USTC SNST 2015 Spring Semester Lecture Series

Title: Introduction to Plasma-Facing Component (PFC) and Plasma-Material Interaction (PMI) R&D for Tokamak Fusion Energy

Lecture 4: Room 1617, 930-1130, **Saturday** April 25, 2015

L4: Plasma-facing material: bombarded by edge plasma and particles, and supported by plasma facing component

Lecturer: 彭元凯
Class assistant: 徐国梁
Webpage assistant: 王伸吉

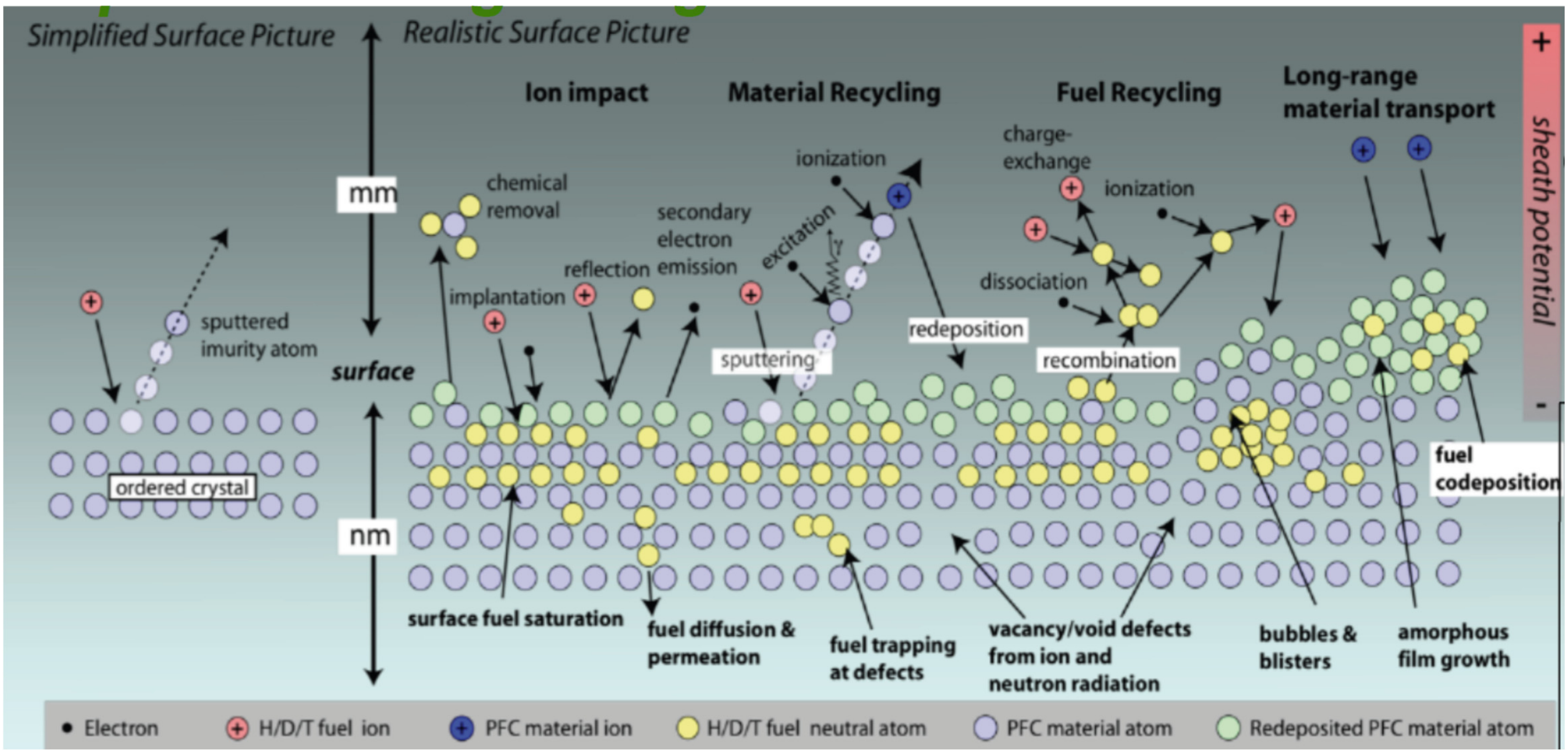
“When rubber hits the road”

(When fusion plasma meets the world)

1. Many messy phenomena emerge. *(Plasma-material interaction involves a plethora of simultaneous multi-scale phenomena.)*
2. Use the best available material. *(W is a low-activation, high-performance material.)*
3. Make the best possible designs. *(High-performance W divertor designs are being built and tested for ITER.)*
4. ITER W divertor will, for the first time, experience the reality of this complexity, under intense thermal-mechanical, nuclear conditions.

Great opportunity: continue improving integrated capabilities of material and design, to enhance tokamak fusion performance/cost ratio.

