV He^+

- Little morphology
- He nanobubbles form
- Occasional blisters

PISCES-B: mixed D-He plasma

M.J. Baldwin et al, NF 48 (2008) 035001

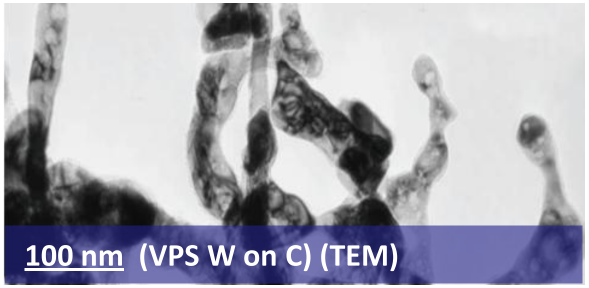
1200 K, 4290 s, $2\text{x}10^{26}$ He^+/m^2, 25 eV He^+



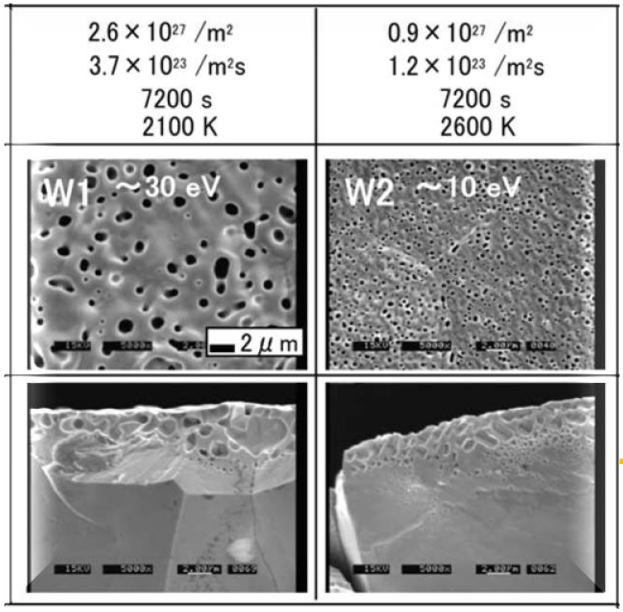
NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

1250 K, 36000 s, $3.5\text{x}10^{27}$ He^+/m^2, 11 eV He^+



- Surface morphology
- Evolving surface
- Nano-scale ‘fuzz’

