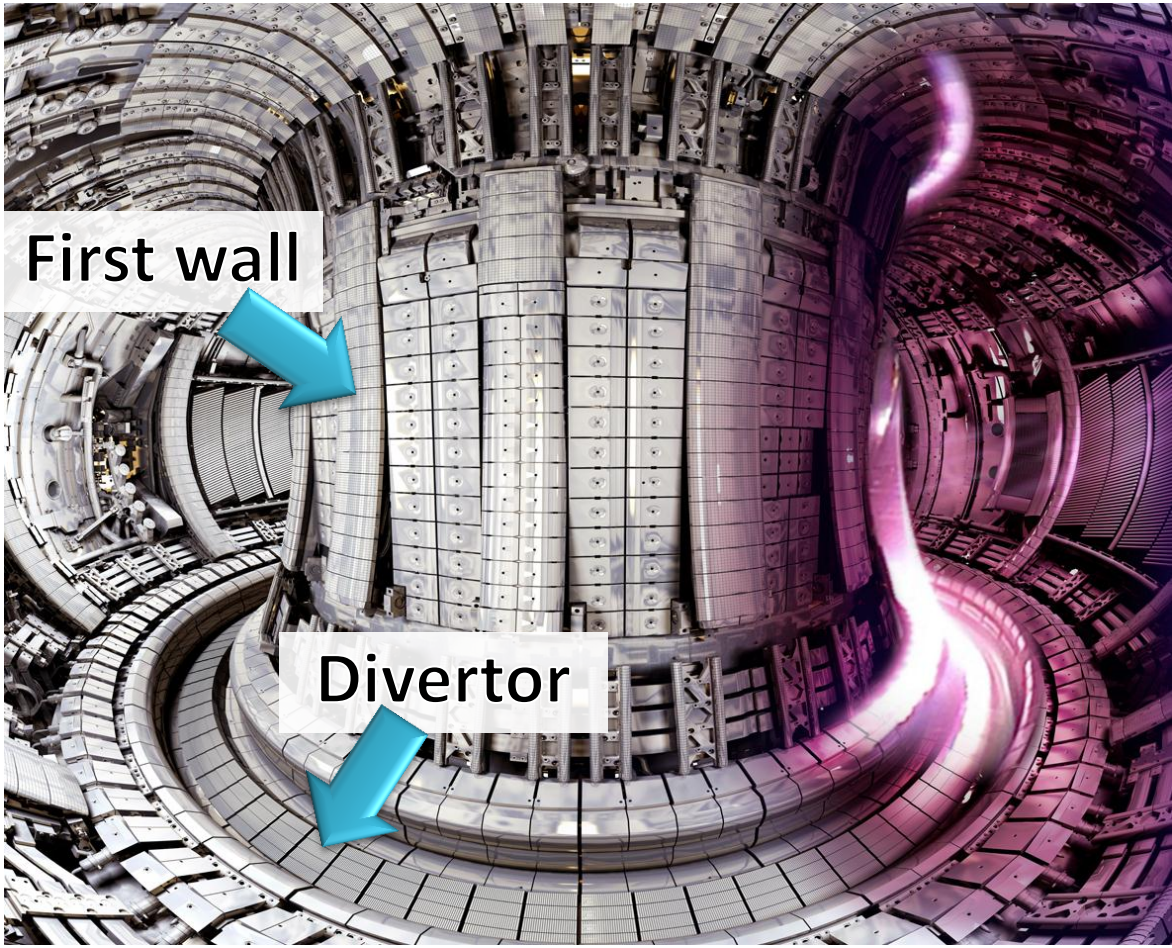
What can face the plasma in a tokamak?

- Plasma-facing materials will face the harshest environment imaginable
- Tungsten is the leading candidate for divertors, possibly for first walls
- RAFM steel is under consideration for use as the first wall PFM in the European DEMO
- Liquid metals (Li, Ga, Sn, SnLi) are also considered as candidate PFMs (with lower TRL)



https://www.euro-fusion.org/jet/

Slide from C. Parish: Microscopy and Microanalysis 2016 talk

A large step from now to ITER and DEMO

B. Unterberg et al., PSI20 Aachen 2012.

	JET	ITER	DEMO*
P/R (MW/m)	11	25	94-130
W_{th}/R (MJ / m)	3	X 20 → 60	125-395
operation time (s/ yr)	$4.0 \cdot 10^4$	$4.0 \cdot 10^5$	X 60 → $2.4 \cdot 10^7$
Averaged neutron fluence (FW) (MW a / m^2)	~0	~0.3	X 30 → ~10
T_{wall} (K)	500	500	X 2 → 1000

*Range given by different models within EFDA- PPCS (2005) [D. Maisonnier *et al* 2007 *NF* **47** 1524]

- **New challenges for all issues related to *fluence*, *neutron damage* and *wall temperature* *(last two will indirectly affect all others via material issues)***

Several issues exist for functionality of PFCs

Solid surfaces:

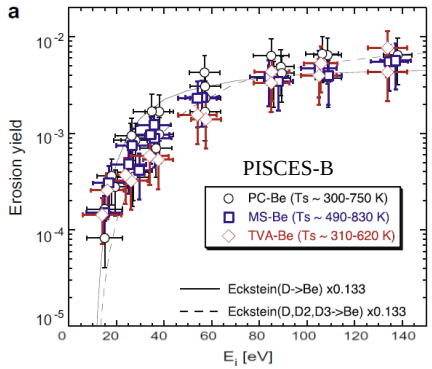
- Lifetime of components
  - Sputtering yields, response to cyclic/transient loads, neutron effects
- Changes in thermo-mechanical properties of components
  - Due to plasma exposure (s.s. & transients), neutrons
- Tritium retention and permeation

Liquid surfaces:

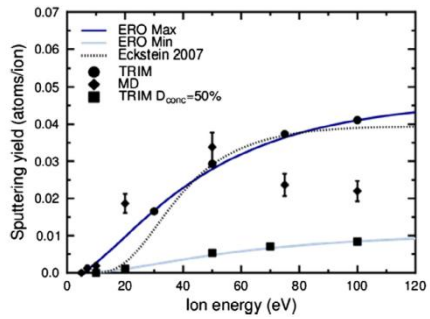
- Need for an integrated design demonstration (slow vs. fast flow, etc)
- Corrosion effects
- Control of flow streams, free surfaces, recirculation
- Purification of flowing materials (tritium and impurities) in real time

Sputtering is one of the most fundamental properties of PMI and it is not well understood in a high-flux plasma

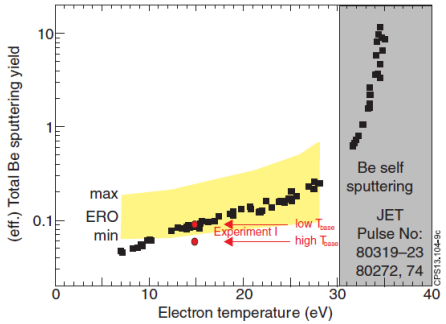
Be sputtering



D. Nishijima et al., JNM 2009.



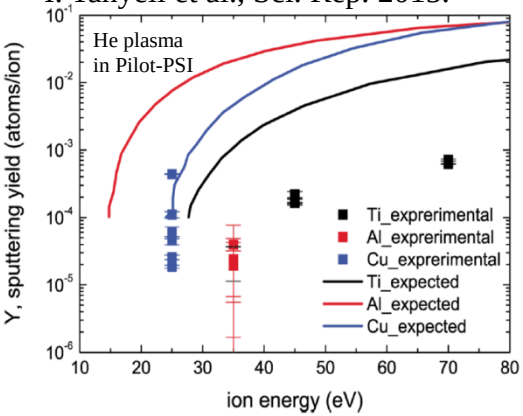
D. Borodin et al., JNM 2013.



S. Brezinsek et al., NF 2015.

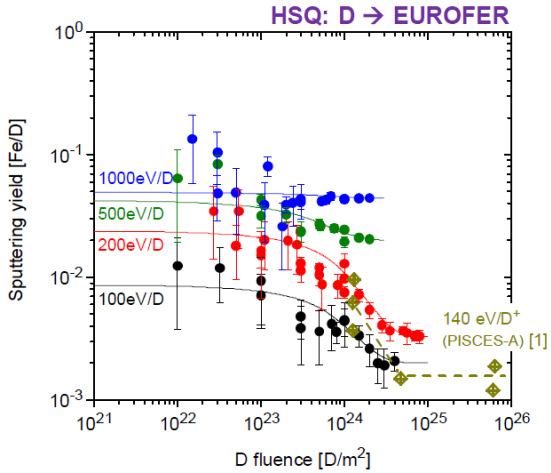
- Sputtering determines PFC lifetime, is the source term for material migration, and is responsible for codeposition with T
- TRIM has been benchmarked against ion beam sputtering measurements
- TRIM overestimates sputtering during high-flux plasma bombardment in LPDs, as well as in tokamaks
- Surface morphology and fuel accumulation are thought to be responsible
- Is this true for liquid surfaces (fast or slow flow)

I. Tanyeli et al., Sci. Rep. 2015.



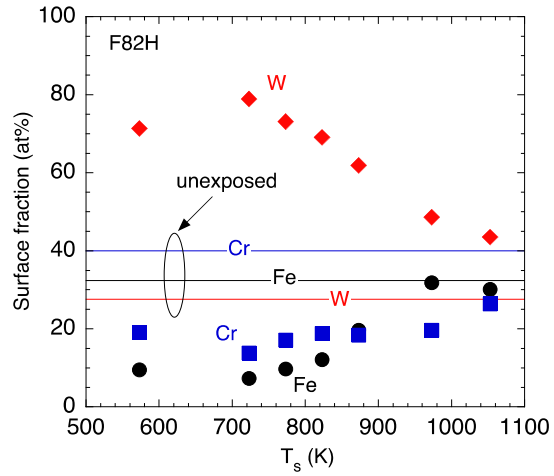
Can sputtering be exploited to achieve a desired PMI surface?

