Burning Plasma-Material Interactions & Tritium Self-sufficiency: Results and Plans in Linear Plasma Device Experiments

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Presented at

IAEA Technical Meeting on Plasma Physics and Technology Aspects of the Tritium Fuel Cycle for Fusion Energy

IAEA HQ, Vienna, Austria, 11-13 October 2022

Acknowledgement: Work Supported by

U.S. DOE DOE -DE-SC0022528

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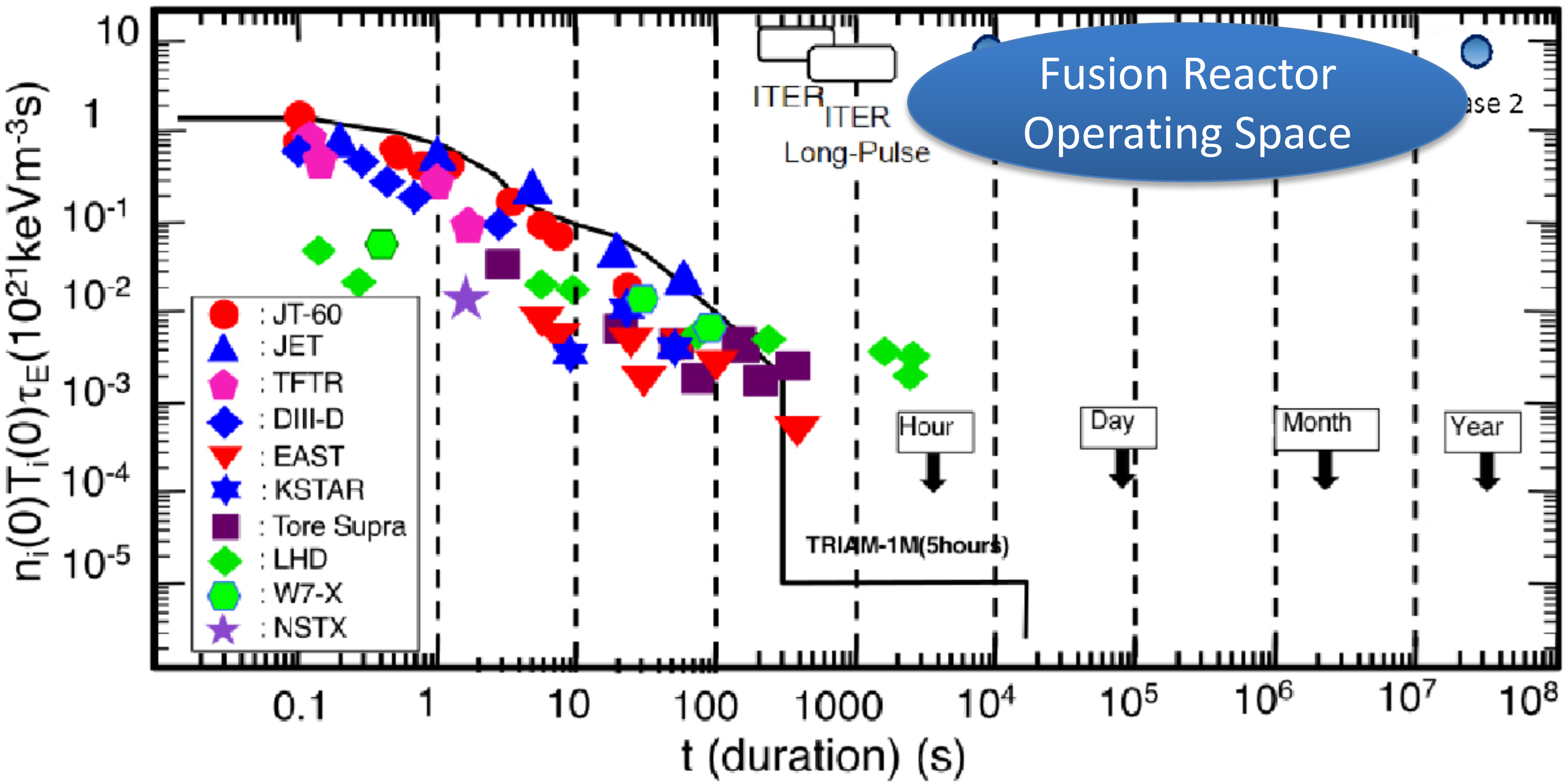
Where we have been…and where we need to go….



Kikuchi, Springer-Verlag 2012

Hierarchy of challenges for a pilot plant

seconds
minutes
hours
days
months

- Adequate fusion triple product
- Sustained plasma operations
- Tritium processing
- Tritium breeding
- TBR>1
- Matl's Degradation
- Power production
- Load following
- Reliability, Availability, Maintenance and Inspectability (RAMI)
- Economic operation

ITER, EAST, etc…

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ITER, EAST, etc…

B-PMI has strong effect on these emerging challenges

Main points of this talk

- Permanent T retention in plasma-facing materials does not appear to have been considered in T-handling system models
- There is a very low allowable probability of permanent T retention in PFCs while keeping TBR>1
- We need to have high-fidelity, high-confidence predictions of retention for a. credible FPP design
- There are ***<u>MANY</u>*** *B*-PMI effects that influence retention that must be understood & incorporated in these predictions
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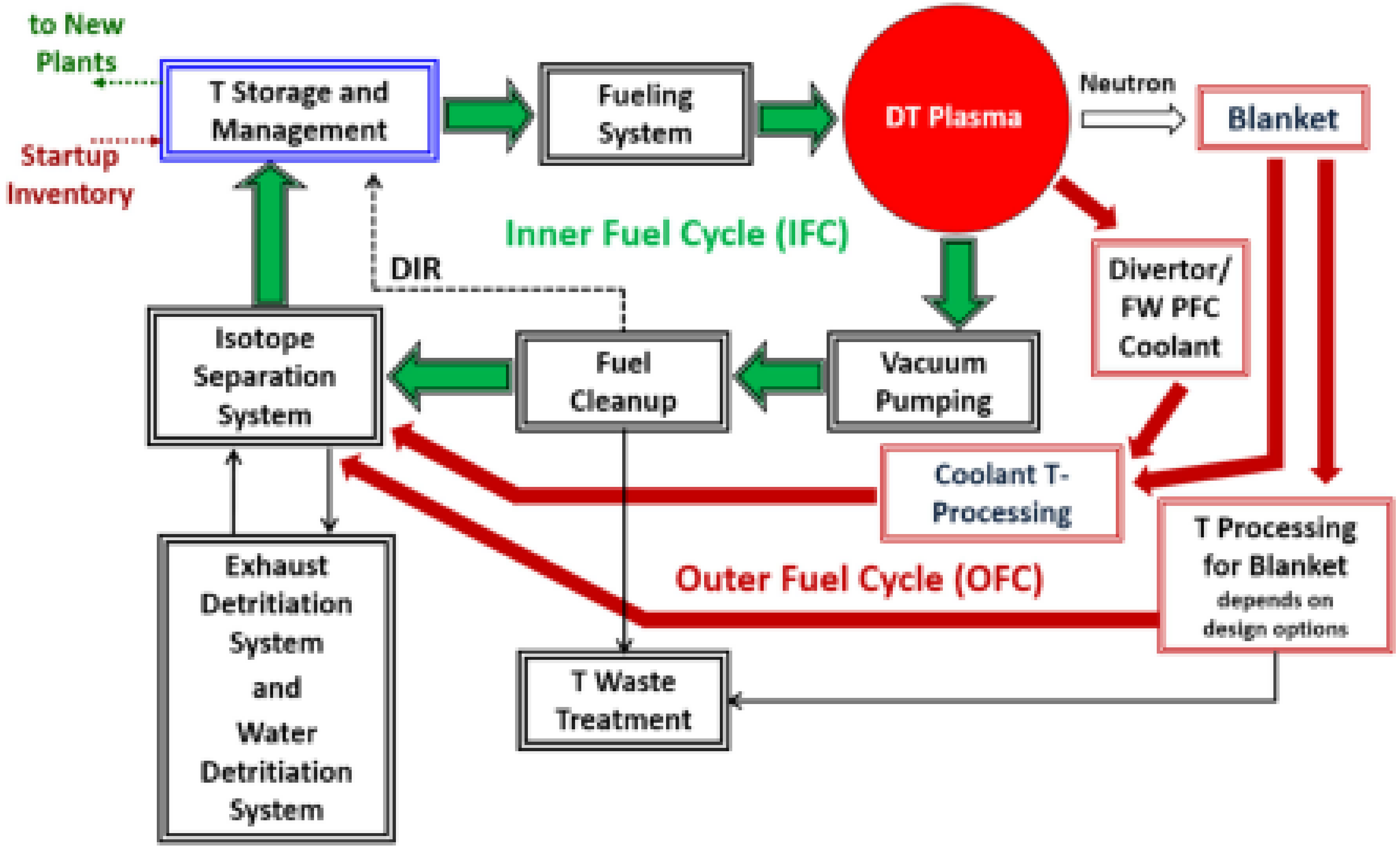
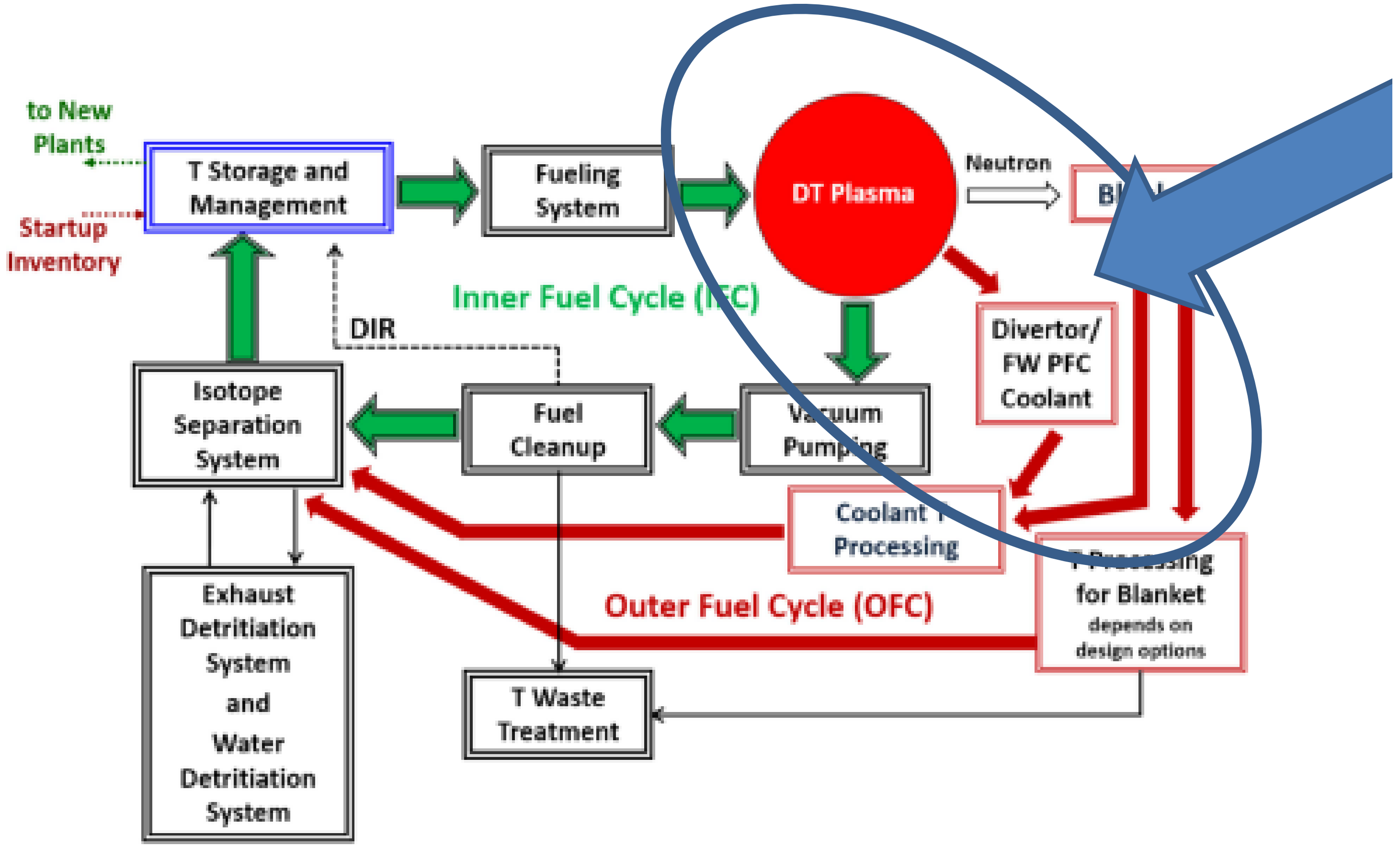
Schematic of Tritium fuel handling



Ref: Abdou et al, NF 2021

Schematic of Tritium fuel handling models



Focus of this talk

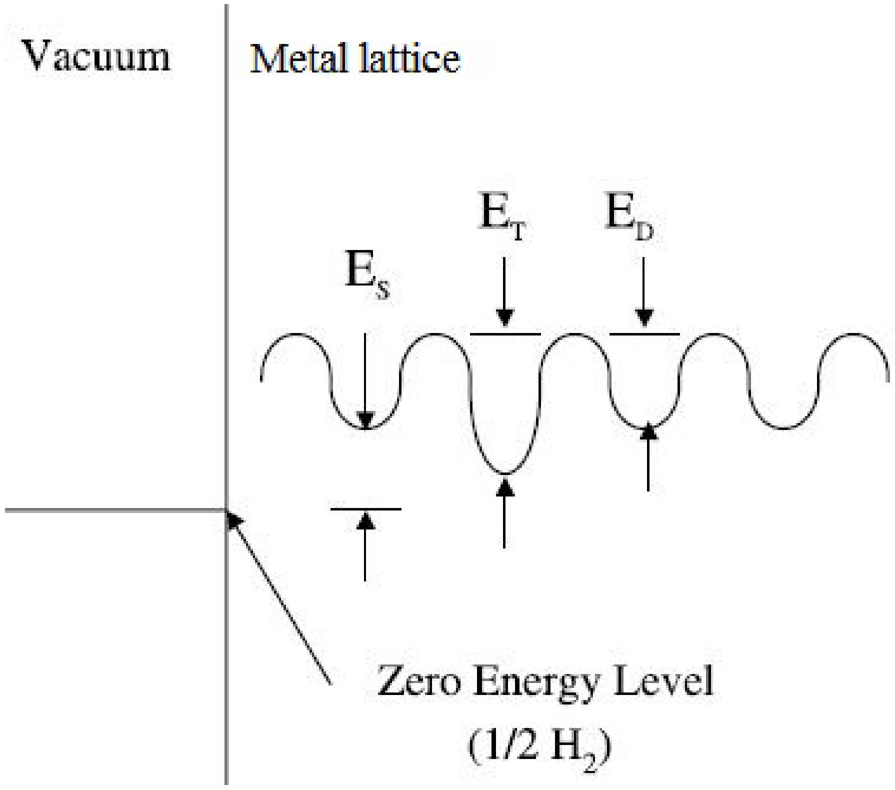
Fuel cycle modeling
Assumes exponential
Release of trapped
Tritium Inventory
In First Wall/Divertor
i.e.