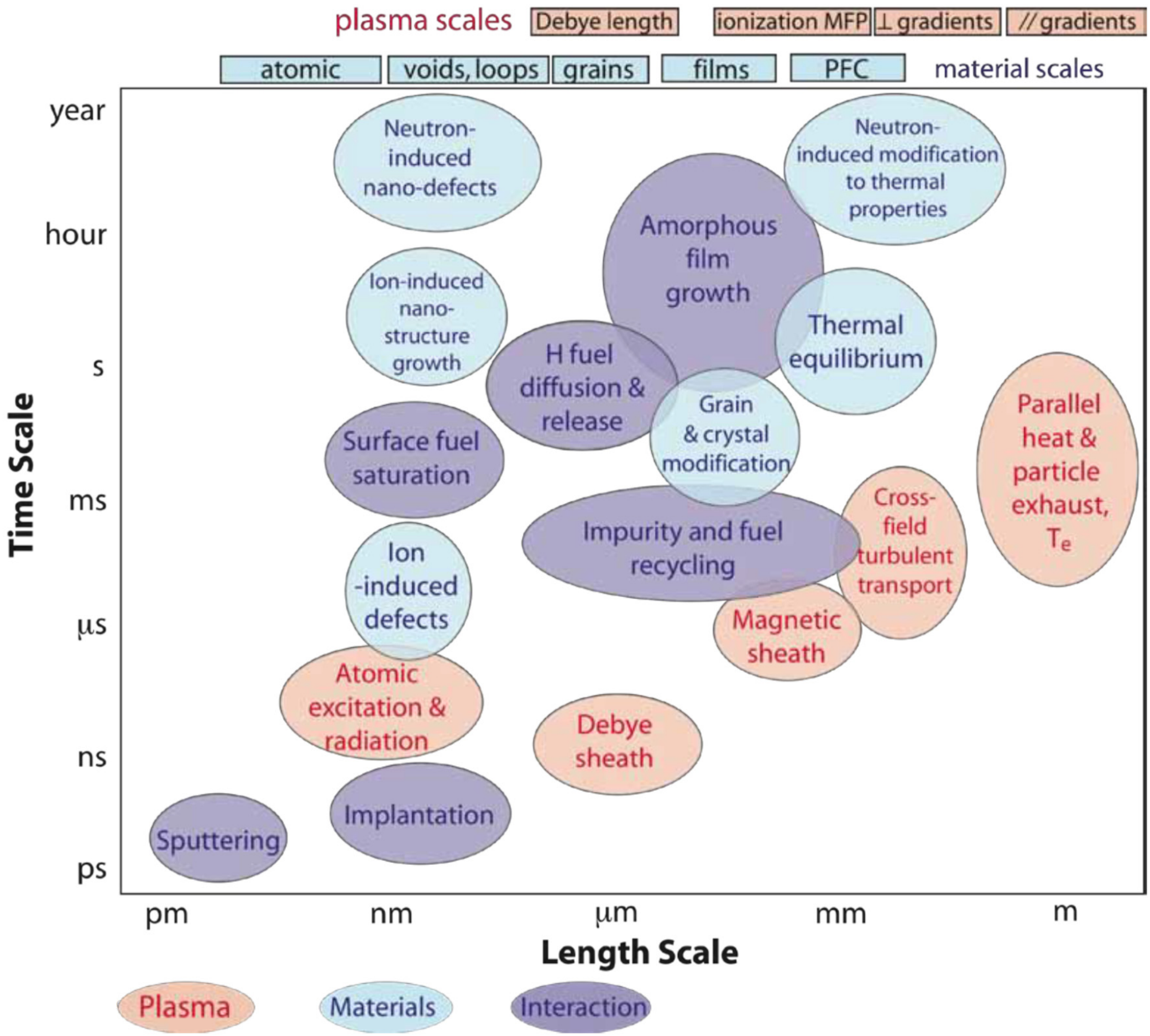
The phenomena of plasma material interaction are complex



[Wirth, Nordlund, Whyte, Xu, MRS Bulletin (2011)]

Well, this may not be complex enough.

Plasma-material interactions are multiscale and interactive



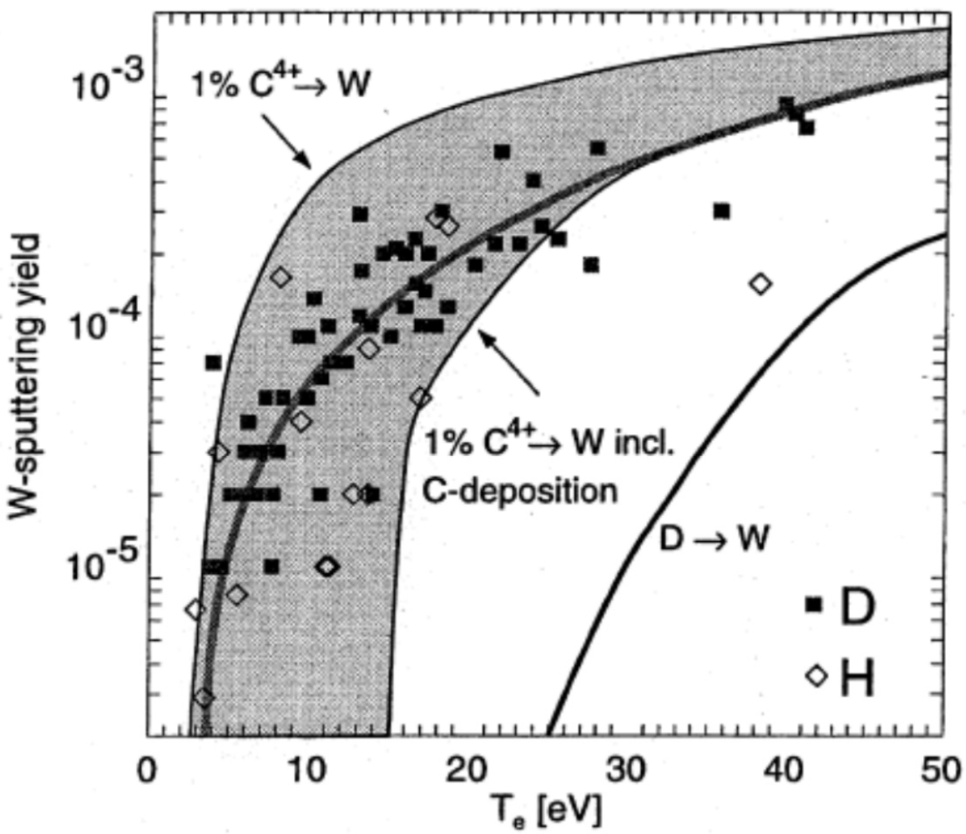
What is tungsten or wolfram (W)?

1. Atomic number 74; atomic weight 183.84
2. Melting point 3695 K; boiling point 6203 K
3. Density 19.25 g/cm^3; molar heat capacity 24.27 J/mol/K
4. Crystal structure bcc (crystalline form α)
5. Thermal expansion 4.5μm/m/K (at 25^{o}C); thermal conductivity 173W/m/K
6. Electrical resistivity 52.8 nΩ-m (at 20^{o}C)
7. Young's modulus 411 GPa; shear 161 GPa; bulk 310 Gpa
8. Mohs hardness 7.5; low H solubility (great)

[Quiz: which country has the most reserve and annual production?]

What W properties in a fusion plasma environment?