- EUROFER, F82H, CLAM, RUSSFER all contain few % W
- EUROfusion believes preferential sputtering of Fe and Cr from RAFM steel will provide W-enrichment of the surface
- CX energy must be low-enough not to sputter W from first wall
- At high operating temperature effect may disappear due to Fe(Cr) diffusion to the surface
- Surface morphology changes at high fluence may mask improvements due to W surface

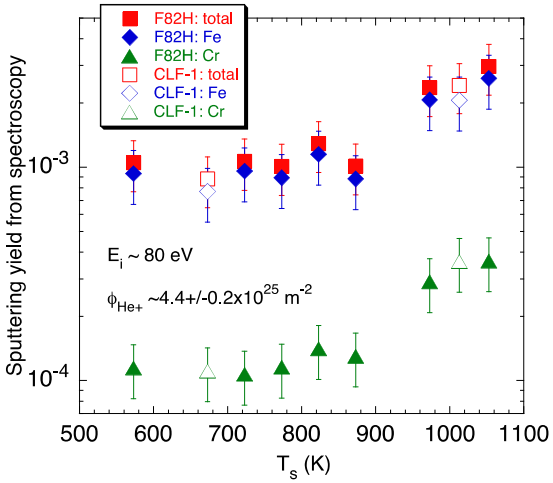


Sputtering yield of EUROFER steel by D ion irradiation with different D energies as a function of D fluence (320 K)

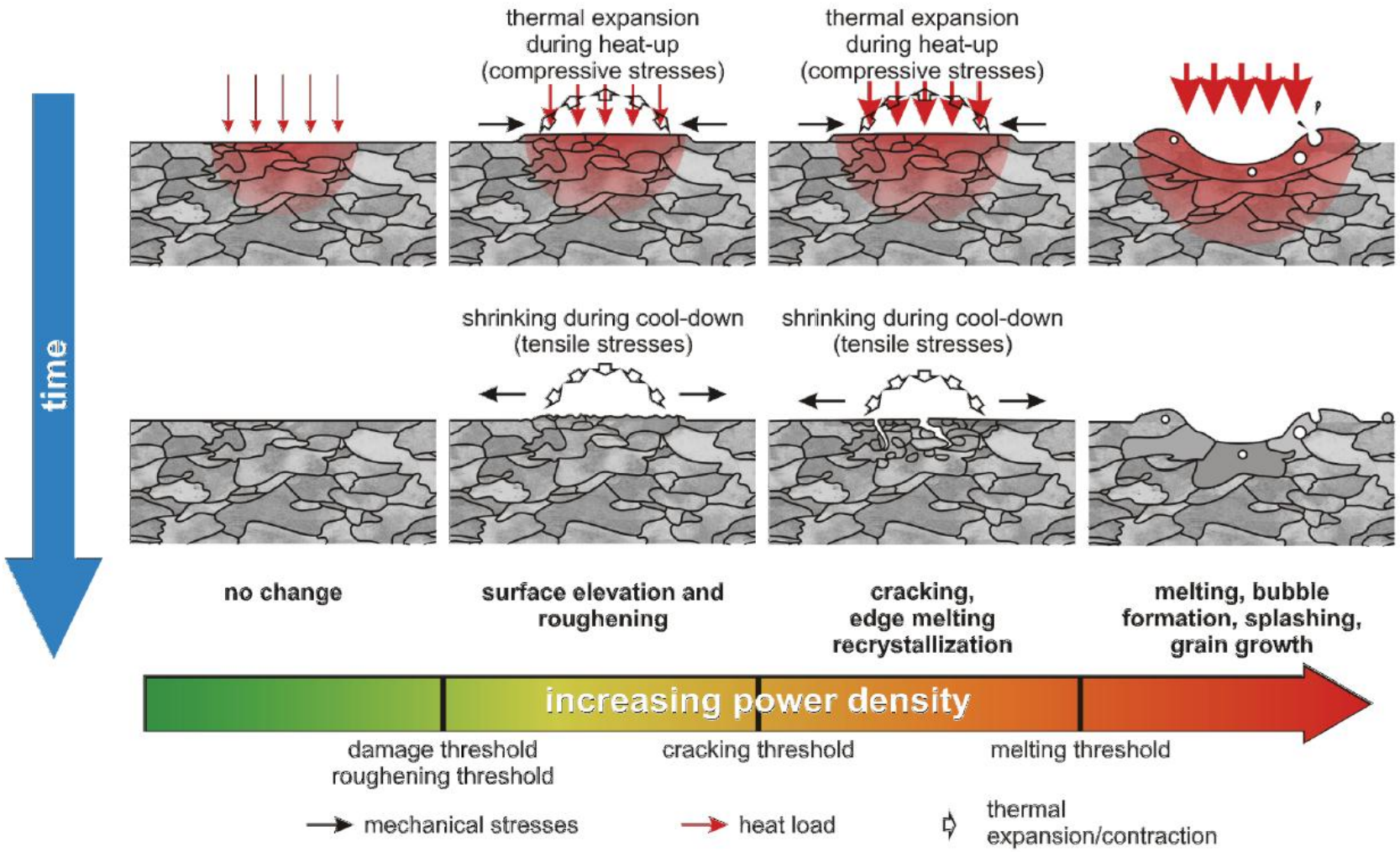
W. Jacob et al, ICFRM17 Aachen 2015.