$$I_{FW} \sim I_0 \exp(-t/t_{release})$$

Unfortunately PMI experiments show small but finite **permanently trapped T inventory** in plasma-exposed materials – which has a **significant impact on TBR**

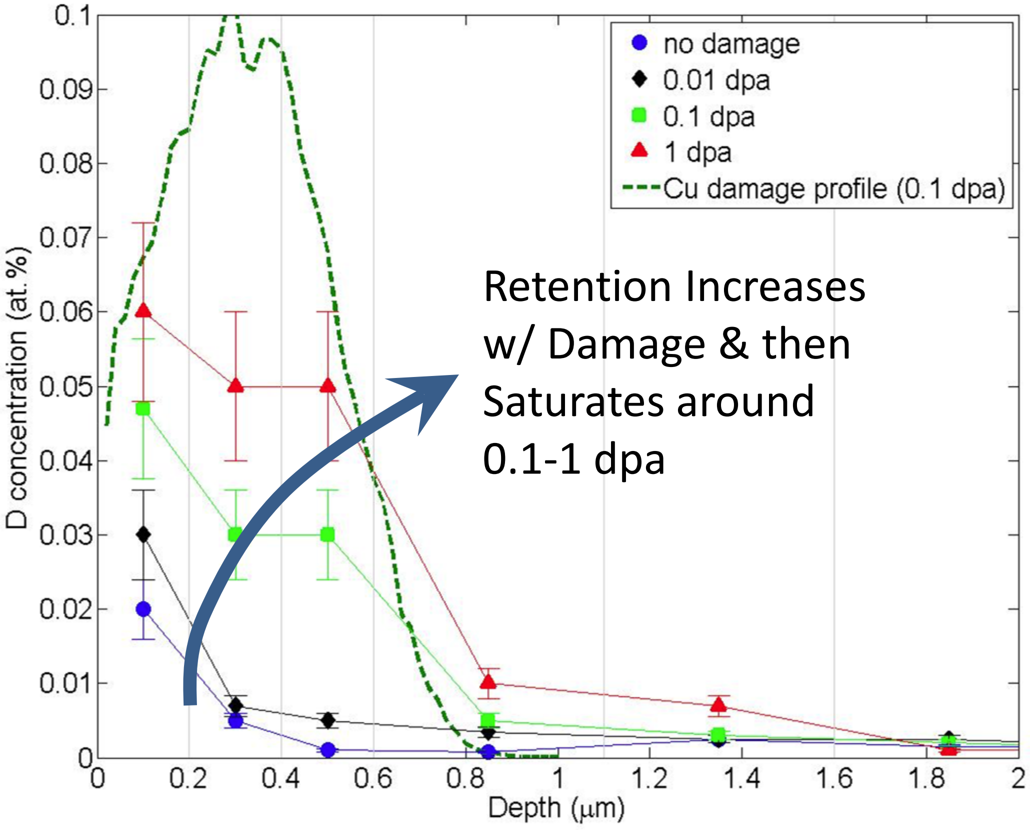
Ref: Abdou et al, NF 2021

Displacement Damage Increases Fuel Retention in Plasma-exposed PFCs



Causey JNM 2002

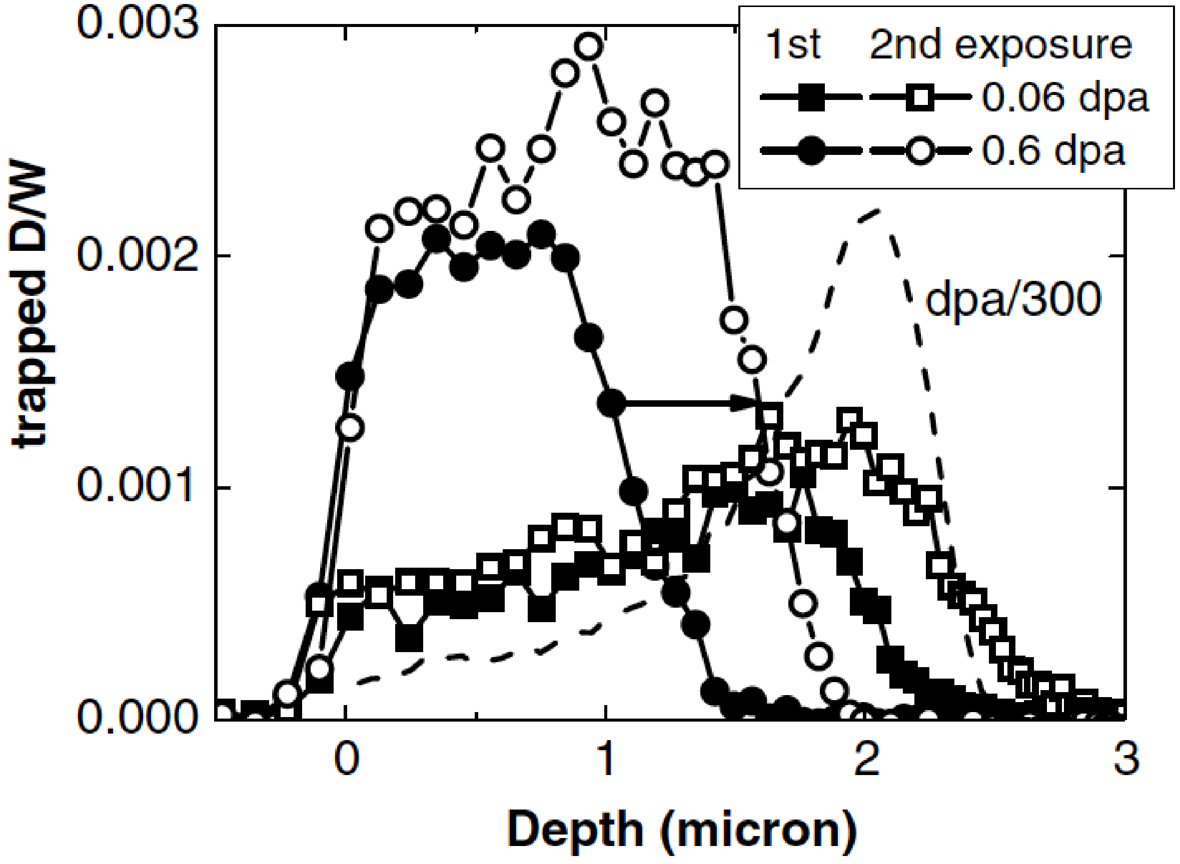
ITER-grade W 300 K damage



Barton, PhD dissertation, UCSD 2016

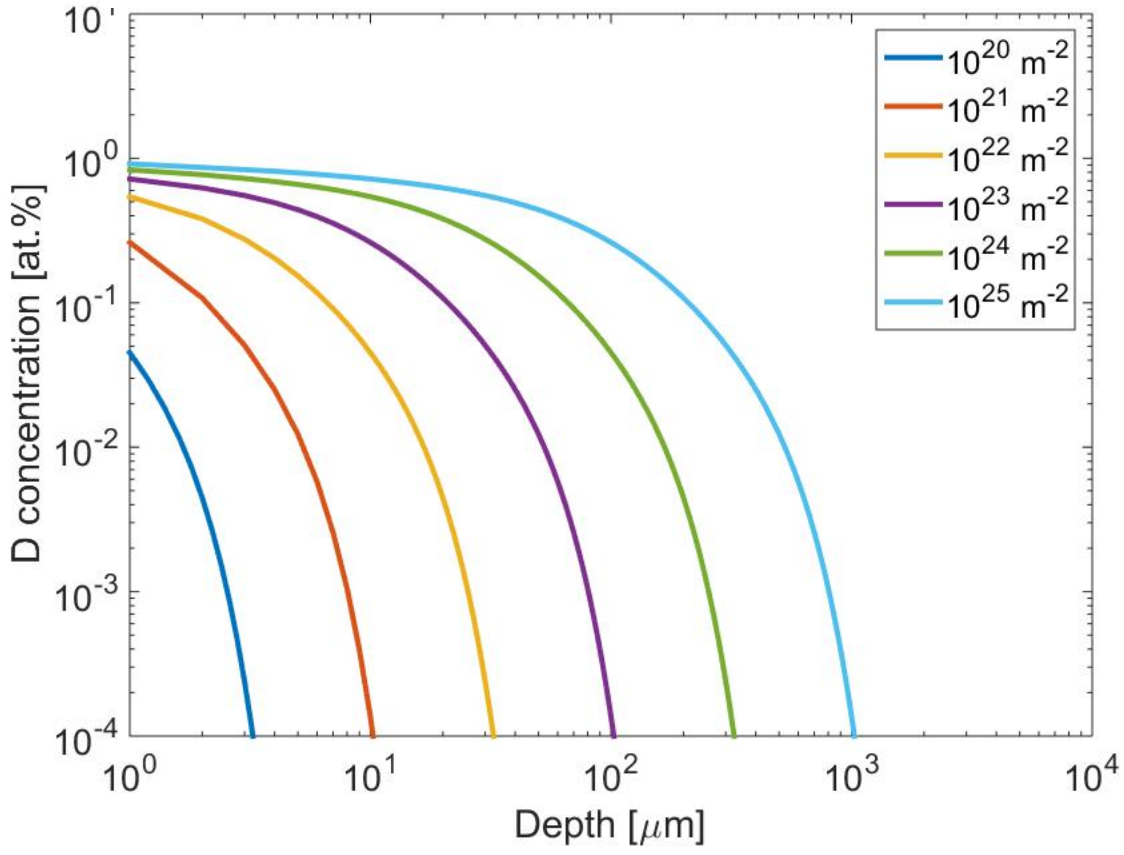
This leads to inward diffusion front of deeply trapped fuel in FW & PFCs

Ion Beam + PISCES Plasma Exposure



Wampler & Doerner NF 2009

Modeled Trapped D vs Depth for Increasing Fluence, 0.1 dpa 110 deg C



Barton, private comm., 2016

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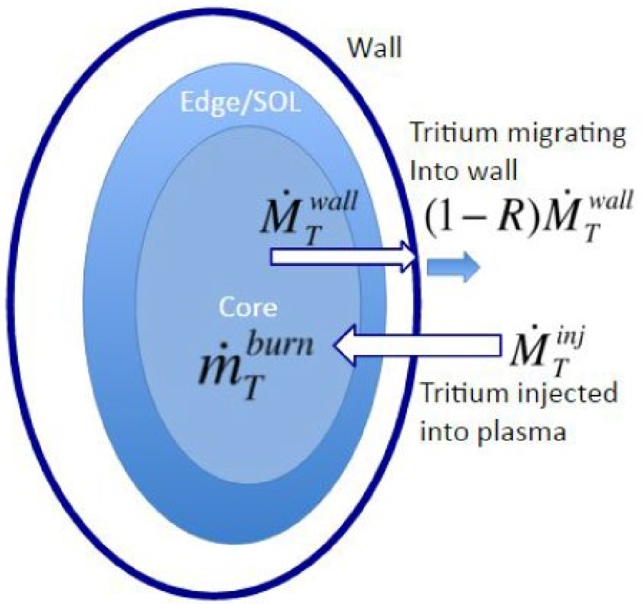
- These require multi-effect (ion flux, composition & energy; surface temperature; trace impurities; displacement damage) B-PMI experiments
- Linear plasma edge/divertor simulators provide requisite platform

Global tritium particle balance model

[from G.R. Tynan, PSI Rome 2016, NME 2017]



Where:
TBR = Tritium breeding ratio
R = Recycling coefficient
p_{burn} = fraction of tritium burned
η_{fuel} = fueling efficiency

In steady state, the rate of T injection must equal the rate of loss (burned or trapped in the surrounding material)

$$\dot{M}_{\mathrm{T}}^{\mathrm{inj}} = \dot{M}_{\mathrm{T}}^{\mathrm{burn}} + (1-R)\,\dot{M}_{\mathrm{T}}^{\mathrm{wall}},$$

The rate of T burned is

$$p_{\mathrm{burn}}\eta_{\mathrm{fuel}}\dot{M}_{\mathrm{T}}^{\mathrm{inj}} = \dot{M}_{\mathrm{T}}^{\mathrm{burn}}$$

The total change in the mass of T is defined by the TBR

$$\Delta\dot{M}_{\mathrm{T}} = (\mathrm{TBR}-1)\,\dot{M}_{\mathrm{T}}^{\mathrm{burn}}$$

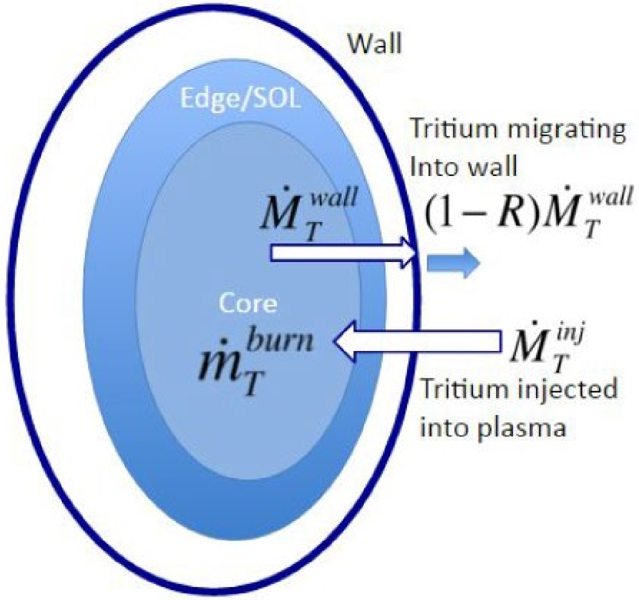
define $$p_{\mathrm{trapped}} = \frac{\dot{M}_{\mathrm{T}}^{\mathrm{trapped}}}{\dot{M}_{\mathrm{T}}^{\mathrm{wall}}}$$

and require $$\dot{M}_{\mathrm{T}}^{\mathrm{trapped}} \ll \Delta\dot{M}_{\mathrm{T}}$$

Particle balance model for tritium fuel cycle self-sufficiency

$p_{trapped}$ = trapping probability due to implantation

$$p_{\rm trapped} \ll (TBR-1)\,(1-R)\,\frac{p_{\rm burn}\eta_{\rm fuel}}{1-p_{\rm burn}\eta_{\rm fuel}}.$$