Tungsten has small sputtering yield for T_e ~ 10eV or below



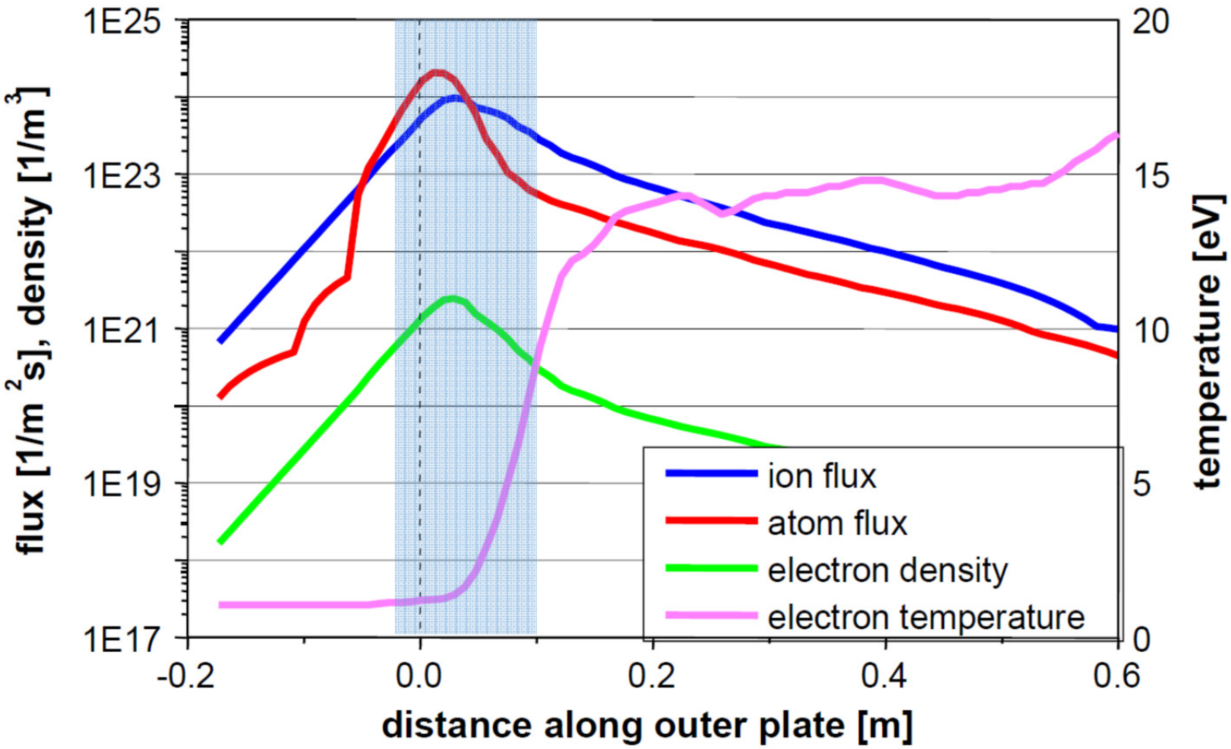
Krieger JNM ***266-269*** *(1999)*

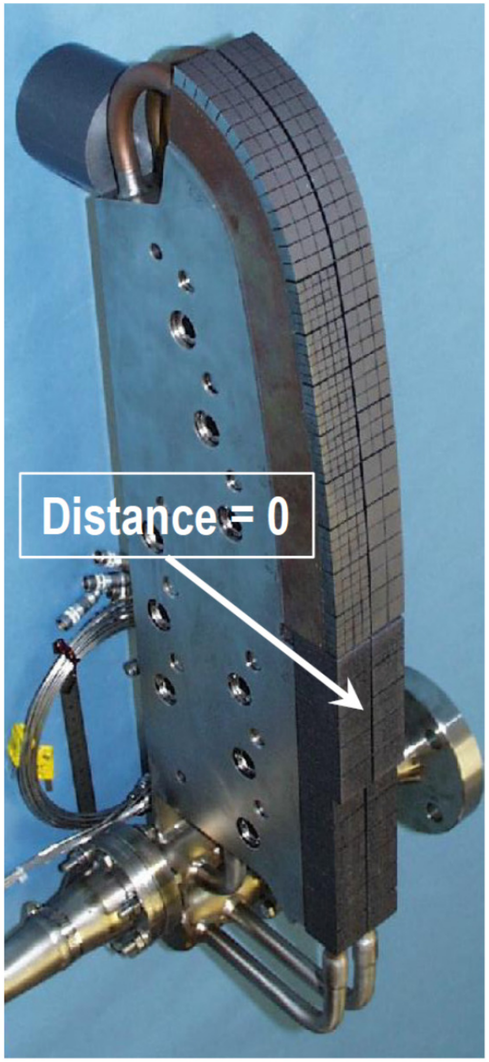
- Observed in AUG tokamak.
- Sputtered W ion redeposits promptly ⇒ a few % escape rate.
- ⇒ net W/D yield < 10^{-4}.
- Need high-recycling divertor plasma conditions to keep T_e low at the high flux "footprint".

Can this be achieved in ITER?

Anticipated ITER divertor plasma conditions on W targets

B2-Eirene simulation for the ITER outer divertor, including impurities (A.S. Kukushkin)