D. Nishijima et al., PSI22 Rome 2016.

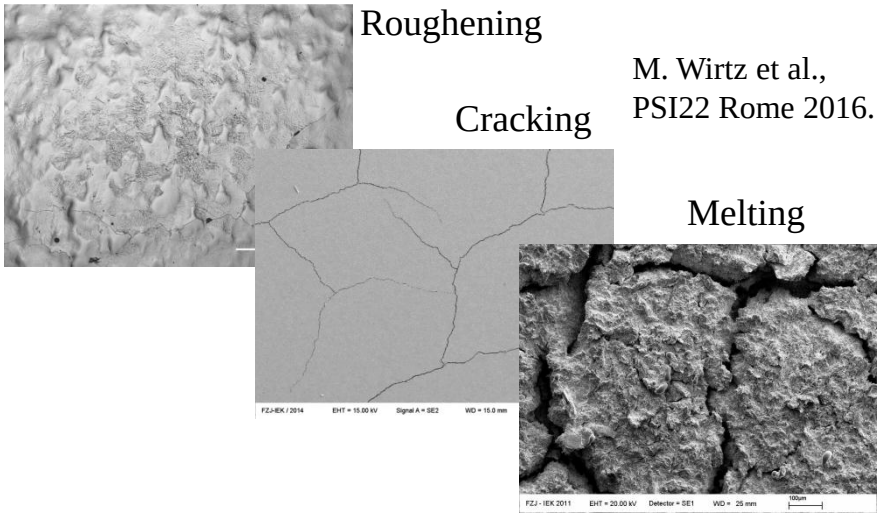


Cyclic surface loading can promote positive feedback damage to occur on solid PFCs

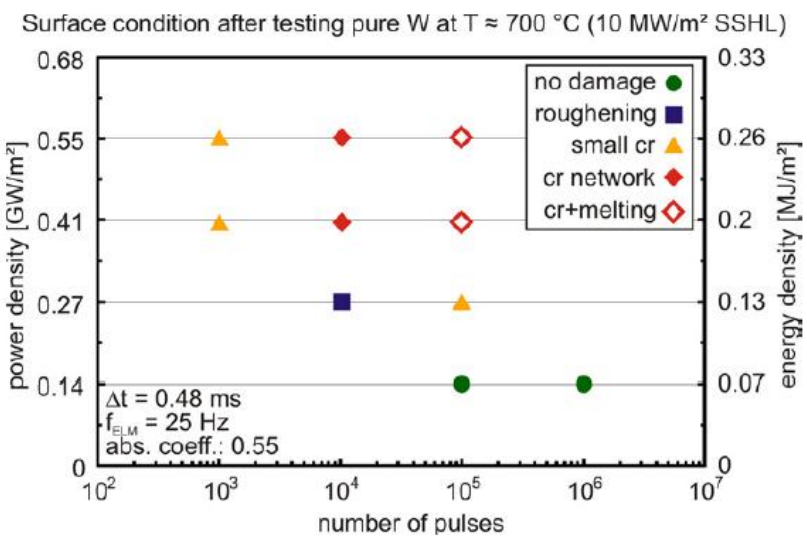


Th. Loewenhoff et al., PMIF4, Oak Ridge 2013.

Increasing number of cyclic power load (ELMs) events increases surface damage



M. Wirtz et al., PSI22 Rome 2016.



Th. Loewenhoff et al., Phys. Scr., 2011.

- A DEMO/reactor PFC will likely experience a huge number of cyclic loading events
- Where is the damage threshold as the number of pulses approaches infinity
- How does simultaneous plasma exposure and cyclic loading impact surface damage
- What will be the role of neutron damage
- Liquids may provide benefits, but little is known about how free surfaces respond to transients

He in W is an issue for ITER, DEMO & FNSF.