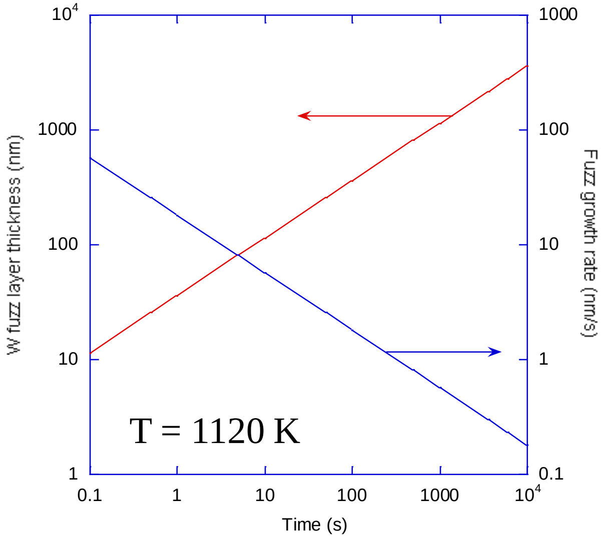


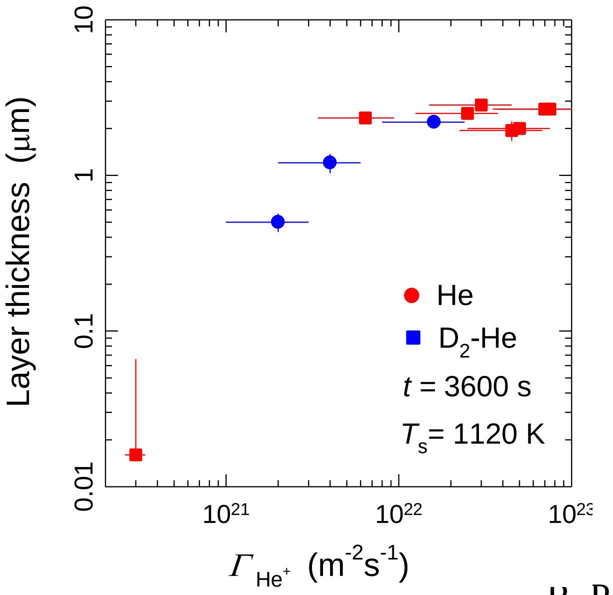
NAGDIS-II: He plasma

D. Nishijima et al. JNM (2004) 329-333 1029

- Surface morphology
- Shallow depth
- Micro-scale

Growth rate of W fuzz surface layer



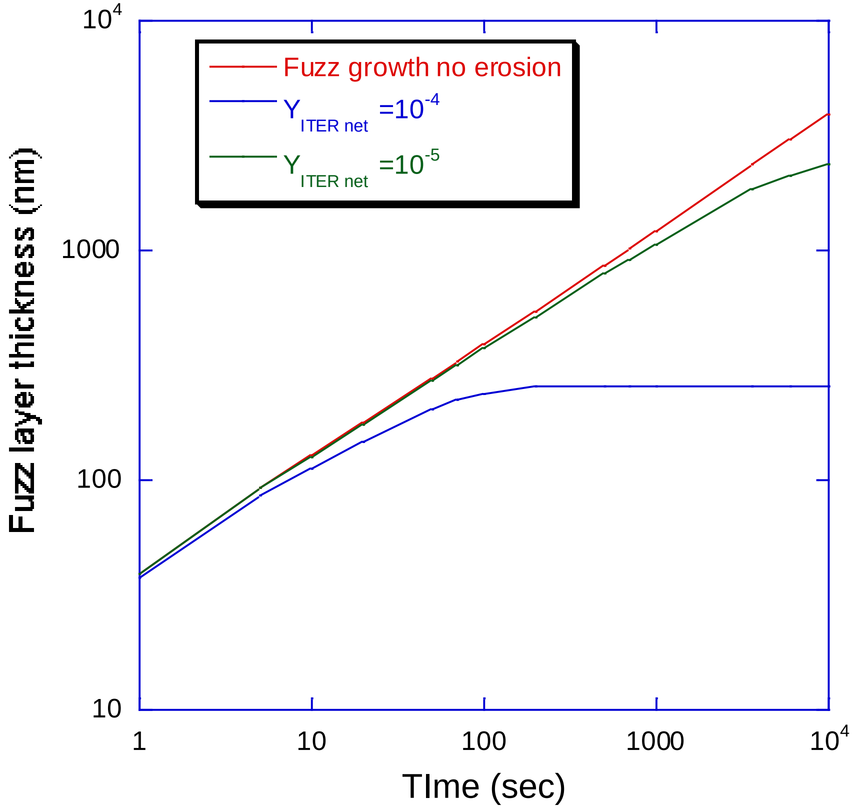


- Fuzz thickness, λ, obeys Fick's Law, $\lambda = (2Dt)^{1/2}$
  [M. Baldwin et al., NF 48(2008)035001]
- Fuzz growth rate exhibits $t^{-1/2}$ behavior, $d\lambda/dt = (D/2t)^{1/2}$
- Arrhenius relationship with surface temperature, $E_a \sim 0.7$ eV
- Similar growth for pure He or D_2-He mixed plasma
- W fuzz growth rate saturates once He flux is sufficient to promote maximum fuzz growth
  [From M. Baldwin et al., JNM 390-391(2009)886]