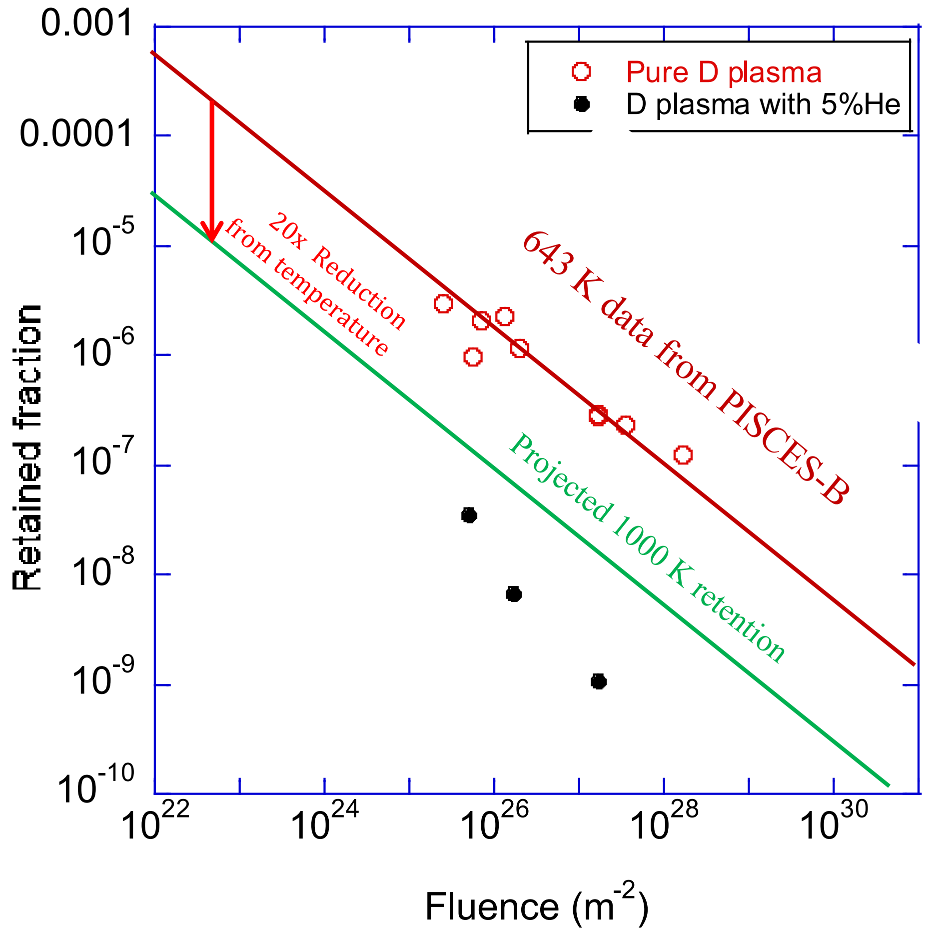


Where:
TBR = Tritium breeding ratio
R = Recycling coefficient
p_{burn} = fraction of tritium burned
η_{fuel} = fueling efficiency

Typically: TBR ~ 1.05, R ~ 0.99-0.999, p_{burn} ~ 0.05, η_{fuel} ~ 20-30%

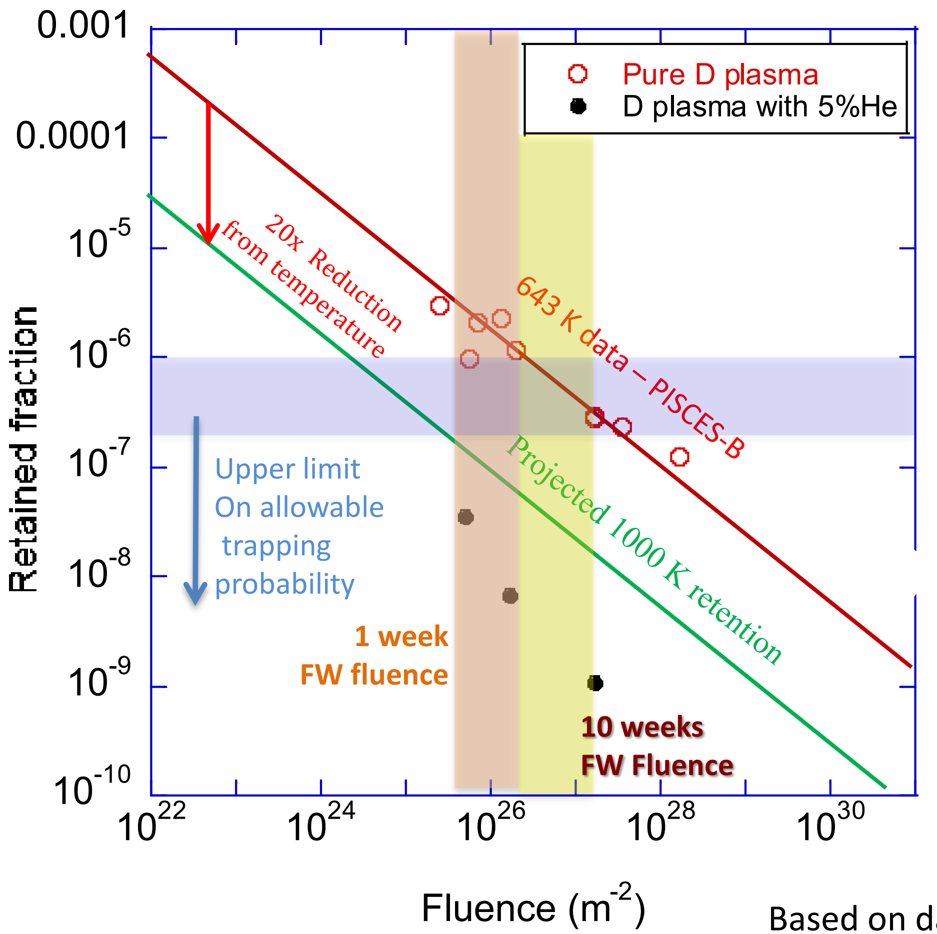
Gives $p_{trapped} \sim 10^{-6} - 10^{-7}$

Experiments show retention probability drops with fluence in undamaged W



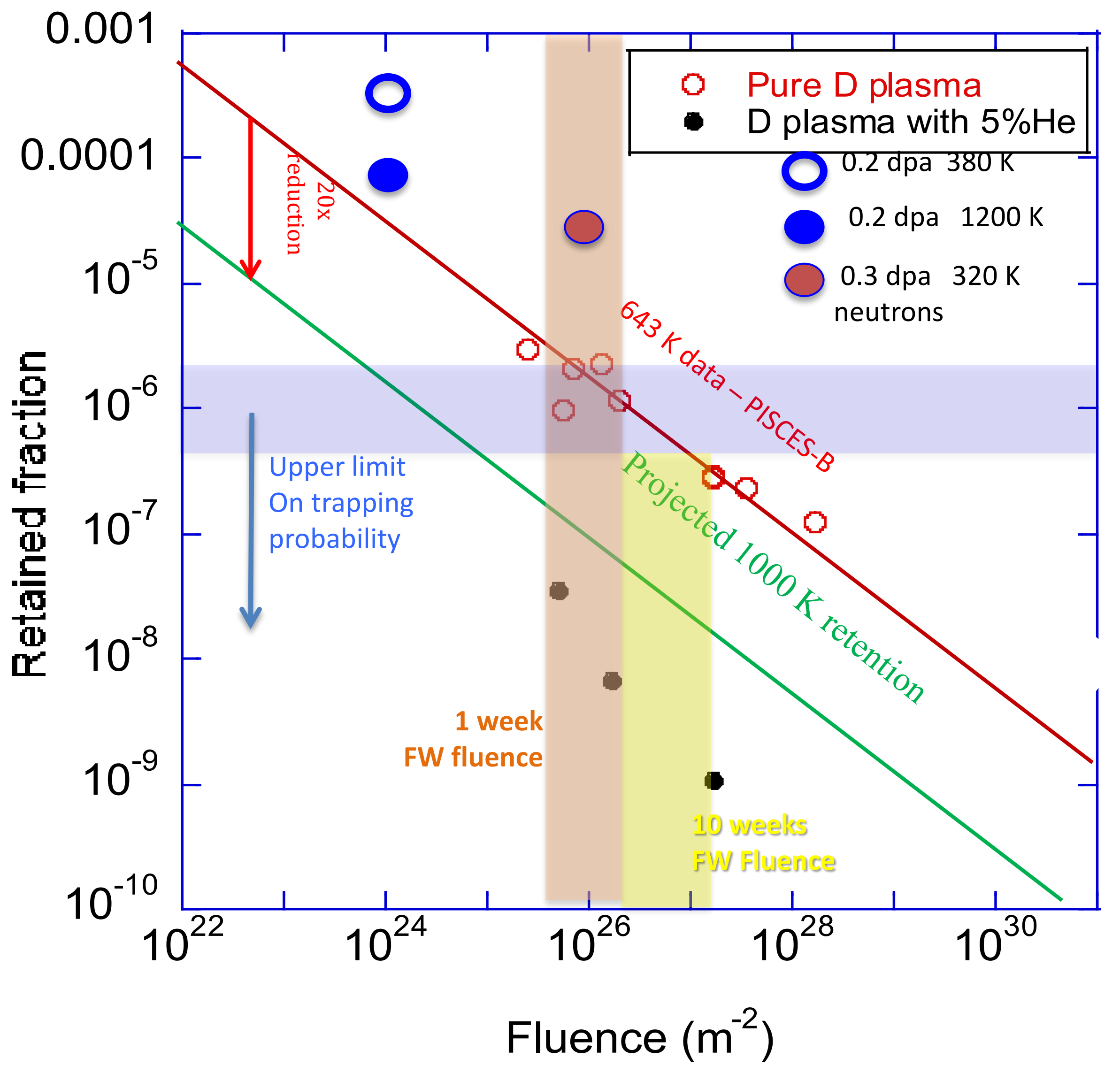
Based on data from
Doerner 2016 & Baldwin, NF 2011

Retention fraction within limits in undamaged W



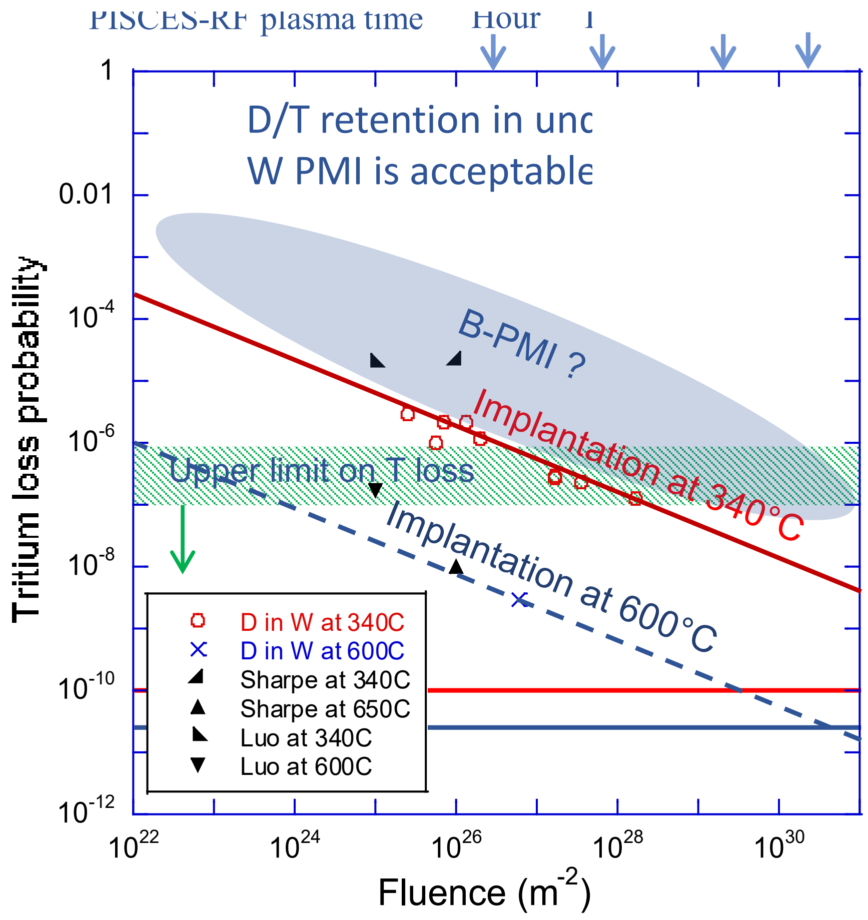
Based on data from
Doerner, in press, '16 & Baldwin, NF 2011

But there is a Substantial Retention Increase in Damaged W



Based on data from
Doerner 2016 Simmonds 2017
Baldwin NF 2011, Shimada NF '15

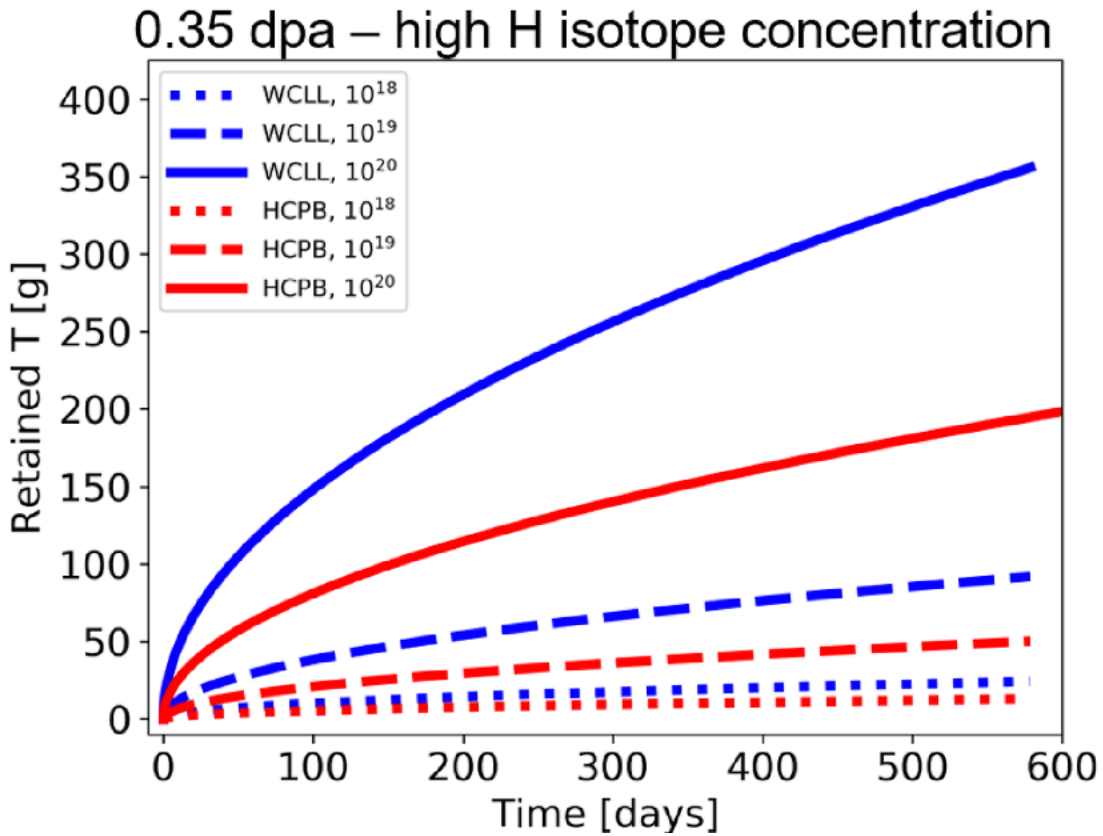
Will W have acceptable D/T retention for self sufficient tritium breeding (TBR >1) after displacement damage?