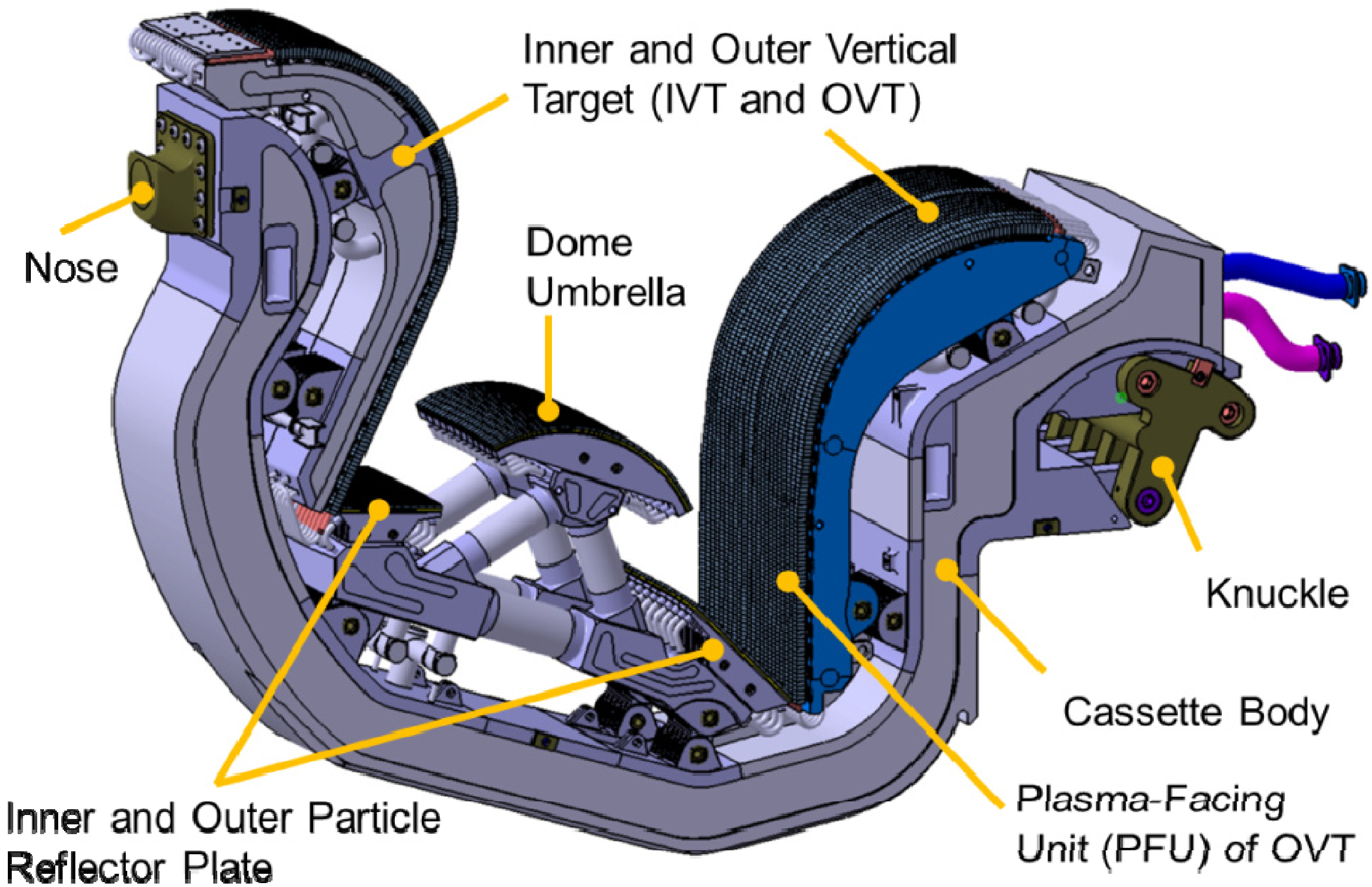




- $n_e = 3 \times 10^{21}\ m^{-3}$
- $T_e = 1 – 10\ eV$
- $\Gamma_{D,T} = 10^{24}\ m^{-2}\ s^{-1}$
- $q_{div} = 10\ MW/m^2$
- Surface temperature (up to 1600 ^oK)

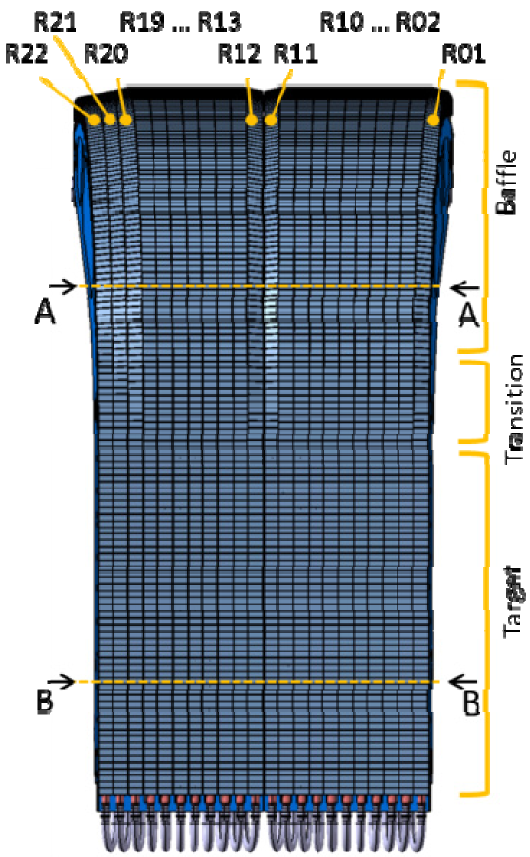
Sputtering Okay!

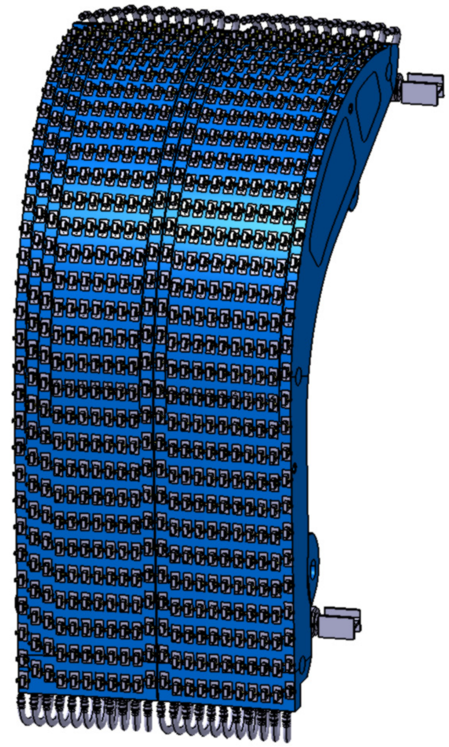
The outer vertical target (OVT) will take the brunt of plasma heat and particle fluxes