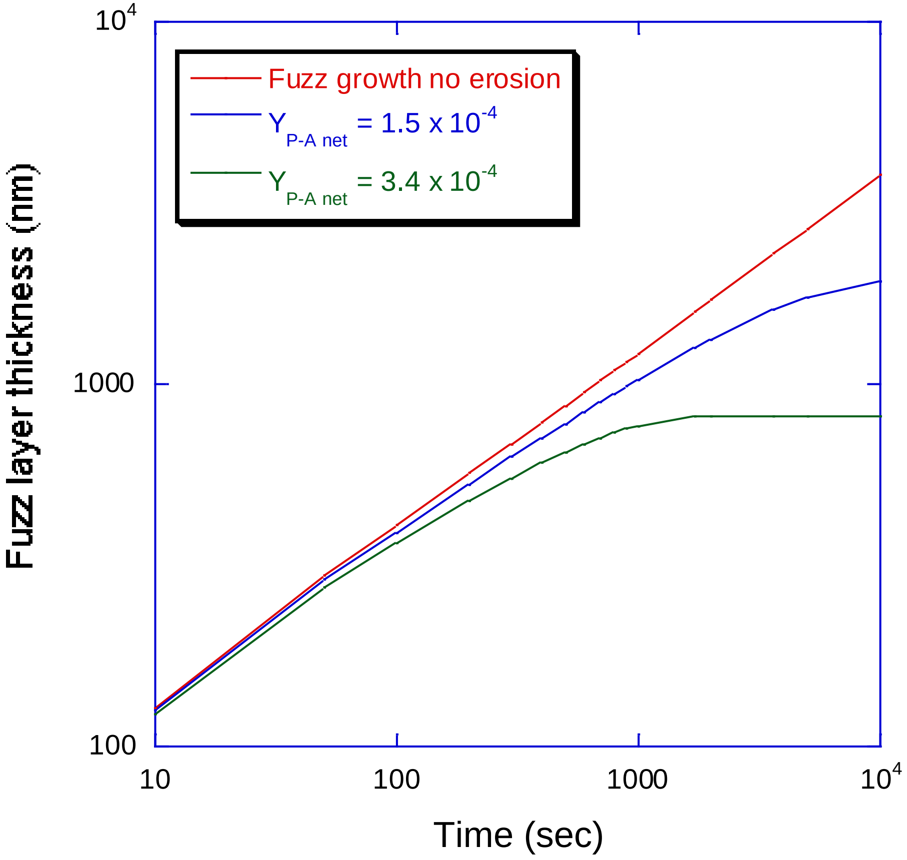
W fuzz growth should be balanced by erosion

- ITER outer divertor strikepoint only area in net erosion and hot enough for fuzz growth
  [J. Brooks et al., NF 49(2009)035007]
- Assume He fraction in divertor is >1%, so maximum possible growth rate is achieved
  [M. Baldwin et al., JNM 390-391(2009)886.]
- Net erosion rate in ITER is uncertain but can be estimated (assume $Y_{\text{ITER net}} = 10^{-4} – 10^{-5}$)
- So fuzz layer thickness, λ, is
  $\lambda = \int((D/2t)^{0.5} – Y_{\text{net}})dt$

ITER outer divertor ion flux ~ 1 x 10 ^{24} $m^{-2}s^{-1}$
Surface temperature ~ 1120 K