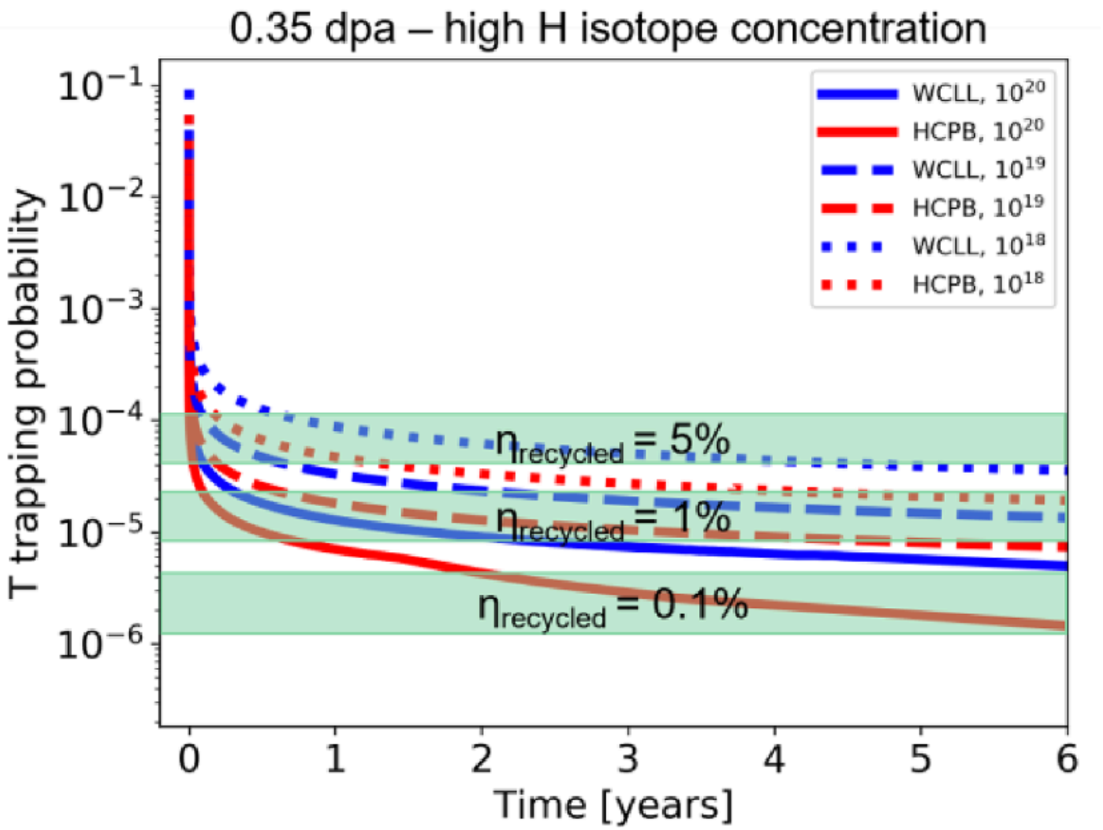


- Losses below 1 in 10^6 T into the first wall, or lower, is needed for fusion to be self sufficient in breeding T fuel.
  - With W PMI (no damage) this can be achieved. Not so clear with simultaneous damage occurring.
- Simultaneous displacement damage and plasma exposure changes the relaxation cascade dynamics
  - Vacancies are stabilized.
- No D retention data at high fluence and high dpa.
- Existing D retention data is from sequential displacements followed by plasma exposure.
- **No data exists for D retention due to simultaneous displacement damage and plasma exposure.**

R. P. Doerner *et al.*, Nucl. Mater. Energy **18**, 56 (2019)

Euro-DEMO modeling shows significant B-PMI impact on T inventory & time to TBR>1





Arrndondo et al NME 2021

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- There are ***MANY*** *B*-PMI effects that influence retention that must be understood & incorporated in these predictions
- These require multi-effect (ion flux, composition & energy; surface temperature; trace impurities; displacement damage) B-PMI experiments
- New PMI facilities being prepared to permit these multi-effect studies

Many *interlinked* aspects to this modeling challenge

- Cross-field and parallel edge/SOL transport modeling
  - Turbulent-based transport (BOUT++, etc…) & time-averaged fluid modeling (SOLPS, etc…)
- Wall & Divertor Erosion and Redeposition
  - ERO, GITR, DIVIMP, etc….
- Surface & Near-surface Evolution from Plasma Irradiation
  - WALDYN, ???
- Bulk Material Evolution due to Neutron Irradiation w/ Transmutation, Defect Production & D/T/He retention
  - -???

- **On FPP-relevant timescales (> hours to days of discharge duration) these processes are inter-dependent**
- **Thus we need interlinked validated models to predict T behavior in FW and PFCs**

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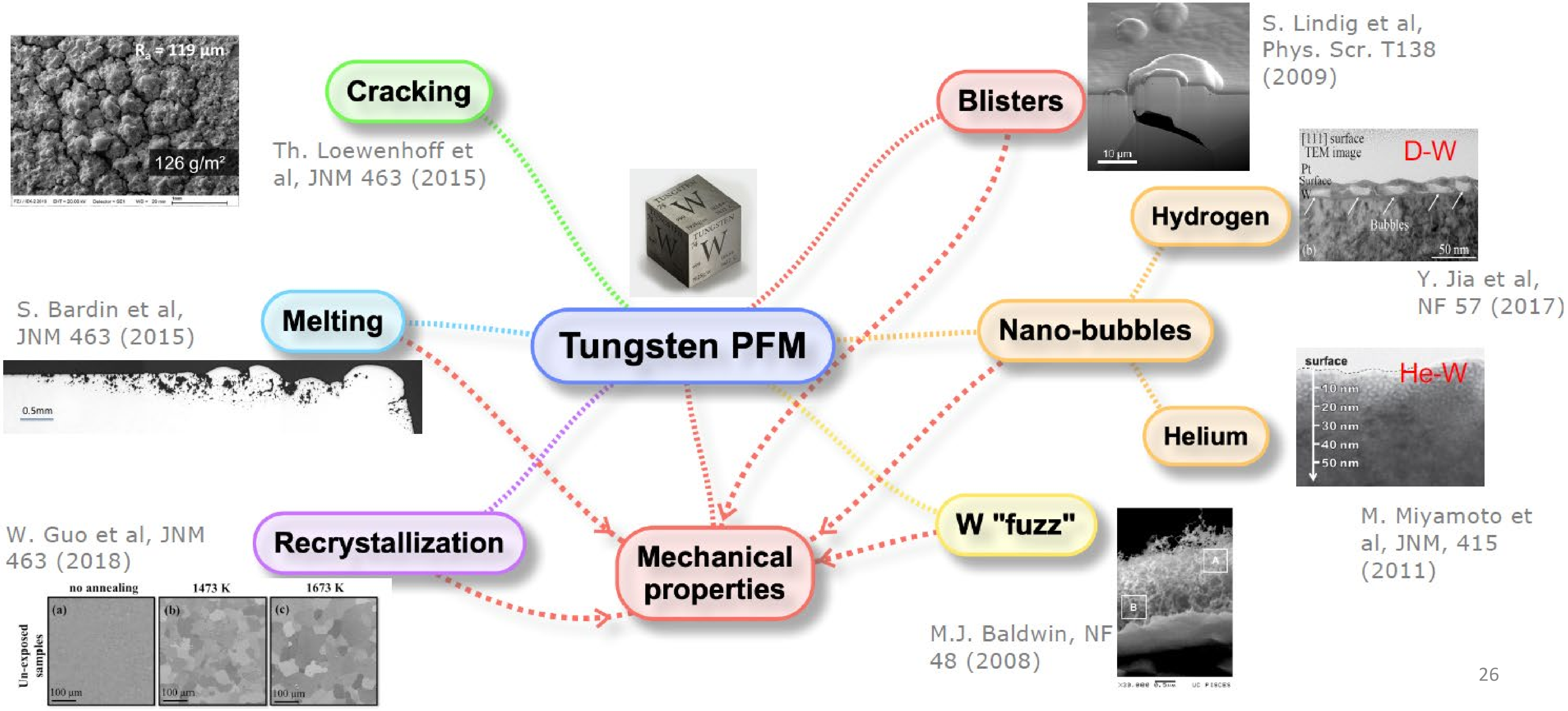
B-PMI modifies near-surface zone….which will impact retention behavior….

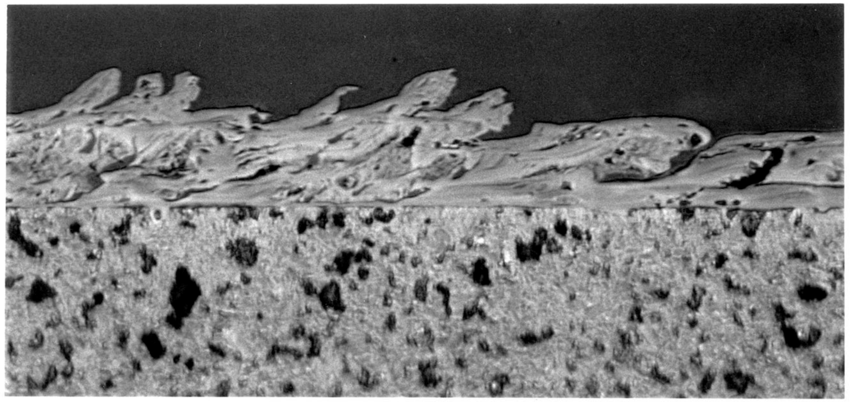


<u>*MANY*</u> *B*-PMI effects that influence retention that must be understood to confidently predict retention in FPP

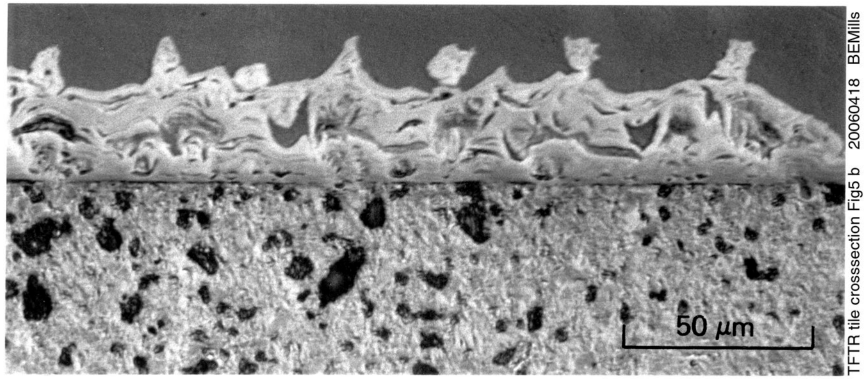
- **Mixed materials**
- **Co-deposition**
- He nanobubbles: can inhibit fuel migration into bulk
- Nano-fuzz: Can shield substrate from plasma; modifies matl properties
- Nano & microscale morphology evolution: changes transport of eroded material in plasma
- Displacement Damage w/ Plasma Irradiation: May inhibit defect annealing

Perhaps the most famous plasma created mixed-material surface comes from TFTR

Poloidal direction



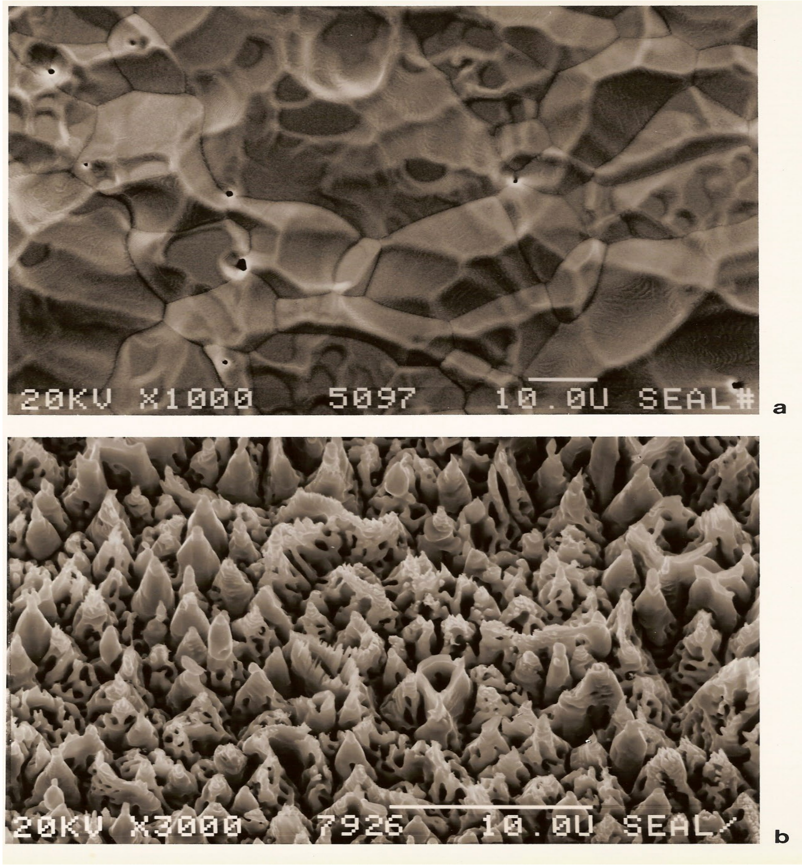
Toroidal direction



- Inner bumper limiter tiles showed regions of erosion, regions of deposition and regions of both erosion and deposition (seen here)
- Composition and morphology of mixed-material surface was much different than the originally designed plasma-facing surface (dubbed ‘tokamakium’)
- Surface layers consist of C, D, O and metals
- Layer composition changed with depth (i.e. with tokamak operational conditions)

B. E. Mills et al., J. Nucl. Mater 162-164(1989)343.

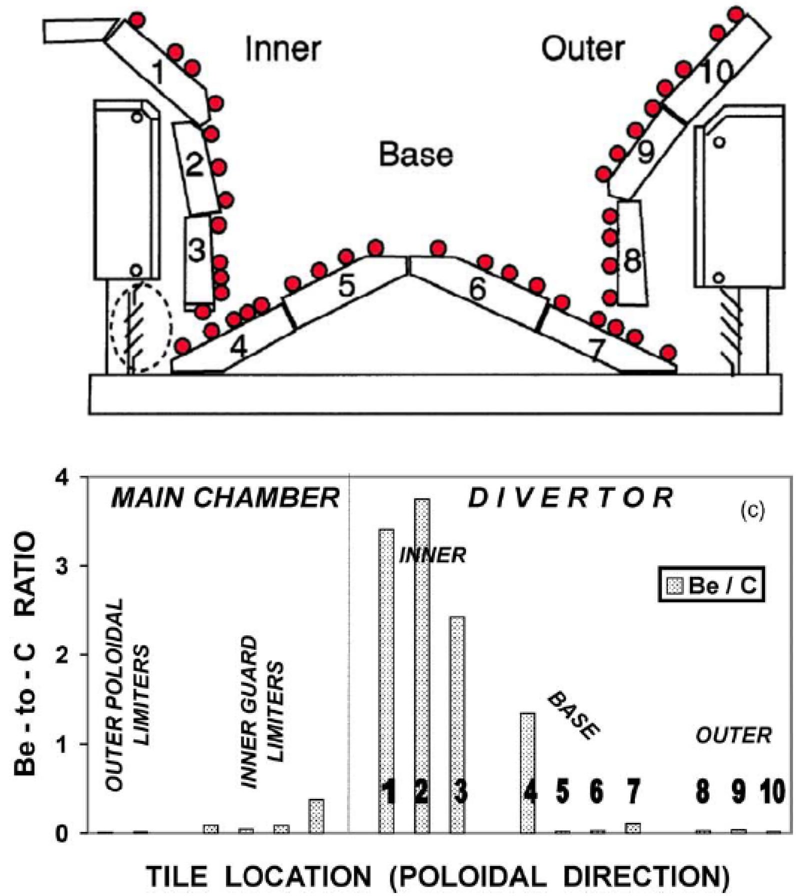
The complexity of mixed-material formation conditions was demonstrated at PISCES in the mid 1980s