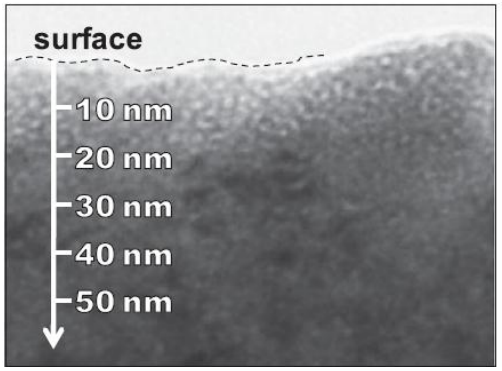
ITER

DEMO

~ 600 - 700 K

~ 900 – 1900 K

> 2000 K



PISCES-A: D_2-He plasma

M. Miyamoto et al. JNM 415(2011) S657

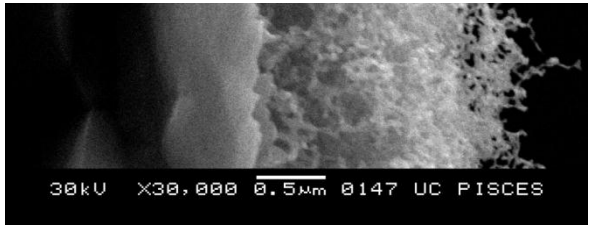
600 K, 1000 s, 2.0x10^{24} He$^+$/m^2, 55 eV He$^+$

- Little morphology
- Occasional blisters

PISCES-B: pure He plasma

M.J. Baldwin et al, NF 48 3 (2008) 035001

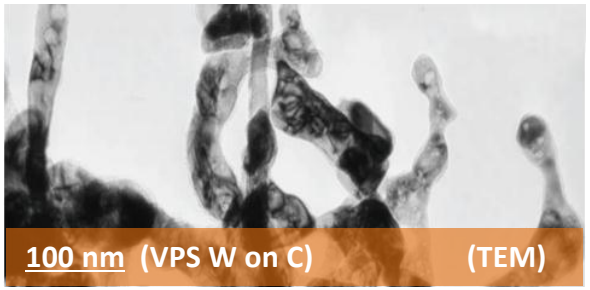
1200 K, 4290 s, 2x10^{26} He$^+$/m^2, 25 eV He$^+$



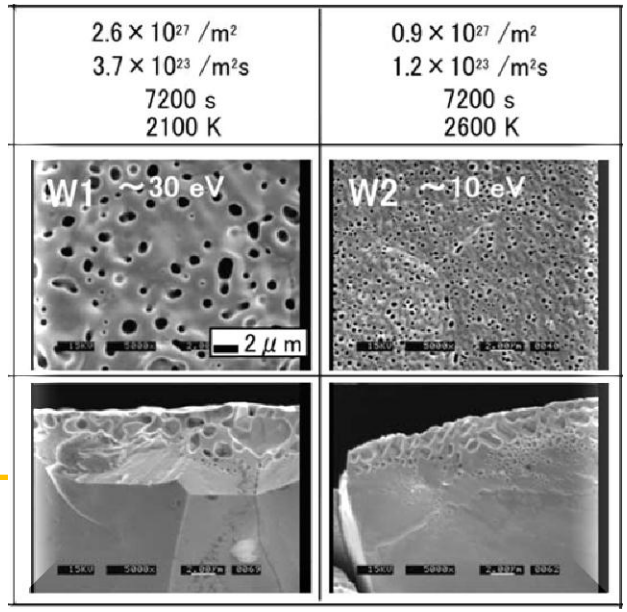
NAGDIS-II: pure He plasma

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

1250 K, 36000 s, 3.5x10^{27} He$^+$/m^2, 11 eV He$^+$



- Evolving surface morphology
- Nano-scale 'fuzz'