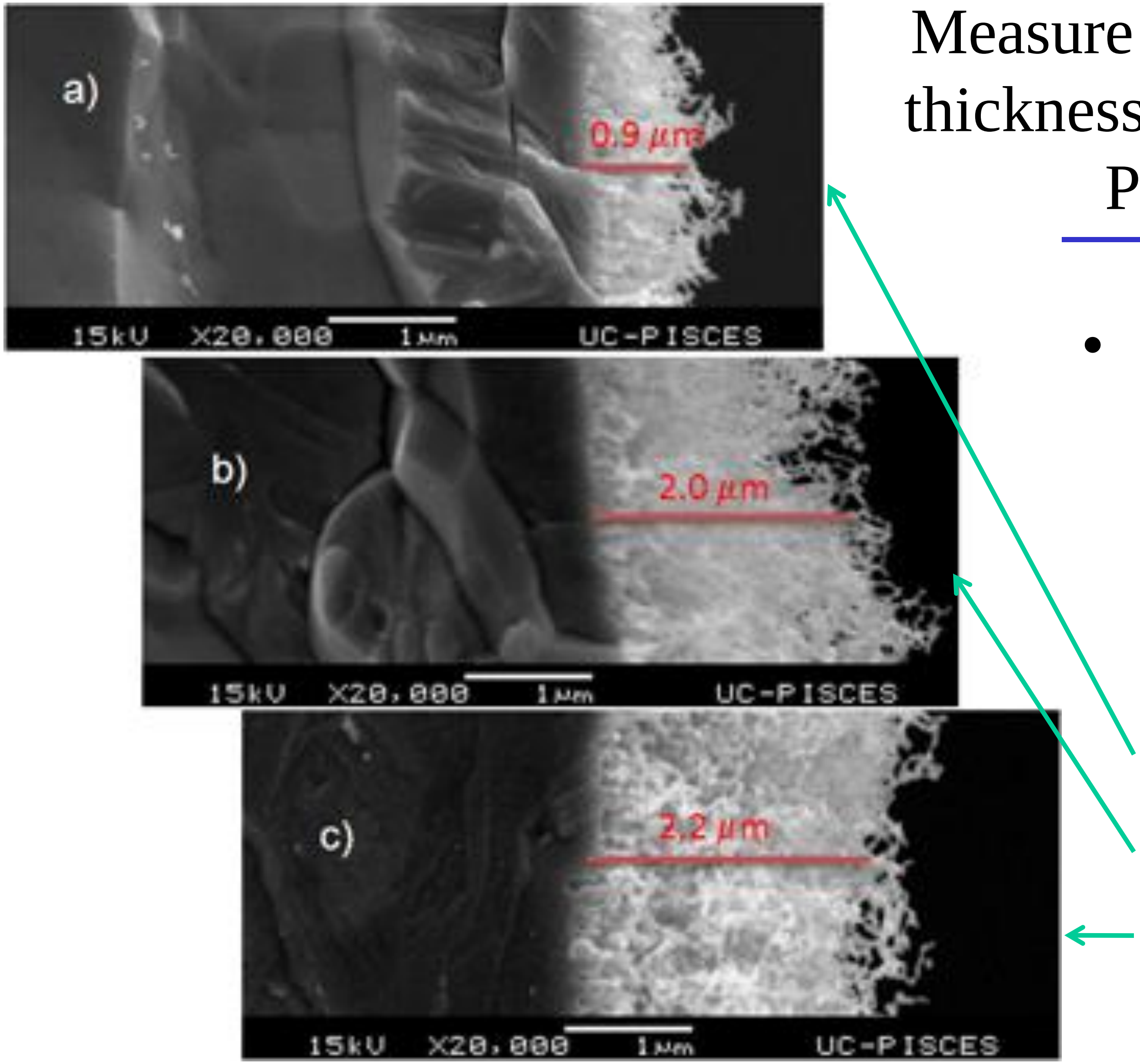
PISCES-A conditions can be used to verify predictions for equilibrium fuzz layer thickness



P-A: $\Gamma_{He} = 1 \times 10^{23}$ m^{-2}s^{-1},
$T_W = 1120$ K

- Growth rate of W fuzz remains unchanged since He flux is sufficient to promote maximum growth
  [From M. Baldwin et al., JNM 390-391(2009)886]
- Weight loss measures net erosion during exposure (includes redep, angular effects, impurity erosion,…) when E_{He^+} is large