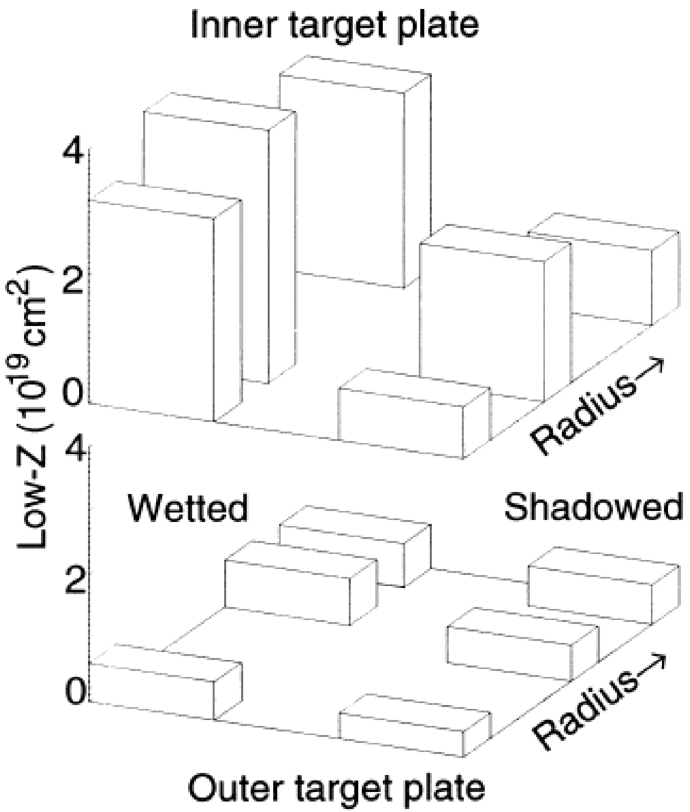
- During identical Ar plasma exposure conditions of SS
  - a) Room Temp. surface w/o Mo impurities in plasma
  - a) 400ºC surface w/o Mo impurities in plasma
  - a) Room Temp. surface with Mo impurities in plasma
  - b) 400ºC surface with Mo impurities in plasma
- Surface temperature is a key variable whose affects may be difficult to predict

D. M. Goebel et al., J. Nucl. Mater. 145-147(1987) 61.

JET (Be/C) and ASDEX (W/C) have also observed mixed-material formation



M. Rubel et al., J. Nucl. Mater. 313-316(2003)321.



H. Maier et al., J. Nucl. Mater. 266-269(1999)1003.

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He or D/He Plasmas Form Near surface He nano-bubbles in W

300ºC

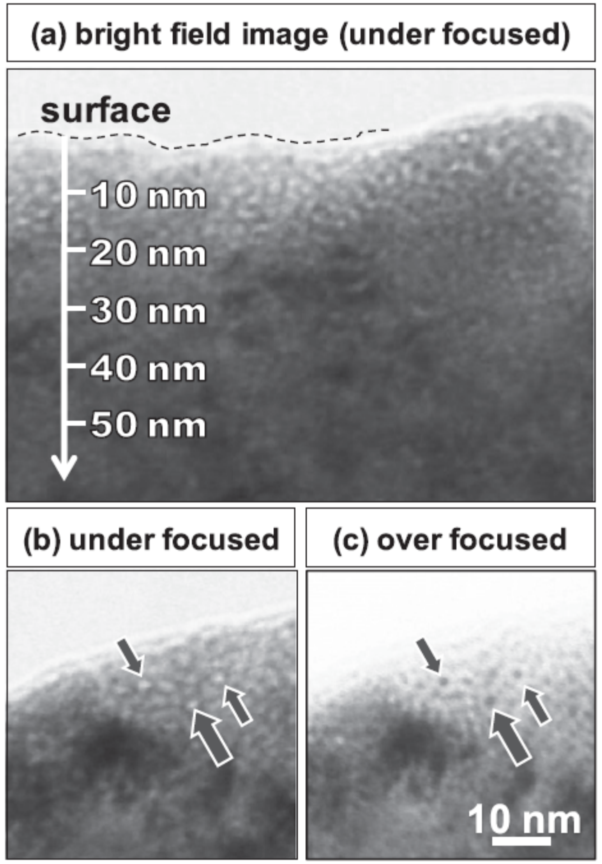


Fig. 2. Cross-sectional microstructure, observed with TEM, in the W sample exposed to D + He mixture plasma at $E_i \sim 60$ eV, $\Phi_D \sim 5 \times 10^{25}$ m^{-2}, $T_s \sim 573$ K, $c_{He} \sim 5\%$. As pointed with arrows, He bubbles have bright and dark contrasts in under (b) and over (c) focused images, respectively.

500ºC

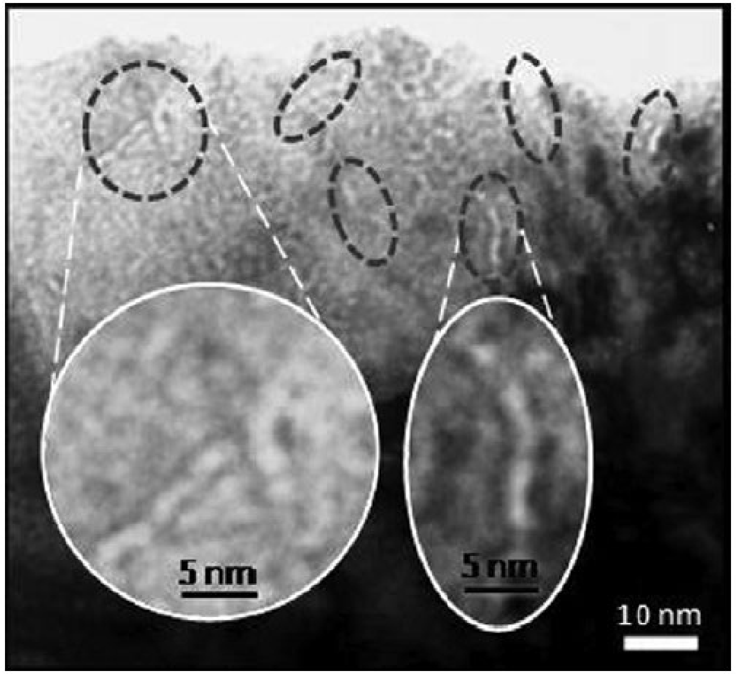


Fig. 4. Cross-sectional microstructure in the W sample exposed to D + He mixture plasma at $E_i \sim 120$ eV, $\Phi_D \sim 5 \times 10^{25}$ m^{-2}, $T_s \sim 773$ K, and $c_{He} \sim 5\%$. As seen in the circles, He bubbles interconnect and make larger clusters.

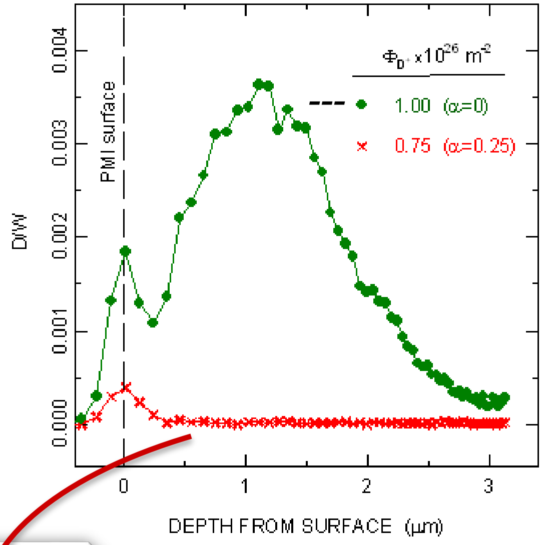
[from M. Miyamoto et al., JNM 415(2011)S657]

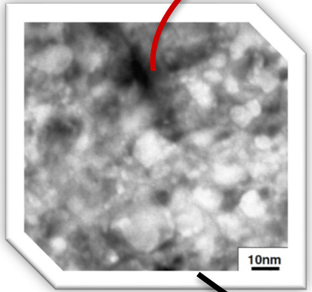
These He bubbles act as a diffusion barrier to D

Single step (D, He) exposure

(**D-0.25He**) T_s= 473 K, E_{ion}= 50 eV

Mixed D_2-He compared to **pure D_2**





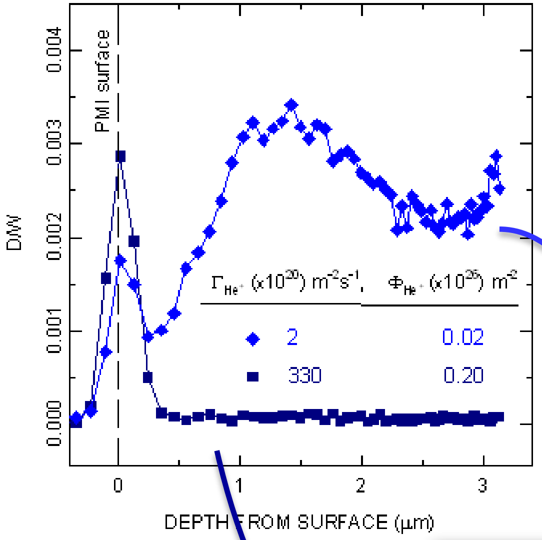
[Miyamoto *et al.*, NF 49 (2009)]

Two step, He pretreat, D plasma exposure

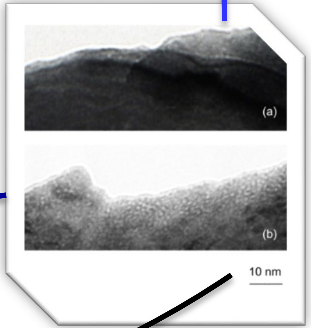
(**He**) T_s= 473 K, E_{ion}= ~30-50 eV

(**D_2**) T_s= 473 K, E_{ion}= 50 eV, F_{D+} = 5-8 x10^{26} m^{-2}

Low/**High** flux He prior to D_2, compared



No bubbles

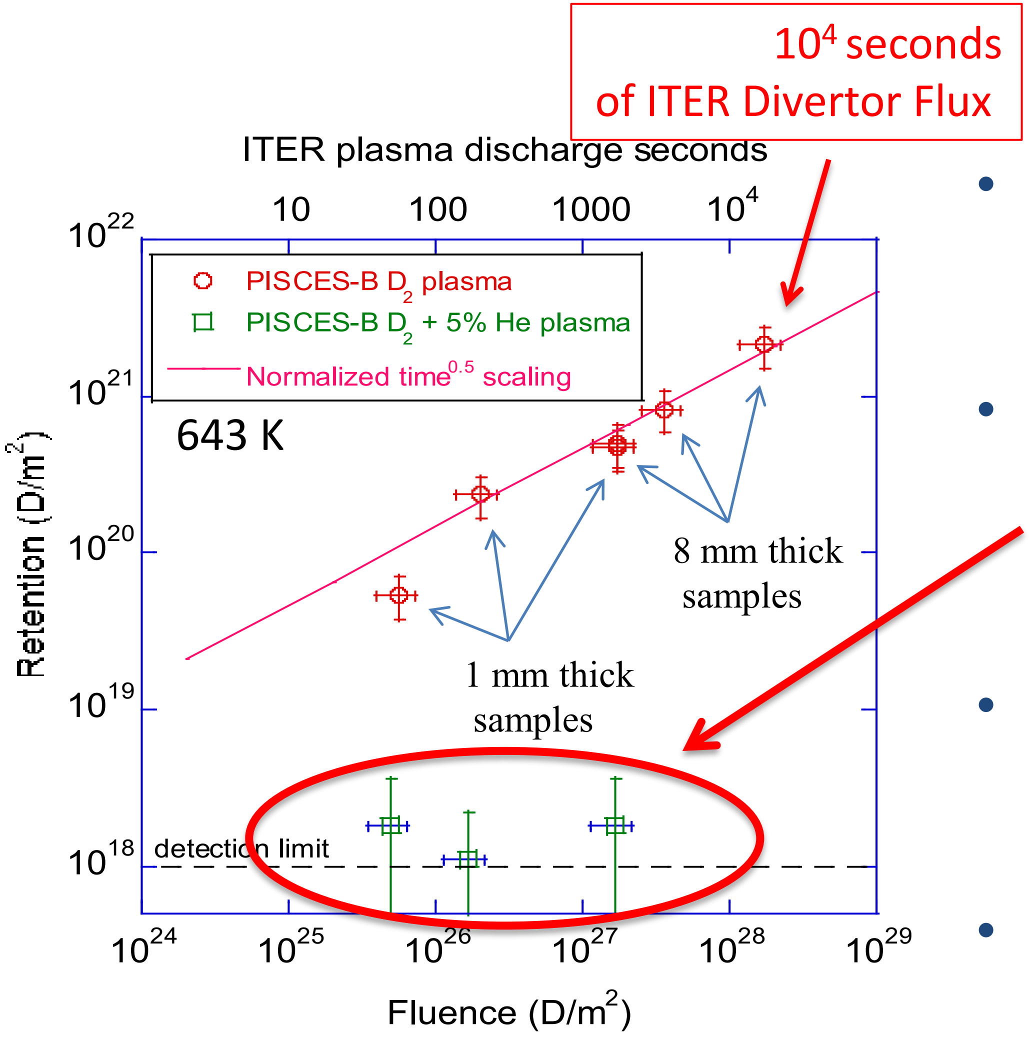


[Baldwin *et al.*, NF (2011)].

Bubble network provides 'return pathways' to PMI surface interrupting D migration to bulk.