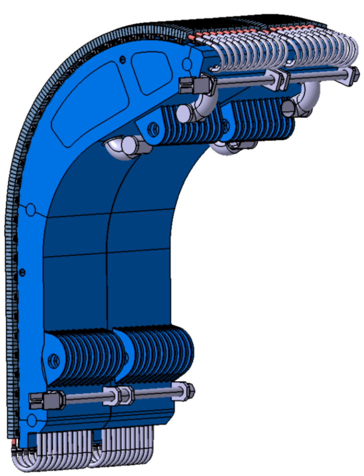
3D view of the ITER W divertor

The outer vertical target (OVT) will take the punishment

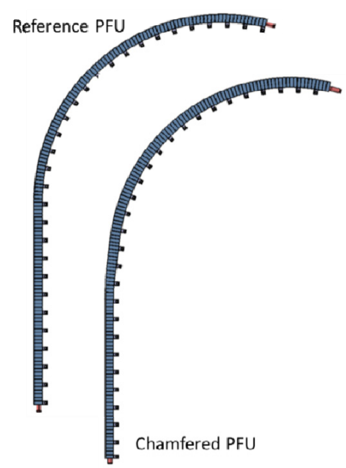




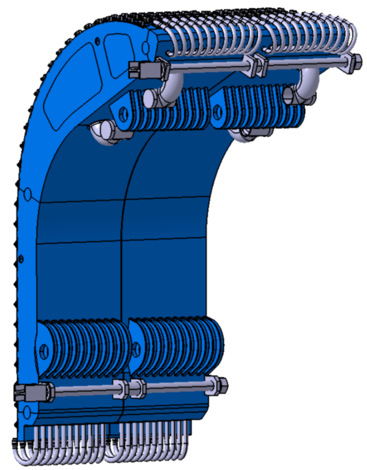
Standard OVT front & back



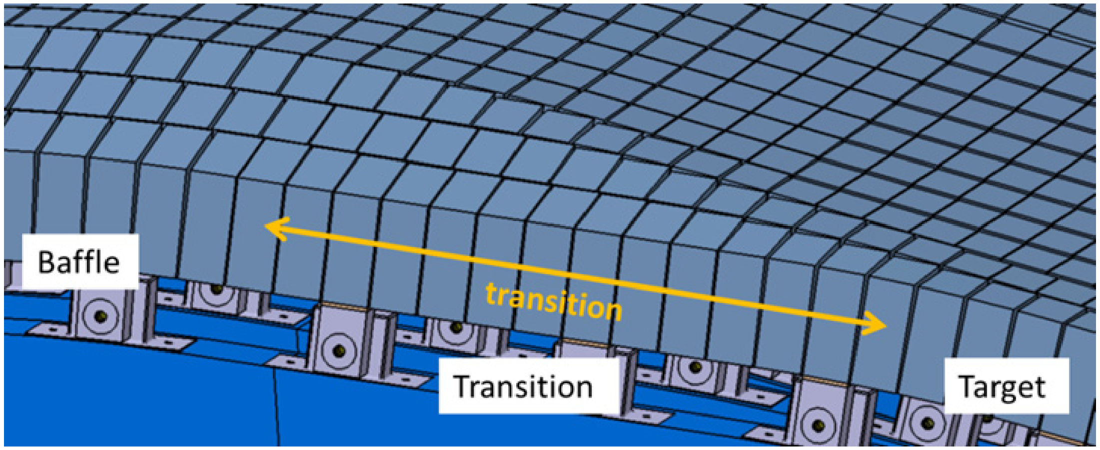
PFU array & element



Steel support structure front & back



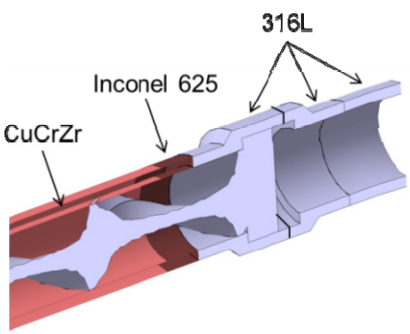
The outer vertical target (OVT) tiles requires high precision

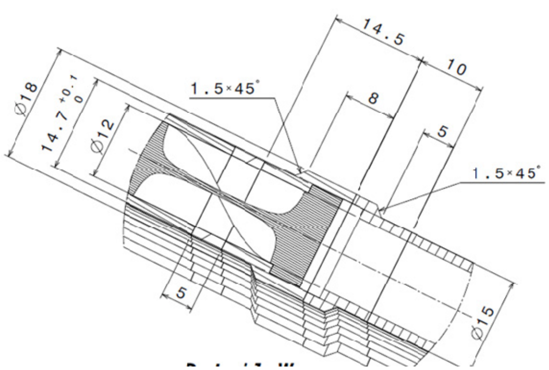


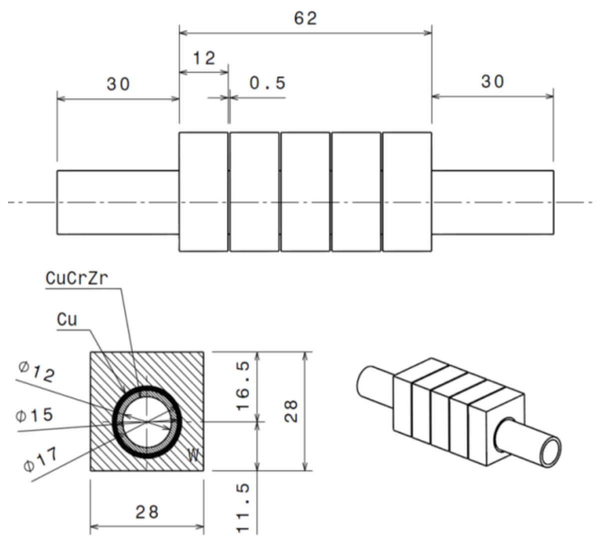
Tilting:

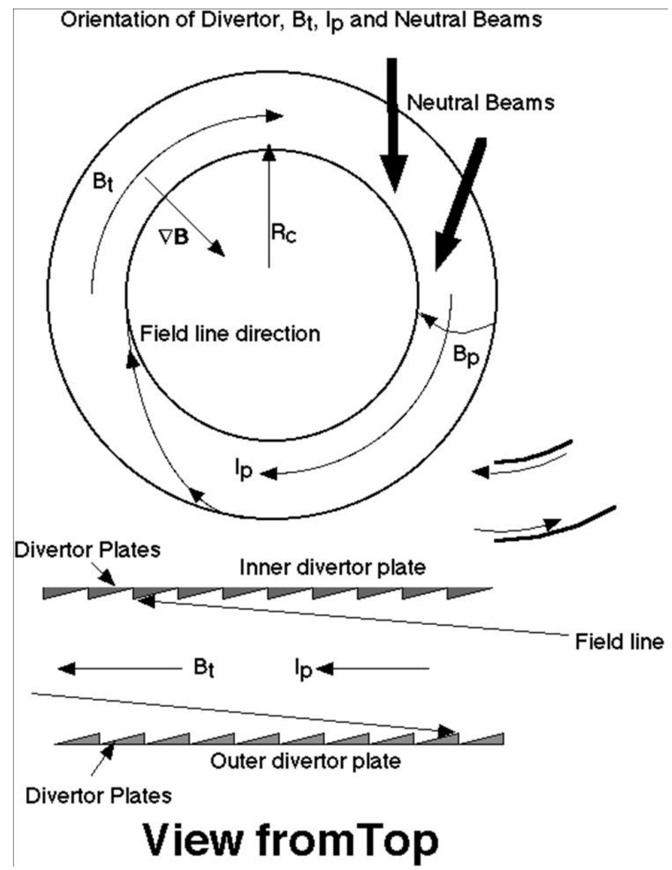
0.74±0.05 deg. self rotation

80±0.05 deg. from radial



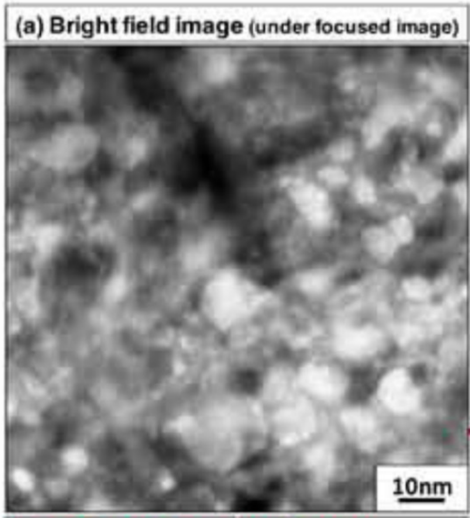






W Temperature & PMI are coupled

~ 600 - 700 K | ~ 900 – 1900 K | > 2000 K



PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

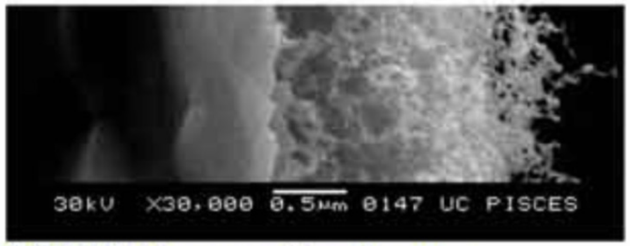
600 K, 1000 s, 2.0x10^{24} He$^+$/m^2, 55 eV He$^+$

- 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, 2x10^{26} He$^+$/m^2, 25 eV He$^+$

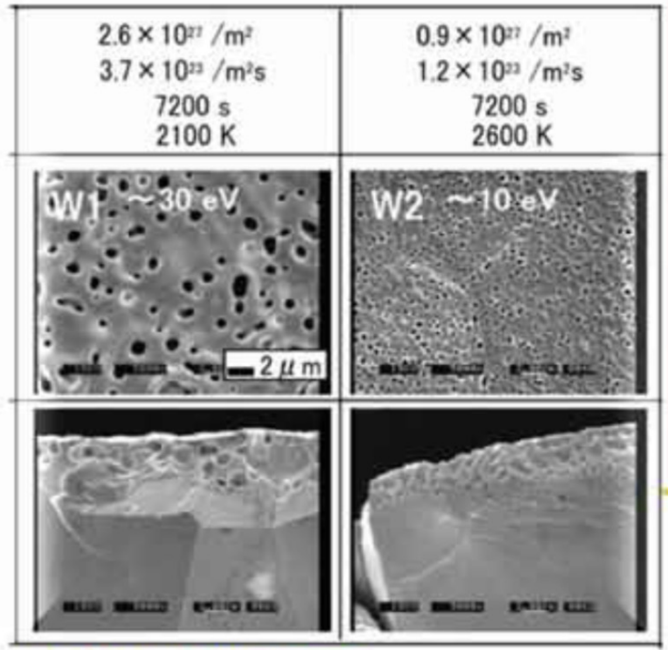


NAGDIS-II: pure He plasma

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

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

- Surface morphology
- Evolving surface
- Nano-scale 'fuzz'



NAGDIS-II: He plasma

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

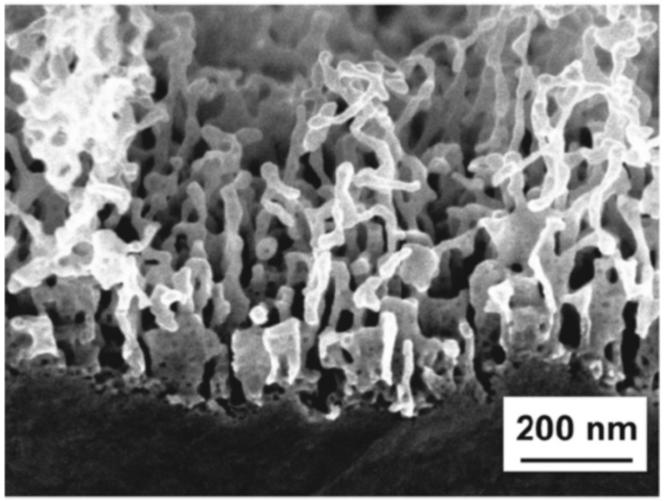
- Surface morphology
- Shallow depth
- Micro-scale

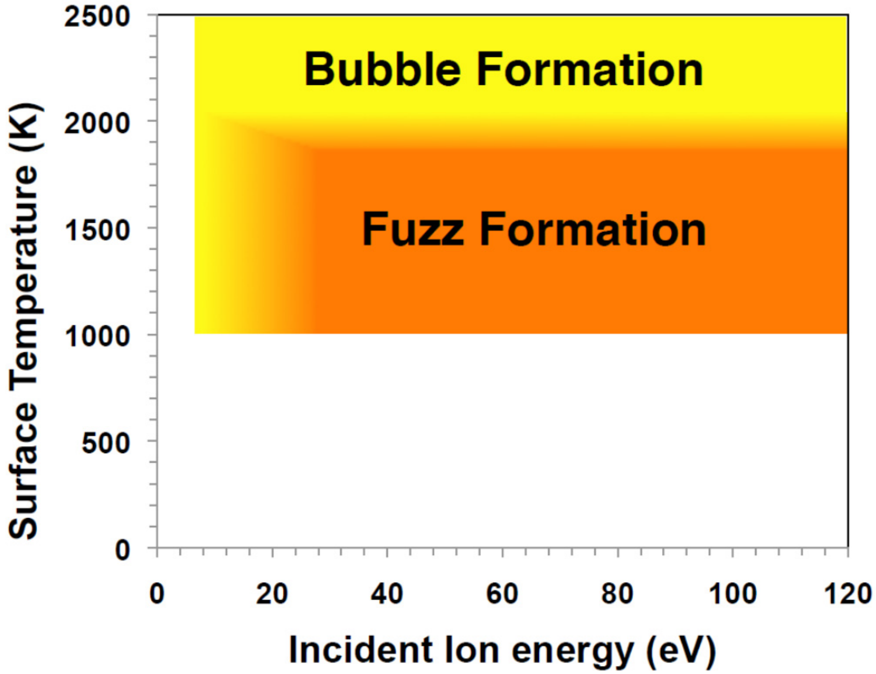
ITER divertor target design temperature: 700-1600 K