Measure equilibrium fuzz thickness while eroding in PISCES-A



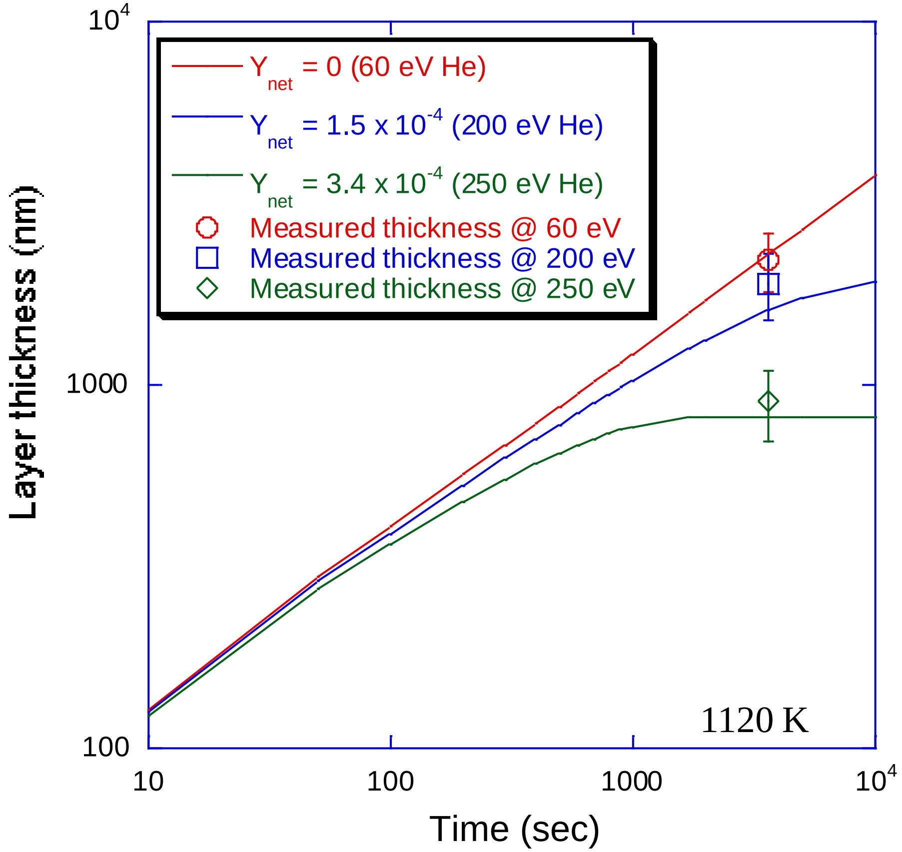
- Expose W to He plasma for 1 hr. at 1120 K while measuring net yield

at 250 eV

at 200 eV

at 60 eV (no erosion case)

Equilibrium fuzz thickness in PISCES agrees with ITER methodology predictions



- Use measured erosion yield for He on W (i.e. net yield) (measured Y is lower than TRIM, but redep is not yet modeled)
- But will fuzz overheat?