He bubbles

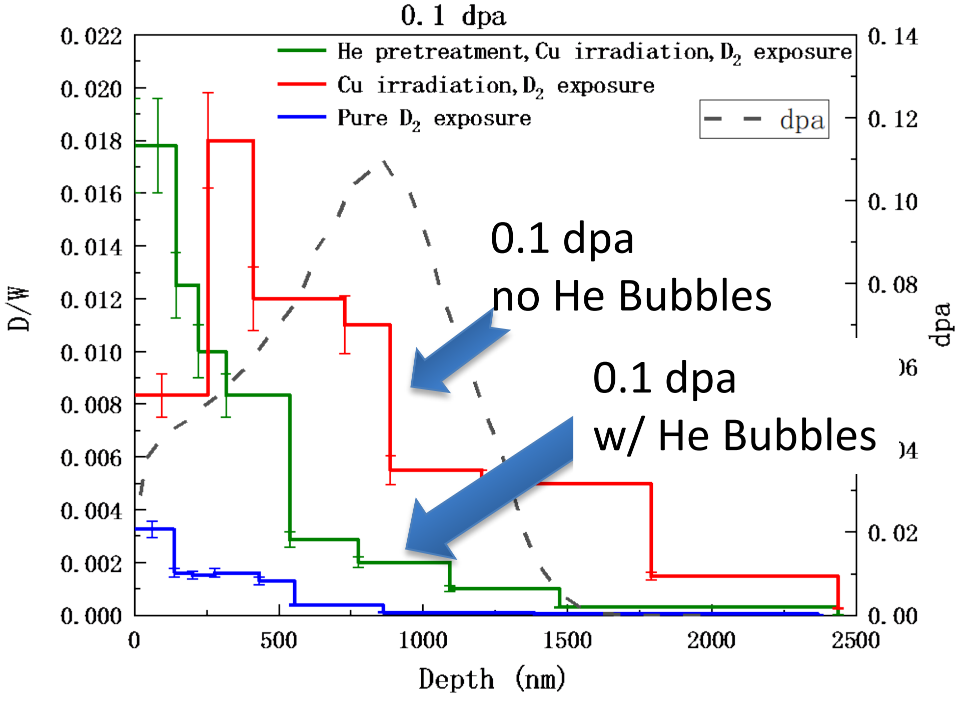
No saturation in D retention up to fluence of 2 x 10^{28} m^{-2}



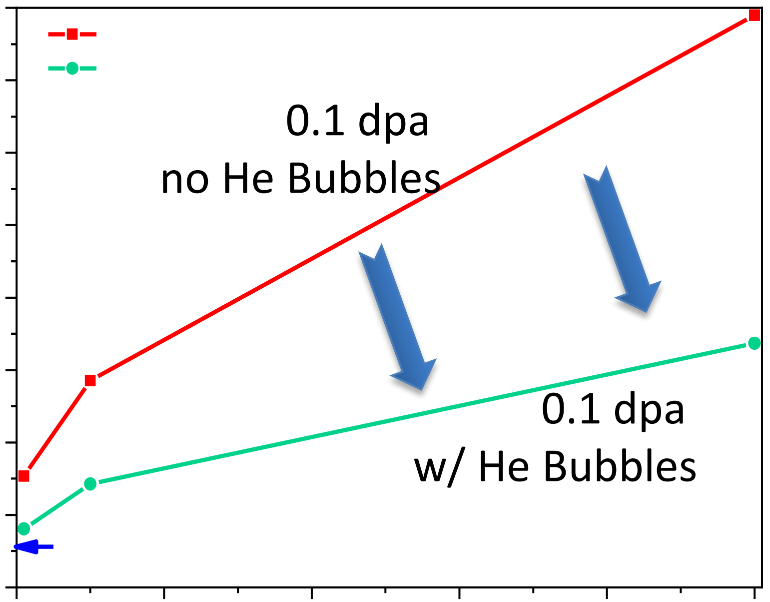
- **No saturation in D retention** in W with high-fluence deuterium plasma exposure
- **5% He^+ flux during deuterium plasma exposure drastically reduces D retention** in W at 643 K
- Evidence for a reduced retention with higher flux, but a systematic study is needed
- NEED STUDIES IN HIGH-TEMP HIGH FLUENCE DAMAGED MAT'LS (NEUTRONS REQ'D)

He bubbles can (partially) survive rad-damage & still reduce D retention

NRA D Profiles



Total inventory v dose



Bai et al NF 2018

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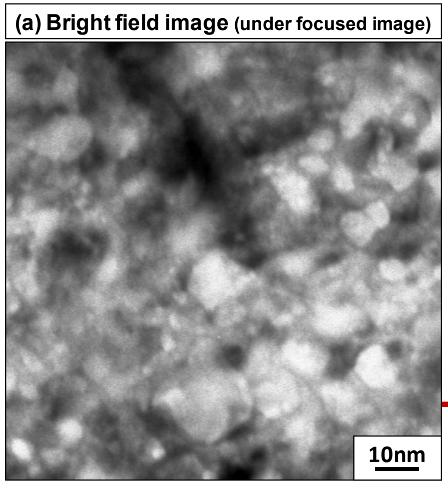
W Temperature Influences PMI Effects

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



PISCES-A: D_2-He plasma

M. Miyamoto et al. NF (2009) 065035

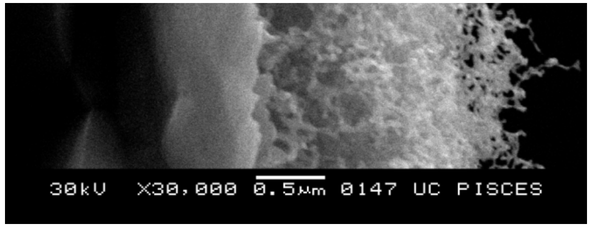
600 K, 1000 s, 2.0x10^{24} He$^+$/m^2, 55 eV He$^+$

- Little morphology
- Occasional blisters

PISCES-B: pure He plasma

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

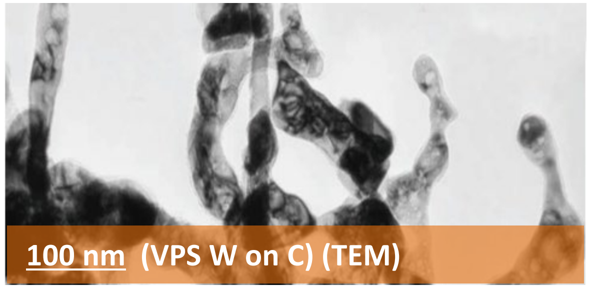
1200 K, 4290 s, 2x10^{26} He$^+$/m^2, 25 eV He$^+$



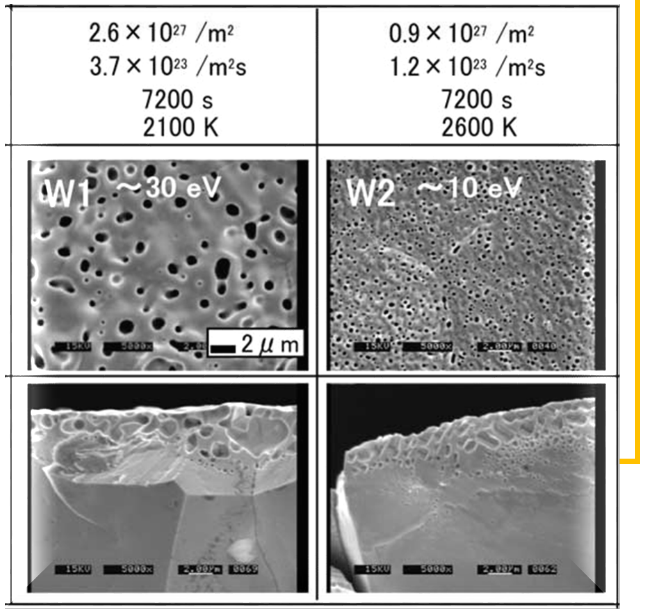
NAGDIS-II: pure He plasma

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

Dissimilar layer expts prove nano-fuzz grows by migration of substrate up into tendrils

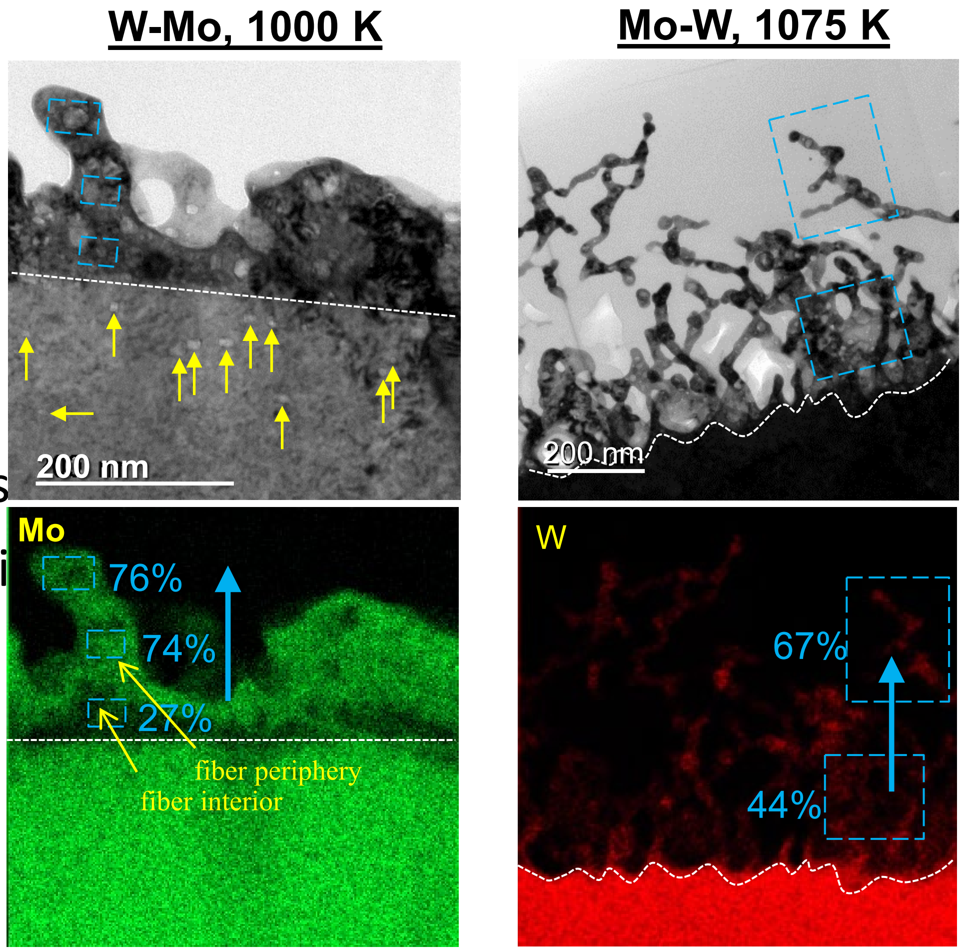
1. Thin nm W/Mo films deposited on Mo/W substrates
2. Exposure to pure ^{4}He plasma at T_s = 340-1075 K
3. Composition by sputter-AES and TEM/EDX

W film on Mo

- $T_s \leq$ 750 K: no material mixing & only 2 nm bubbles
- T_s = 800 K: some material mixing due to He-induced pinholes
- T_s = 1000 K: accumulation of Mo from substrate at the tendril tip

Mo film on W

- T_s = 1075 K: accumulation of W from substrate at the tendril



M I Patino et al 2020 Phys. Scr. 2020 014070

Fuzz growth eventually stops at high He fluence

- Data from PISCES, Univ. of Liverpool, NAGDIS at 10^{24}-10^{28} m^{-2}, 40-80 eV, 1000-1200 K[1]

- Assuming growth is limited by He reaching the bulk (from the analytical model)

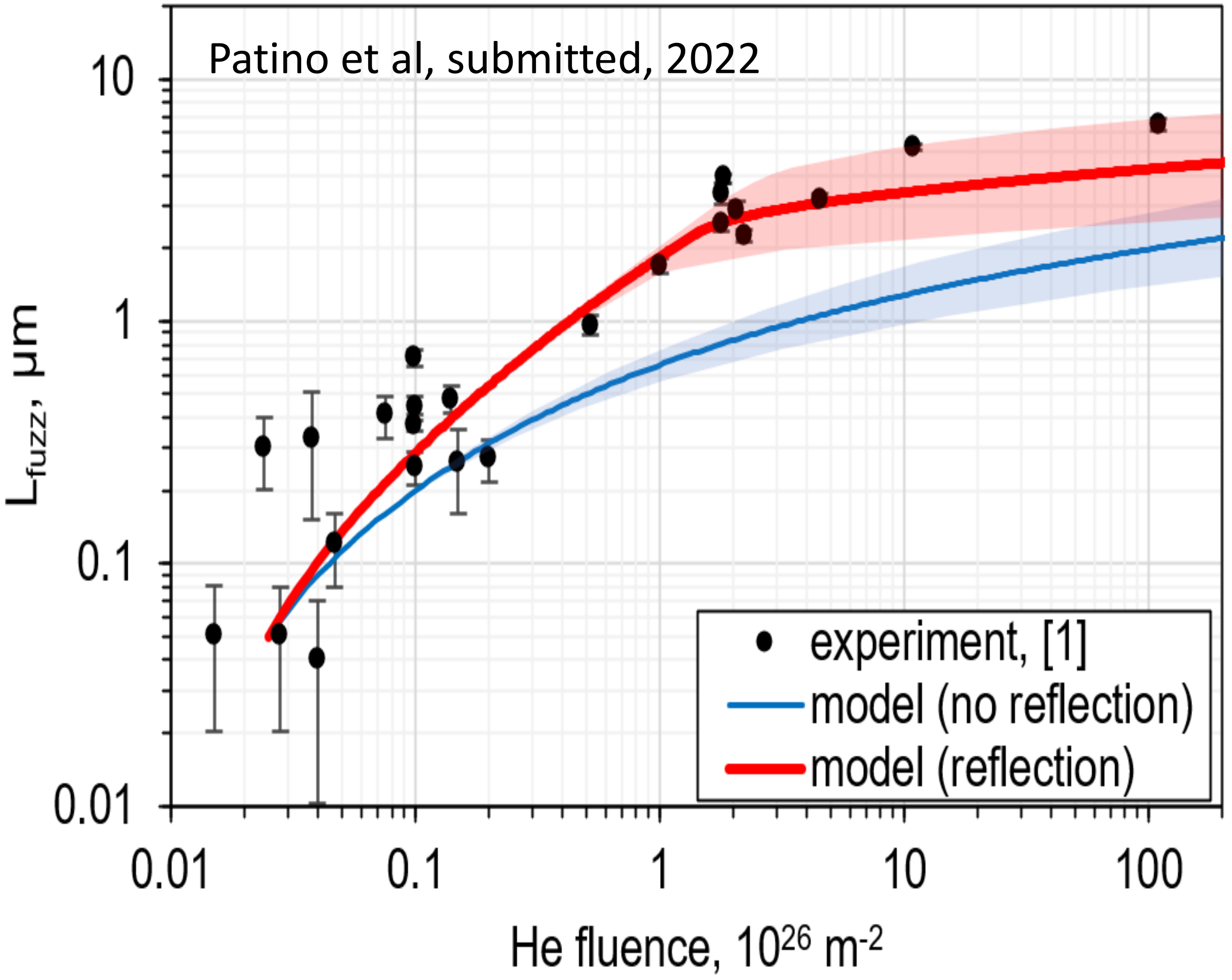
$$\frac{dL_{fuzz}}{dt} = A\Gamma_{bulk} = A\Gamma_{top}\frac{I_{bulk}}{I_0}(L_{fuzz})$$

  – Integrate
  – Apply $\Phi_0 = 2.5\text{x}10^{24}$ m^{-2} at $L_{fuzz} = 0.05$ μm*, $1/A = 2.5\text{x}10^{31}$ m^{-3} (A: const dep on T_s, E_i, thermophysical properties)