Exhaust plasma He fraction: 0.1 – 1%

Pure He-ion flux test results in linear device

1. Bare W surface
2. 1000 K < $T_{surface}$ < 2000 K
3. Flux of He-ions with $E_{He} \geq 20$ eV
4. Layer thickness depends on $t^{1/2}$





[1] S. Kajita et al. Nucl. Fusion **49** (2009) 095005

What would happen in case of 0.1 – 1% He fraction?

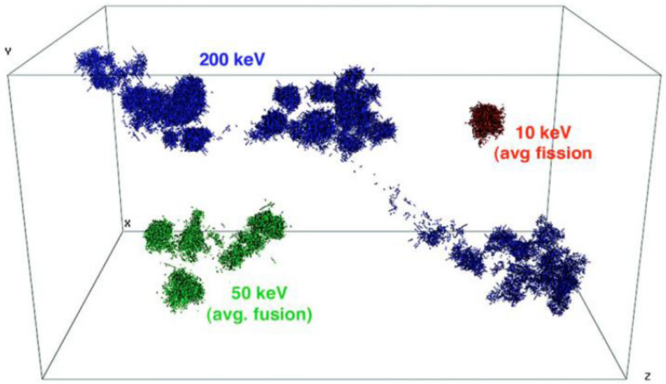
How about damages from neutrons?

Irradiation damages can take the form of voids and dislocation loops

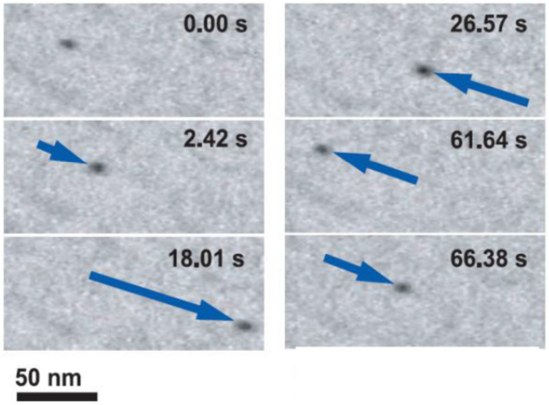
- Movements of these near divertor target surface becomes interesting.

- **Example – formation and dynamics of clusters of defects:**
  - Fusion neutron ⇒ displacement cascades of >10^3 atoms over ~10^2 nm.
  - Clusters of ≥20 point defects and ≤20 nm are formed with energy ~1eV.
  - These clusters undergo 1D motion with activation barriers of ~0.1eV.
  - Observed to move at 1-5 nm/s at ~300 °C, affected by impurity atoms.

How would such clusters affect PMI if and when they migrate near & to plasma facing surface, & vice versa?



Molecular dynamics simulations of neutron induced displacement cascades [Zinkle, Stoller, 2005].

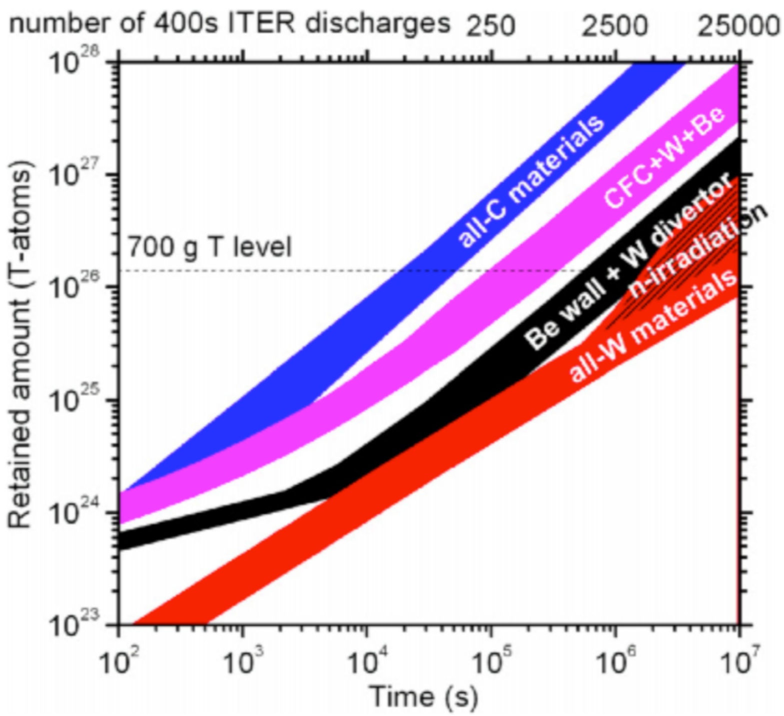


1D movements of defect cluster in bcc iron observed via TEM [Arakawa et al, 2007].