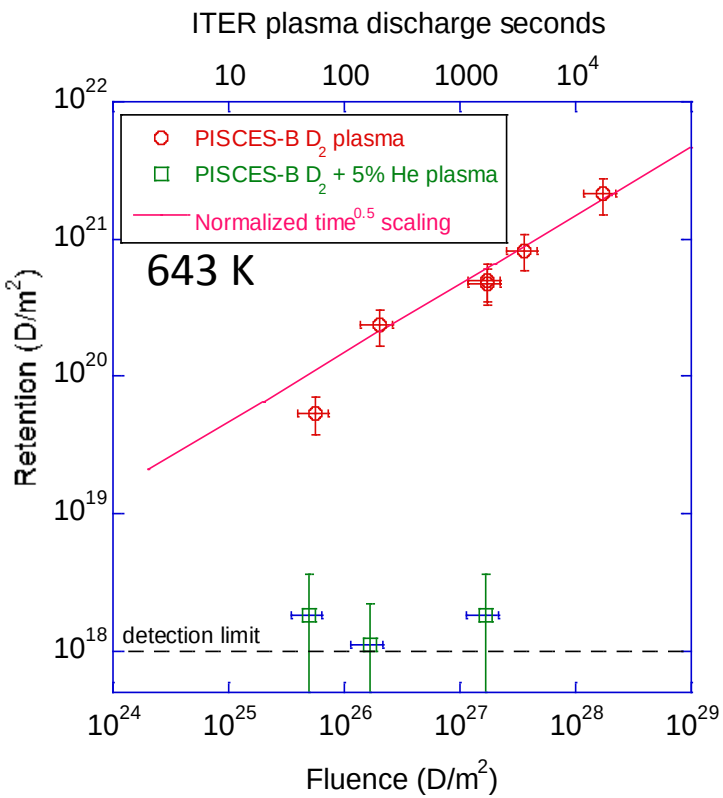


NAGDIS-II: He plasma

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

- Surface morphology
- Shallow depth
- Micro-scale

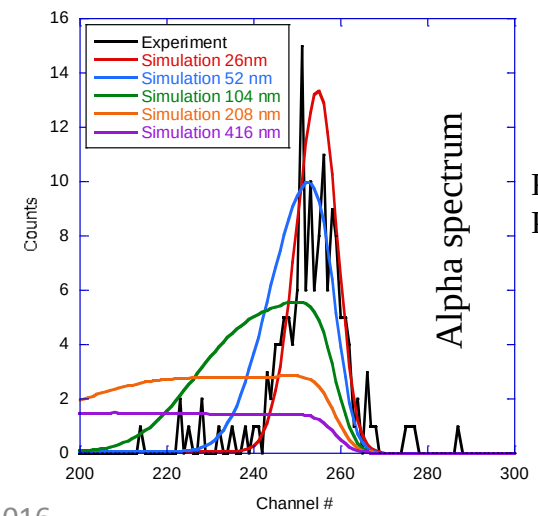
Need to minimize tritium retention/migration in the plasma facing material



- Predictive capabilities (multiscale models) are needed to understand T migration (saturation?) and role of He
- Can we rely on the He containing burning plasma to help solve this problem
- Can novel materials development assist and survive in this environment

Incident He is effective in limiting uptake of D in W. D is trapped in the nano-bubble layer

R. Doerner et al., ICFRM17 Aachen 2015.



R. Doerner et al., PSI22 Rome 2016.

UCSD University of California San Diego

Data is used to validate models of H-He synergies

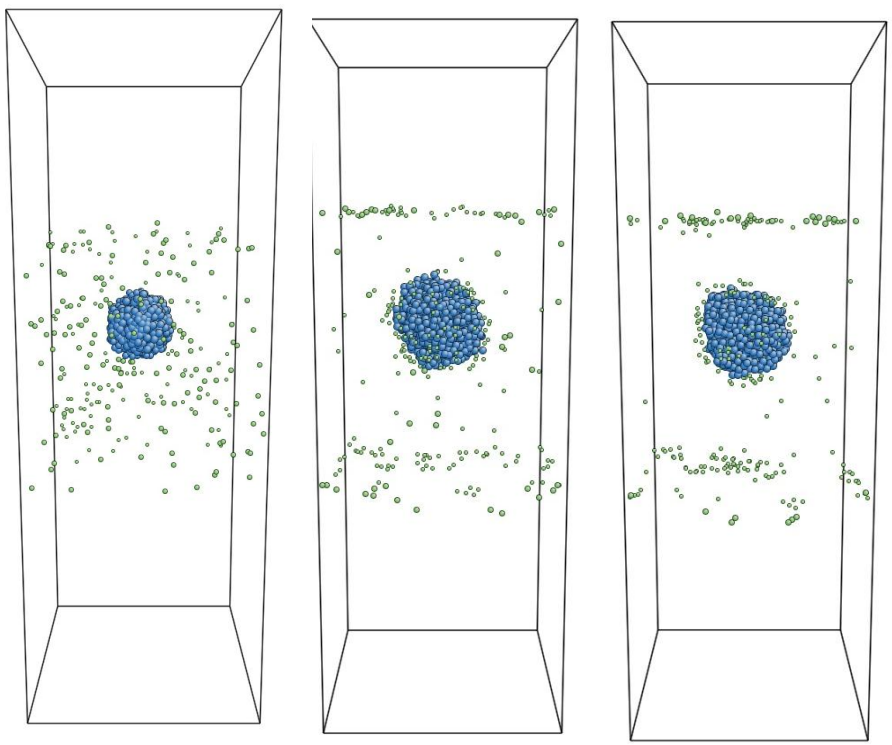
- Initial 2 nm diameter, over-pressurized He bubble created 2 nm below W (110) surface
  - H initially randomly distributed – strong partitioning of H to the bubble surface (~35-40%)