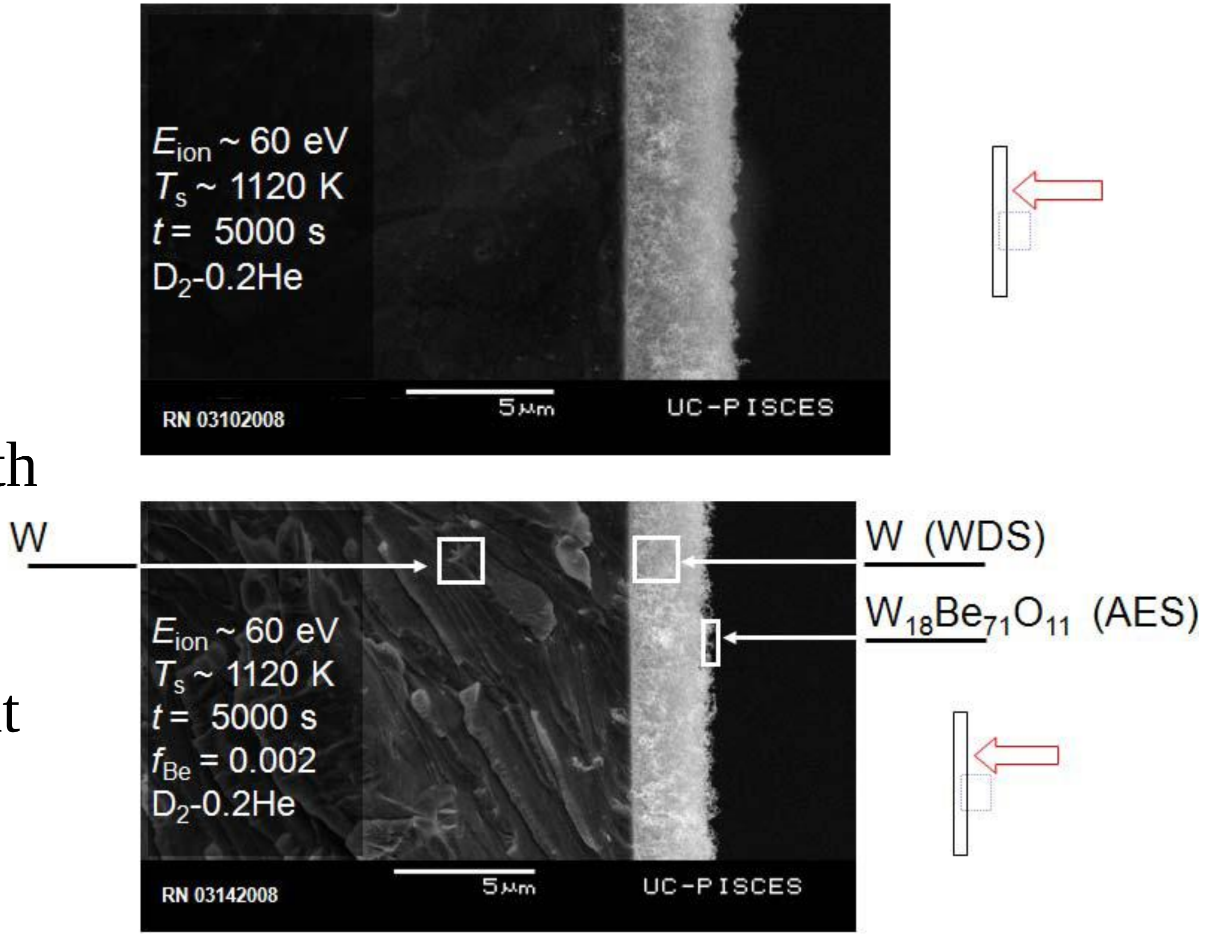
$$\Delta T = (q^*\lambda)/\kappa$$

where $\kappa_W \sim 100$ W/mK

So fuzz won't support much ΔT and won't overheat during steady-state heat loads even with reduced κ_{fuzz}

When sputtering of Be exceeds the incident flux of Be in the plasma, fuzz will form

- When surface is in net erosion, even with Be in the plasma, fuzz will grow
- Net deposition prevents fuzz growth
- Thinner fuzz layer results from Be erosion of W fuzz at 60 eV (no D or He erosion at 60 eV)



How will W fuzz respond to transients?

[D. Nishijima et al., submitted to FusTech]

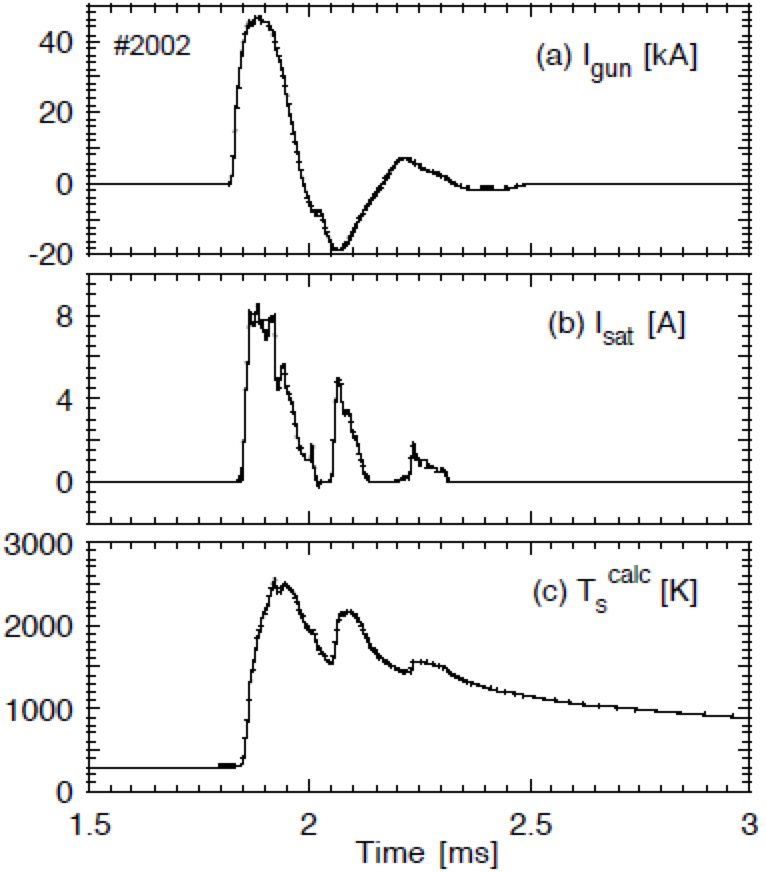


Fig. 1. Time evolution of (a) I_{gun}, (b) I_{sat}, and (c) calculated T_s^{calc}. The absorbed energy density to the target, Q, is ~ 0.7 MJ/m^2.