A. Without ion reflection, L_{fuzz} is significantly underpredicted

B. Considering ion reflection, model matches experimental data

  ➢ **Fuzz growth consistent with He reaching bulk**



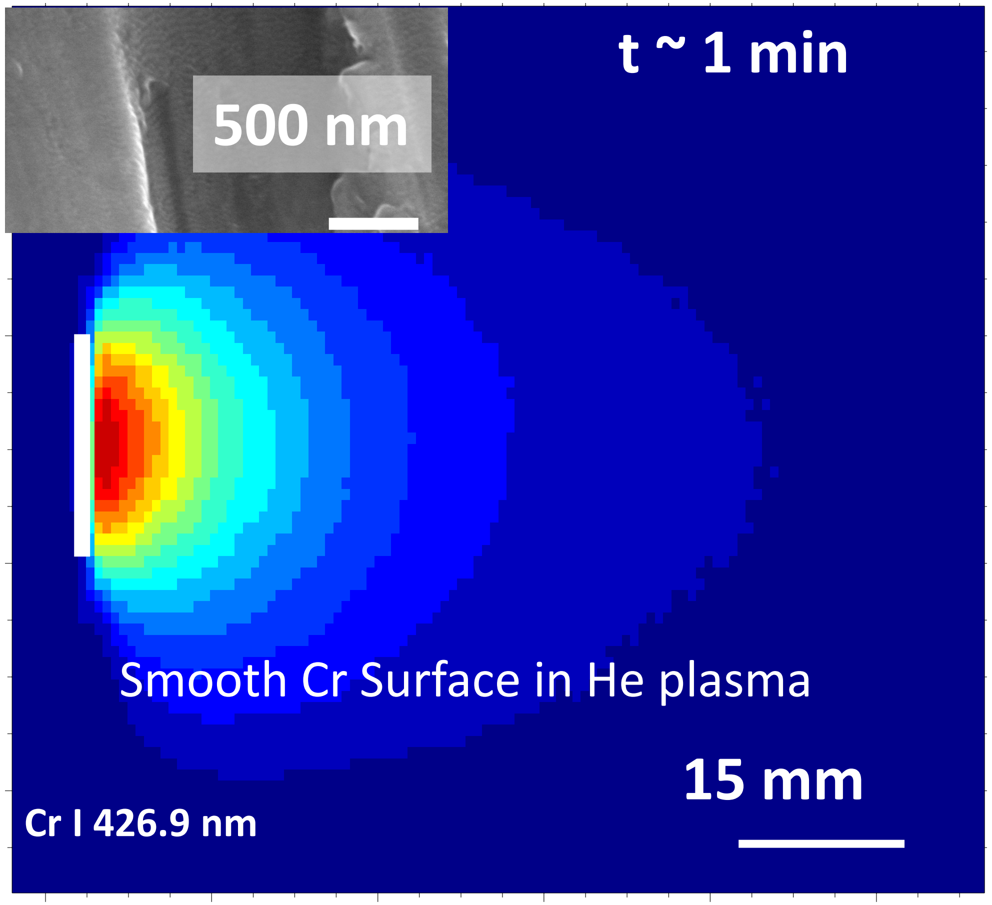
** 0.05 μm is lower limit of fuzz thickness measured and limit for validity of volume fill density*

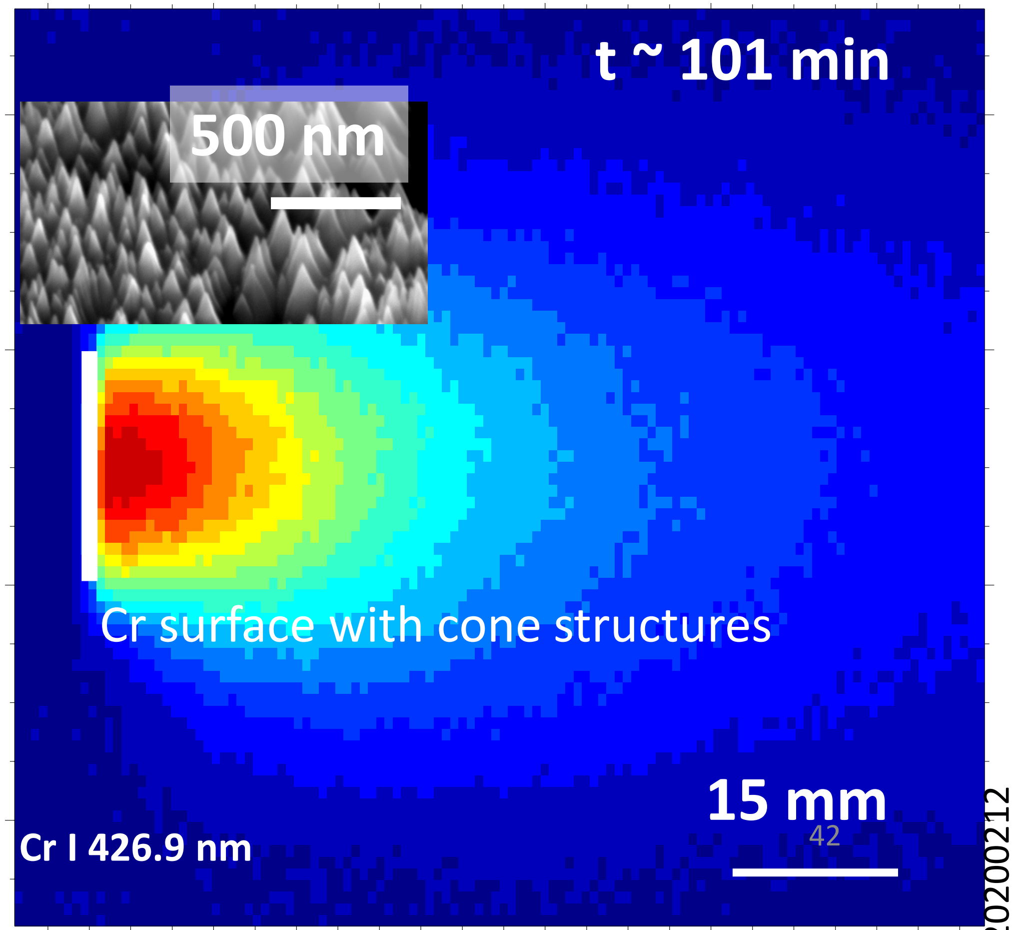
[1] Petty 2015 NF 55 093033

__MANY__ *B*-PMI effects that influence retention that must be understood to confidently predict retention in FPP

- Mixed materials
- Co-deposition
- He nanobubbles: can inhibit fuel migration into bulk
- Nano-fuzz: Can shield substrate from plasma; modifies matl properties
- **Nano & microscale morphology evolution can affect transport of eroded material into plasma**
- Displacement Damage w/ Plasma Irradiation: May inhibit defect annealing

Macroscale transport of eroded material controlled by nanoscale PMI-driven surface morphology





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==>> SOL Impurity transport in hours-long plasmas must connect nano-scale surface w/ macroscale plasma!

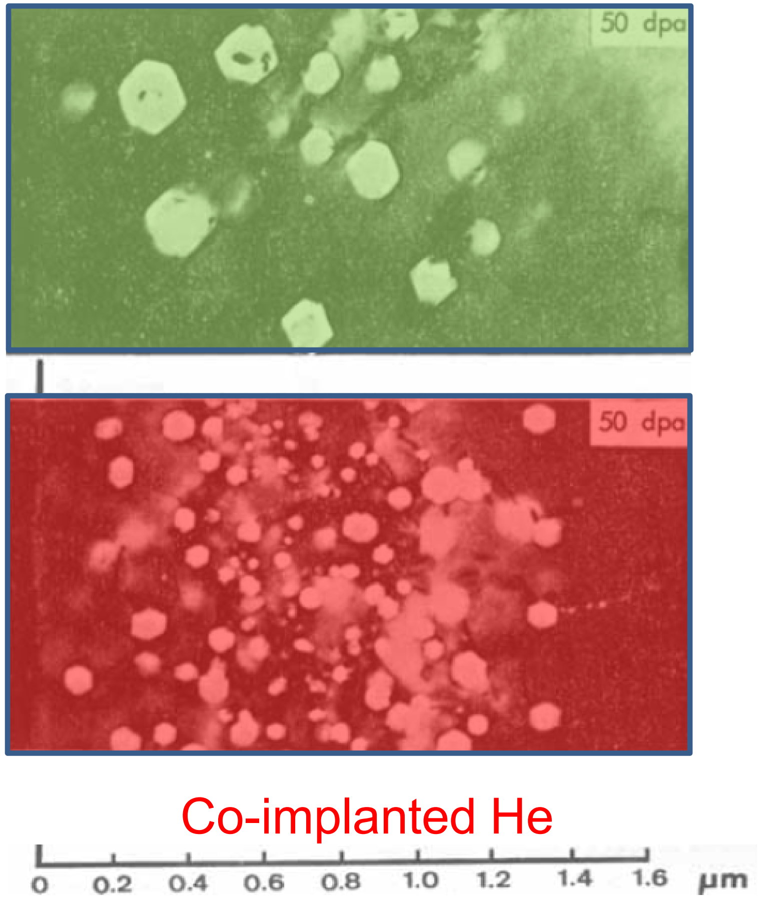
MANY *B*-PMI effects that influence retention that must be understood to confidently predict retention in FPP

- Mixed materials
- Co-deposition
- He nanobubbles: can inhibit fuel migration into bulk
- Nano-fuzz: Can shield substrate from plasma; modifies matl properties
- Nano & microscale morphology evolution: changes transport of eroded material in plasma
- **Displacement Damage w/ Plasma Irradiation: May inhibit defect annealing**

Fission material studies reported synergistic effects, e.g. ***different collisional cascade relaxation when He is co-implanted***

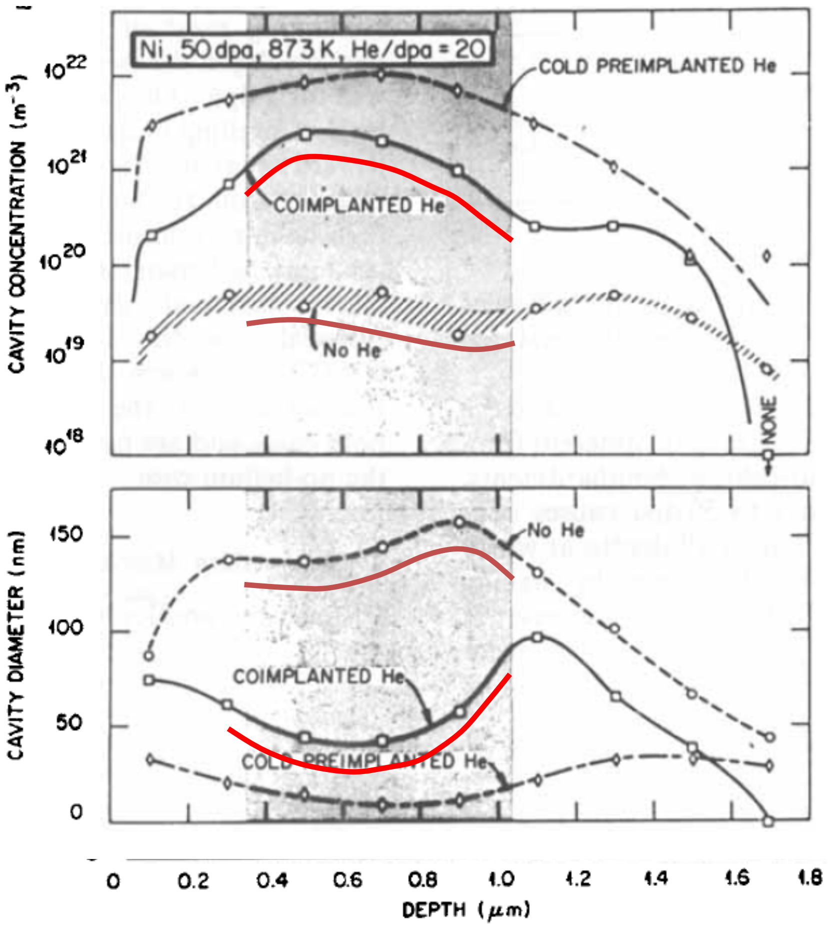
- 4 MeV Ni ion damage on Ni to 50 dpa at 873 K.
- Co-implanted He (1000 appm) in the damage region
    - Decreases cavity volume.
    - Increases cavity concentration.
- Synergism affected swelling in a complicated manner.
- Fusion B-PMI studies are still in their infancy.

No He



Co-implanted He

Peak damage



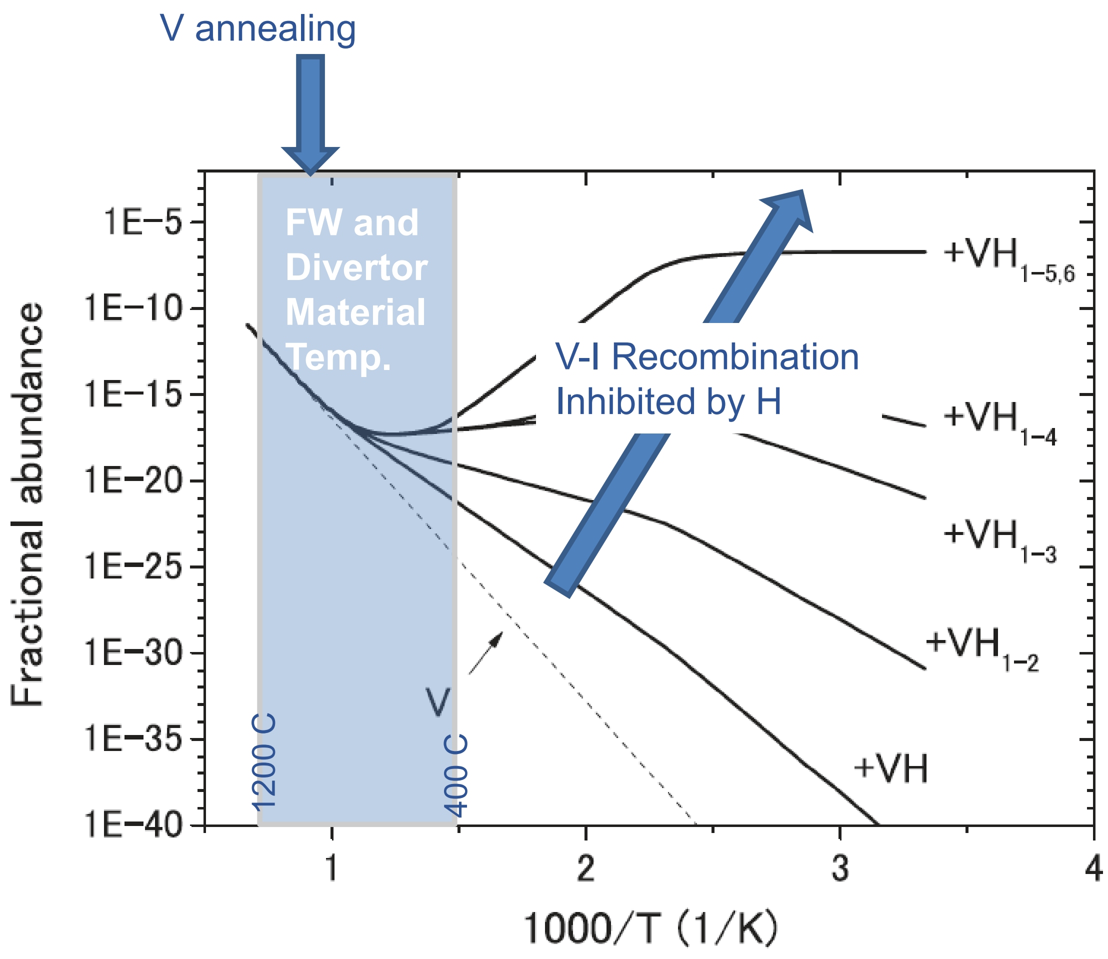
K. Farrell, et al.(1982) Radiation Effects, 62:1-2, 39

DFT calculations show trapped H slows down annealing of damage

- DFT calculations predict that H in W:
    - Produces enhanced vacancy concentration with H clustered in the vacancies.
    - H clustering can prevent a vacancy/self-interstitial recombination.