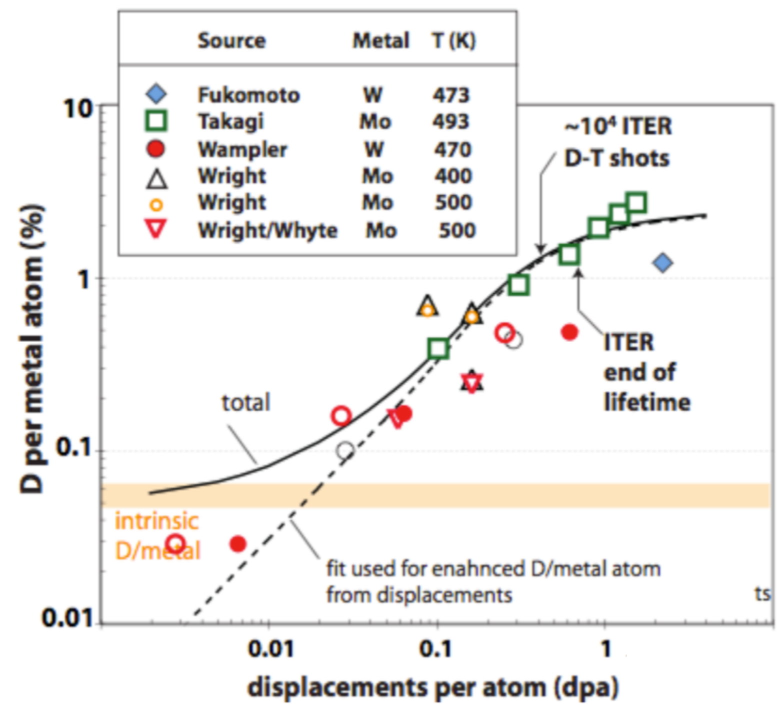
Present ITER tungsten divertor design assumes tolerable tritium retention

- *Tungsten, a candidate PFC for the divertor in ITER, is expected to receive a neutron dose of 0.7 dpa by the end of operation in ITER*
- High energy ion beams have been used to simulate displacement damages by 14 MeV fusion neutron, and provided us three trends in damaged-tungsten:
  1. The trap concentration will most likely saturate at > 1 dpa
  2. T will most likely stay with in a few micro meter
  3. Very small D retention from damaged W at high exposure temperature (> 500C= 773 K)

Reference: J. Roth et. al. PPCF 2008

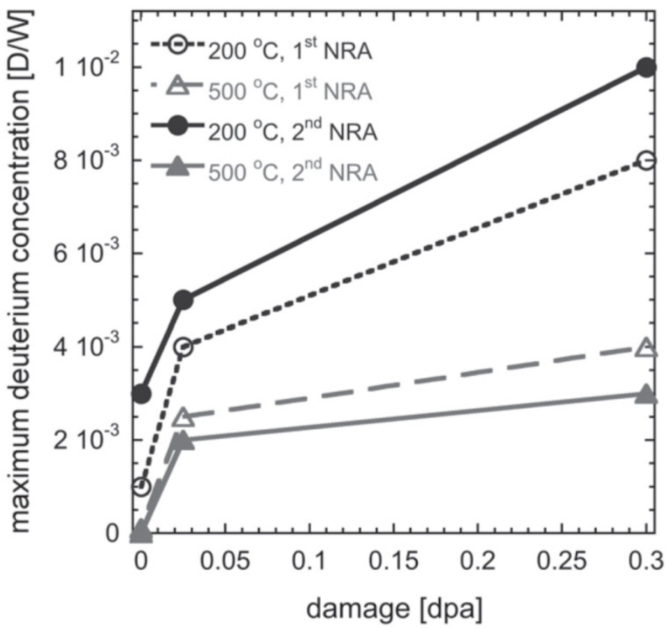


Reference: B.Lipschultz et. al. MIT report 2010

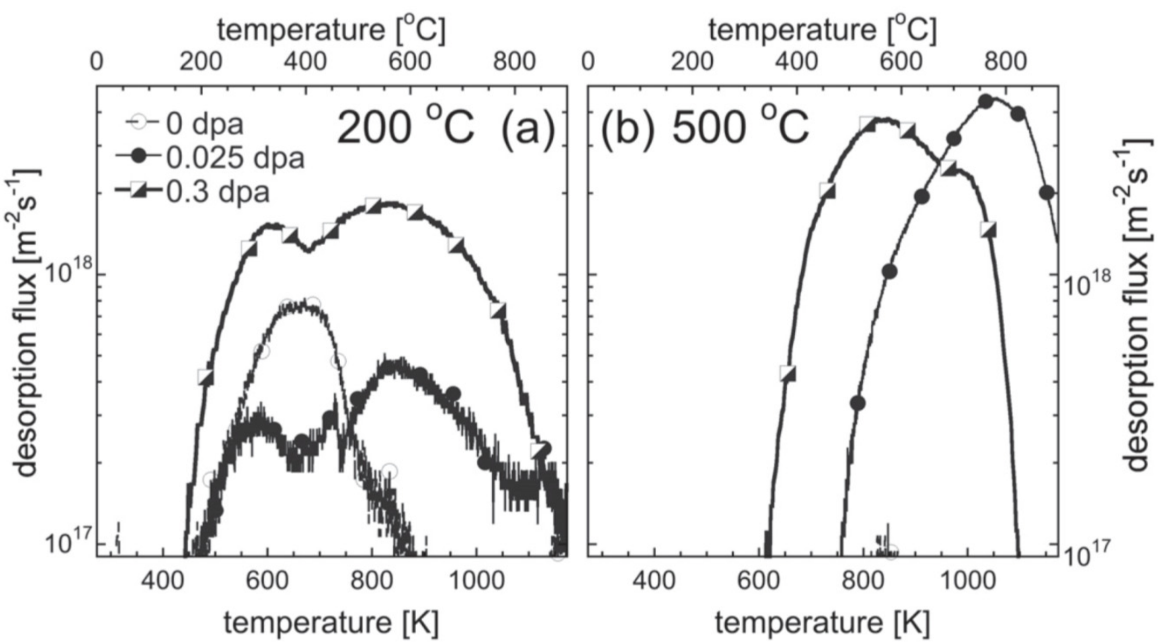


Most recent plasma-tungsten interaction tests suggested important updates

[2015-Shimada-Nucl Fusion-v55-01308]



- Polycrystalline W wafers irradiated to 0.025 & 0.3 dpa at HFIR.
- Bombarded with D plasma to low fluences ($<10^{26}/m^2$, ~100 s ITER operation) at 2 temps.
- Nuclear reaction analysis (NRA) for 0-5μm depth indicated higher D/W values than previously assumed.
- Temperature desorption spectroscopy (TDS) indicated higher and deeper trapping to 50μm.



Considerations?

- Continuing PMI testing.
- Improve polycrystalline W to reduce deep tritium migration (between defect sites)?

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Great opportunity: continue improving integrated capabilities of material and design, to enhance tokamak fusion performance/cost ratio.

Lecture 5: Room 1617, 930-1130, Saturday May 16, 2015