Courtesy of B. Wirth, UTK

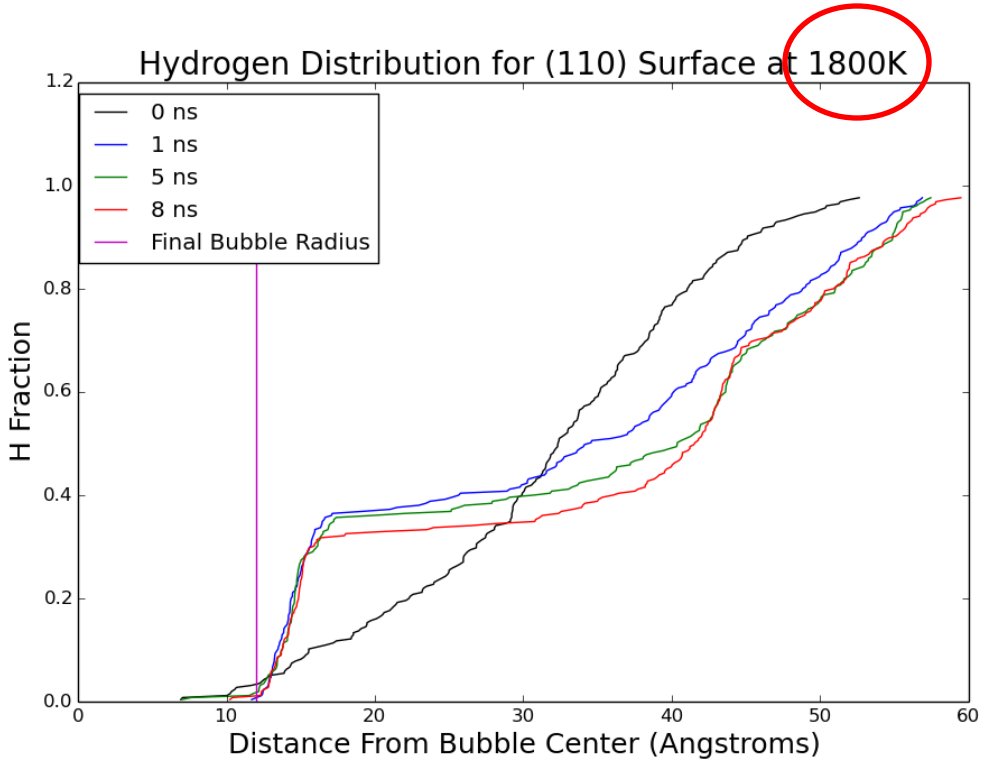
Green: Hydrogen
Blue: Helium

Box Size: 6 nm x 6 nm x 12 nm

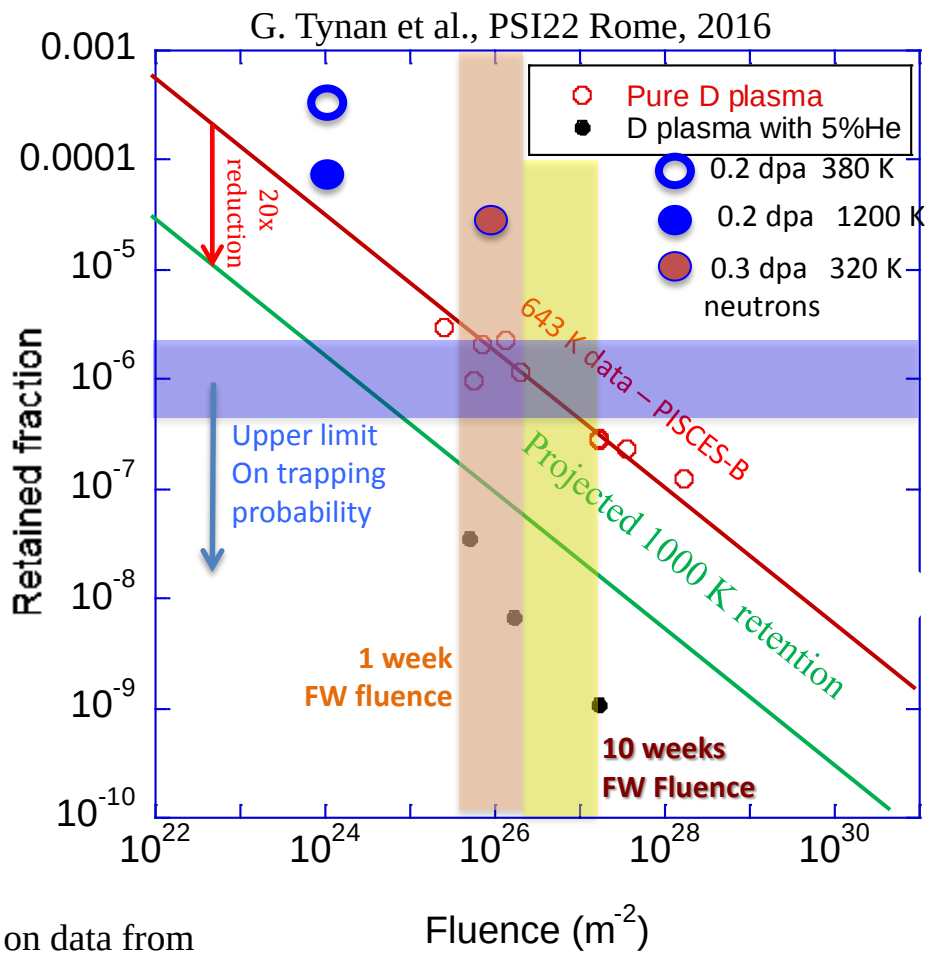
Initial He Pressure: 10 GPa



0 ns 1 ns 8 ns



Accessible TBR sets a limit for T retention in PFM



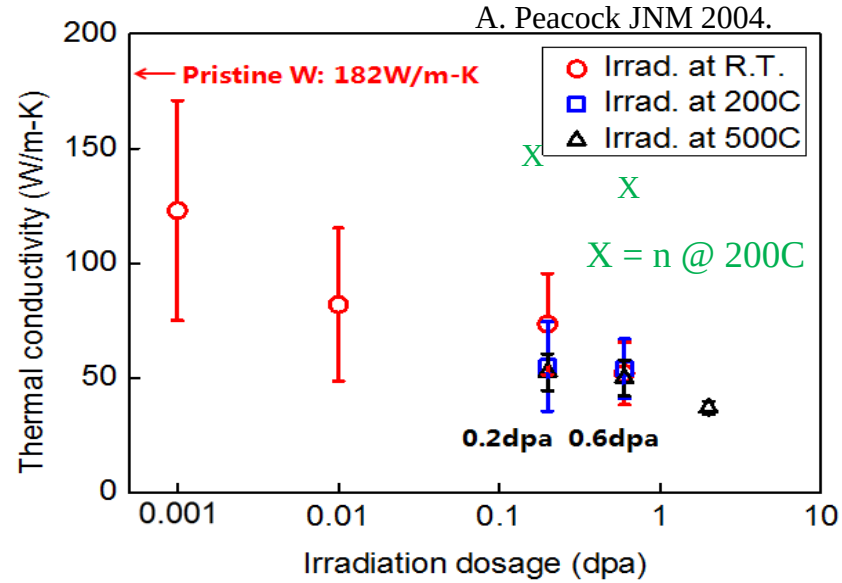
Based on data from Doerner, in press, '16 & Baldwin NF 2011, Shimada NF '15

- Particle balance model, assuming TBR =1.05, sets a limit of less than 10^{-6} retained fraction
- In solid PFMs, this appears possible at high fluence, but need more data on damaged material at high fluence (with & without He)
- 'Best' purification of liquid Li is ~ 1 appm, which could be troublesome (especially when purifying in real time, recirculating environment)

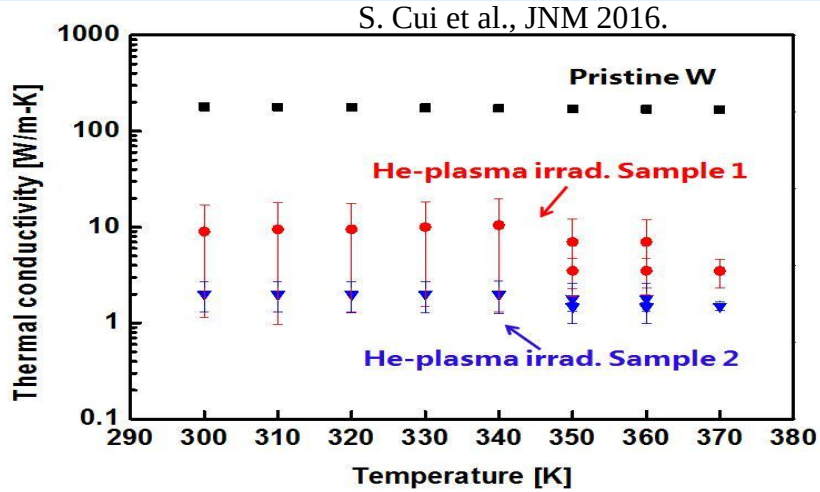
In a reactor, thermomechnaical properties of PFCs will not remain constant at high fluence

- PFC designs must take into account changing material properties
- Thermal conductivity in W drops both due to neutron irradiation as well as plasma exposure
- Neutrons and plasma exposure also both lead to embrittlement
- Resultant damage (high-energy ions vs neutrons vs plasma) needs characterization at various temperatures
- Advantages exist here for liquid surfaces, but properties of solids in contact with the free surface may change (neutrons and corrosion with time)

E. Dechaumphai JNM 2014.
A. Peacock JNM 2004.



S. Cui et al., JNM 2016.



Research needs for developing PFCs compatible with operation in a burning plasma environment

- Need to understand material evolution at high fluence
  - Mechanical and thermal properties, surface changes (including impurity/mixed-material effects), macroscopic erosion terms
  - How do the large surface concentration of D,T, He and other impurities affect PMI
- Need to understand the damage that results from neutrons/plasma in order to develop more resilient/self-healing materials
- Continue development of advanced predictive multiscale models
  - T migration, material property evolution, surface evolution, erosion and material migration
- Liquids have some R&D needs commonality
  - Surface changes (including impurity/mixed-material effects), response to transients, erosion terms, material migration
- Liquids also present special needs
  - Corrosion, purification, free surface stability, recirculation