- Samples exposed to U. of Hyogo (Prof. Nagata) plasma gun pulses
- W samples pre-exposed to He plasma at 300°C show melting and cracking after 10 - 0.5 MJ/m^2 pulses
- W fuzz samples survive 10 - 0.7 MJ/m^2 pulses without cracking or melting (50 $MJ/m^2s^{1/2}$)

Sample	Pre-plasma exposure in PISCES-A	0.7 MJ/m^2 x 10 shots
WU-3	None (mirror)	Cracked
WD-4	D (blister)	Cracked
WHe-B4	He (smooth, bubbles)	Cracked
WHe-F4	He (**fuzzy ~ 3 μm**)	**Not Cracked**

Premade W fuzz samples survive plasma gun heat and particle loads

[D. Nishijima et al., submitted to FusTech]

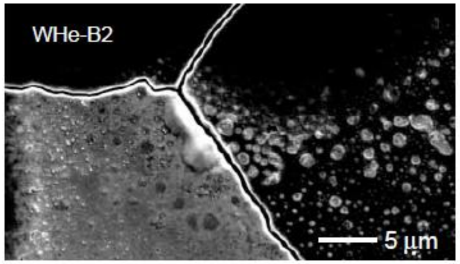


Fig. 3. W surface cracking on WHe-B2 after 10 shots with ~ 0.5 MJ/m^2 per shot.

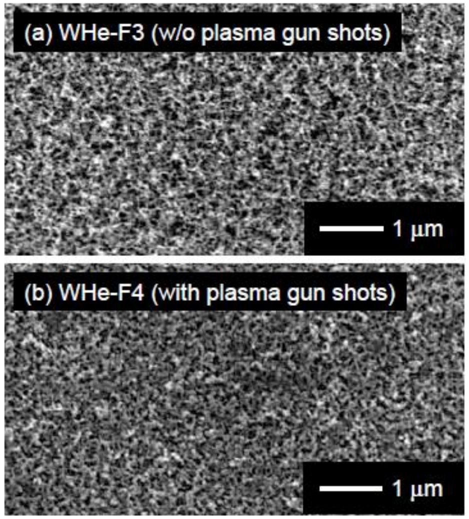
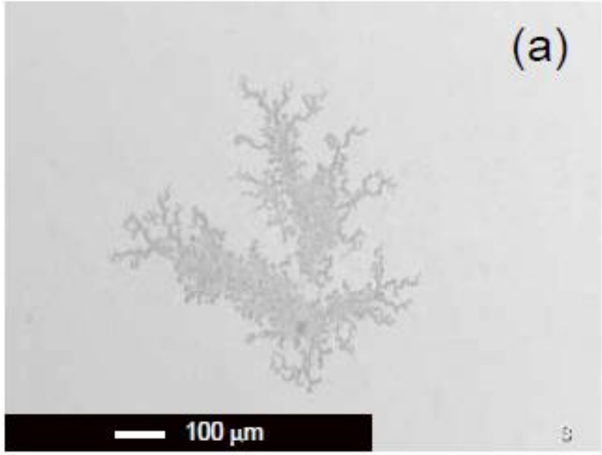


Fig. 4. SEM images of fuzzy W surfaces ($L \sim 3$ μm). (a) WHe-F3: without plasma gun shots. (b) WHe-F4: after 10 plasma gun shots with ~ 0.7 MJ/m^2 per shot.

- 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



Summary : Due to initially fast growth of W fuzz, ITER should expect some equilibrium thickness nanostructure to form in the erosion zone of a W divertor

Pros

- Self limited $t^{1/2}$ growth at surface.
- Erodes with lower sputter yield w.r.t bulk W.
- Very low hydrogen isotope retention.
- Good permeation barrier.
- Seemingly more resilient to power loads.

Cons

- Unknown material properties w.r.t W.
- Potential for enhanced material loss (dust production) during transients.
- Surface and potential deep grain boundary destruction.
- Increased arcing.

Outlook

- Fuzz will manifest in long pulse high T reactors w/ W FW, but can we live with it?
- Is W fuzz an improved plasma-facing material?