- Simultaneous displacement damage may increase fuel retention in fusion materials…

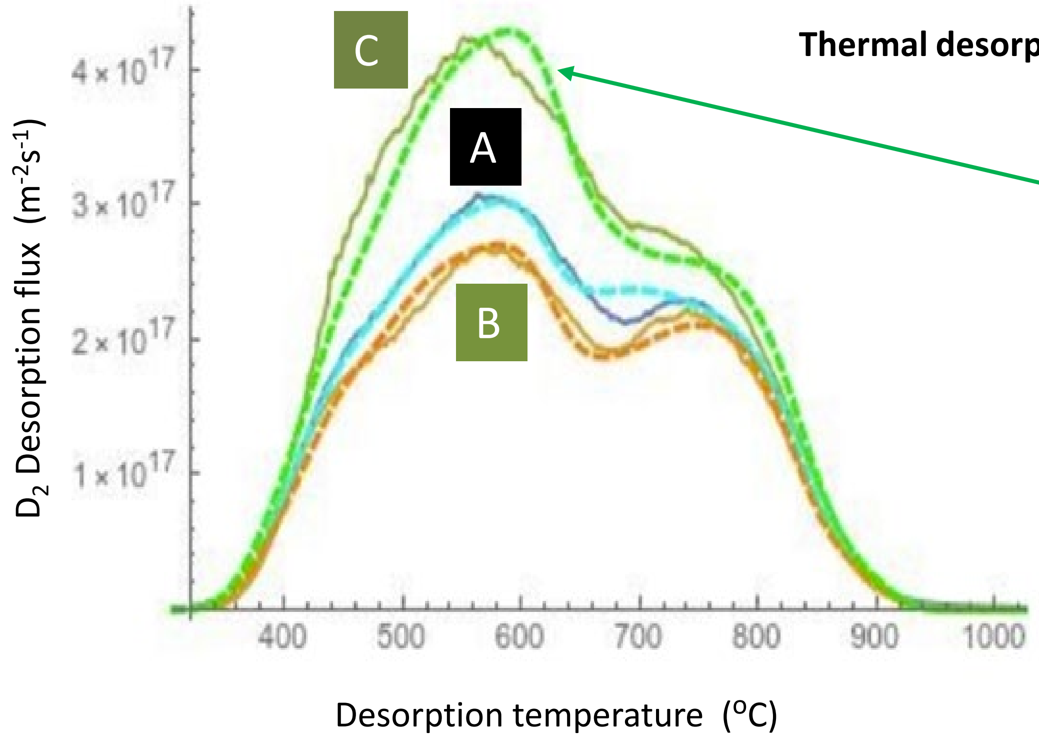
  ….depends on Mat’l Temperature!



D. Kato *et al* (2015) Nucl. Fusion 55 083019

Lab-scale PMI expts consistent w/ inhibited annealing by plasma-implanted D

A	Damaged 20 MeV W^{6+}	Plasma for 3 h 200 °C	TESSIM modeling	
B	Damaged 20 MeV W^{6+}	Annealed for 1 h 200 °C	Plasma for 3 h 200 °C	TESSIM modeling
C	Plasma for 2 h 200 °C	Damaged 20 MeV W^{6+}	Plasma for 3 h 200 °C	TESSIM modeling



Thermal desorption spectroscopy (TDS)

TESSIM simulation with reduced SIA recombination with V by factor 3.5 gives model agreement with experiment.

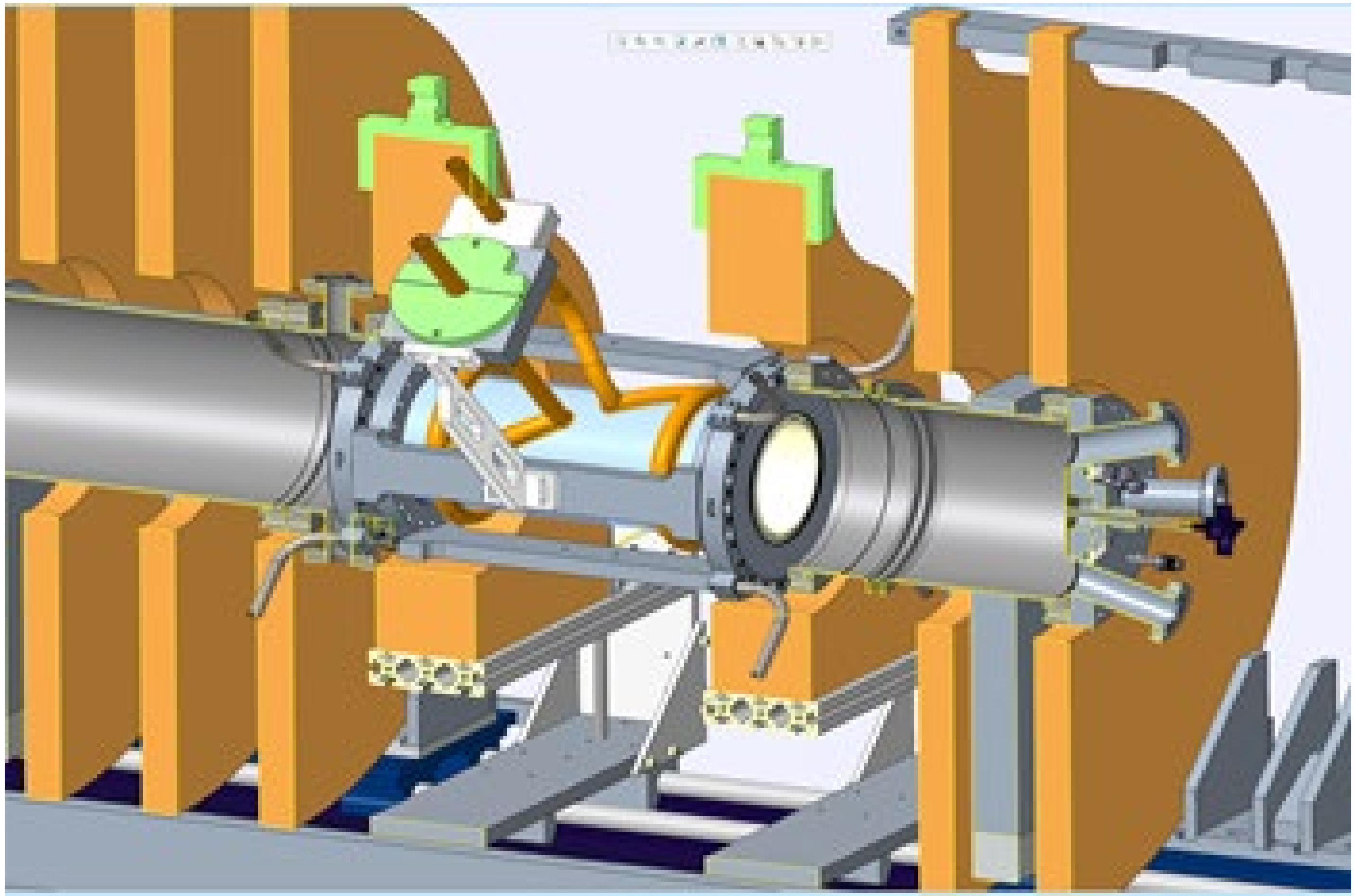
Simmonds & Zalonik, in prep 2022

See also Schwartz-Selinger NME 2018, etc…

Main points of this talk

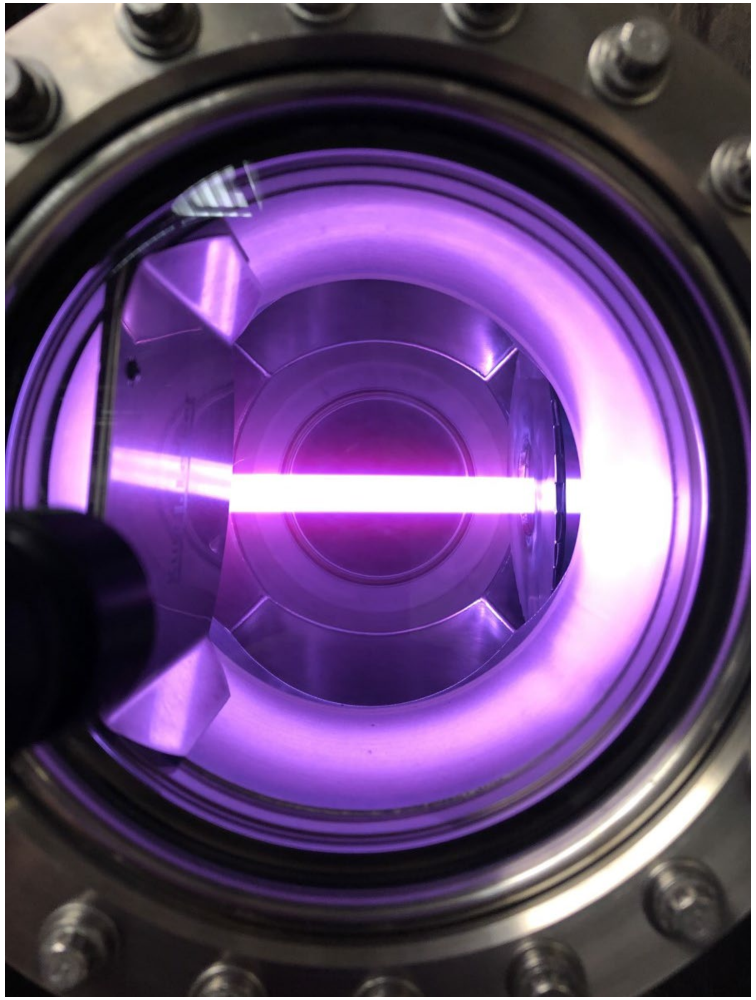
- Permanent T retention in plasma-facing materials does not appear to have been considered in T-handling system models
- There is a very low allowable probability of permanent T retention in PFCs while keeping TBR>1
- We need to have high-fidelity, high-confidence predictions of retention for a. credible FPP design
- There are *MANY* *B*-PMI effects that influence retention that must be understood & incorporated in these predictions
- **These require multi-effect** (ion flux, composition & energy; surface temperature; trace impurities; displacement damage; mech. Stress; heat flux) **B-PMI experiments w/ in-situ & ex-situ diagnostics**
- **New PMI facilities being prepared to permit these multi-effect studies**

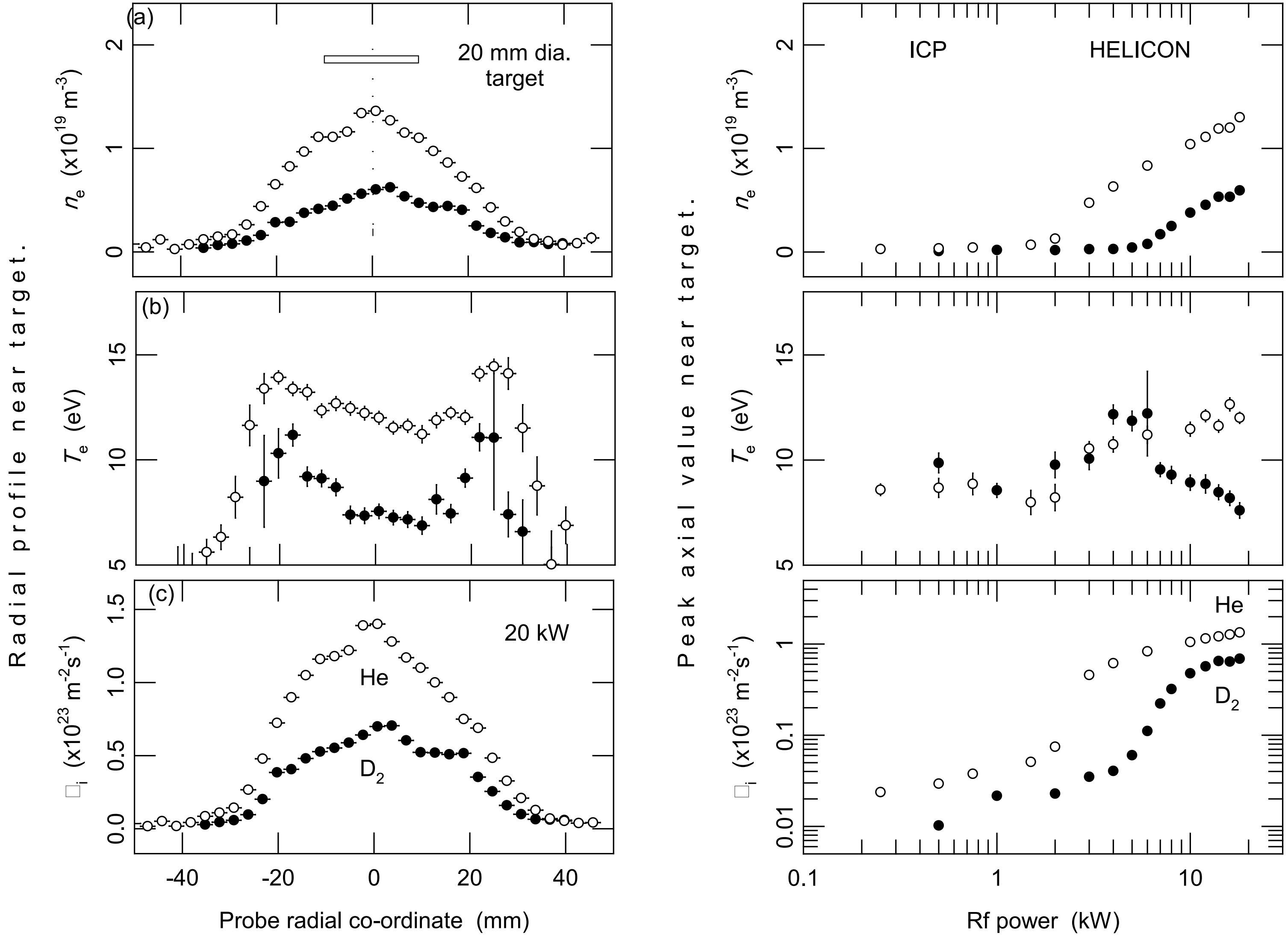
UCSD-PISCES & ORNL developed new high power helicon source for PISCES-RF & MPEX B-PMI studies



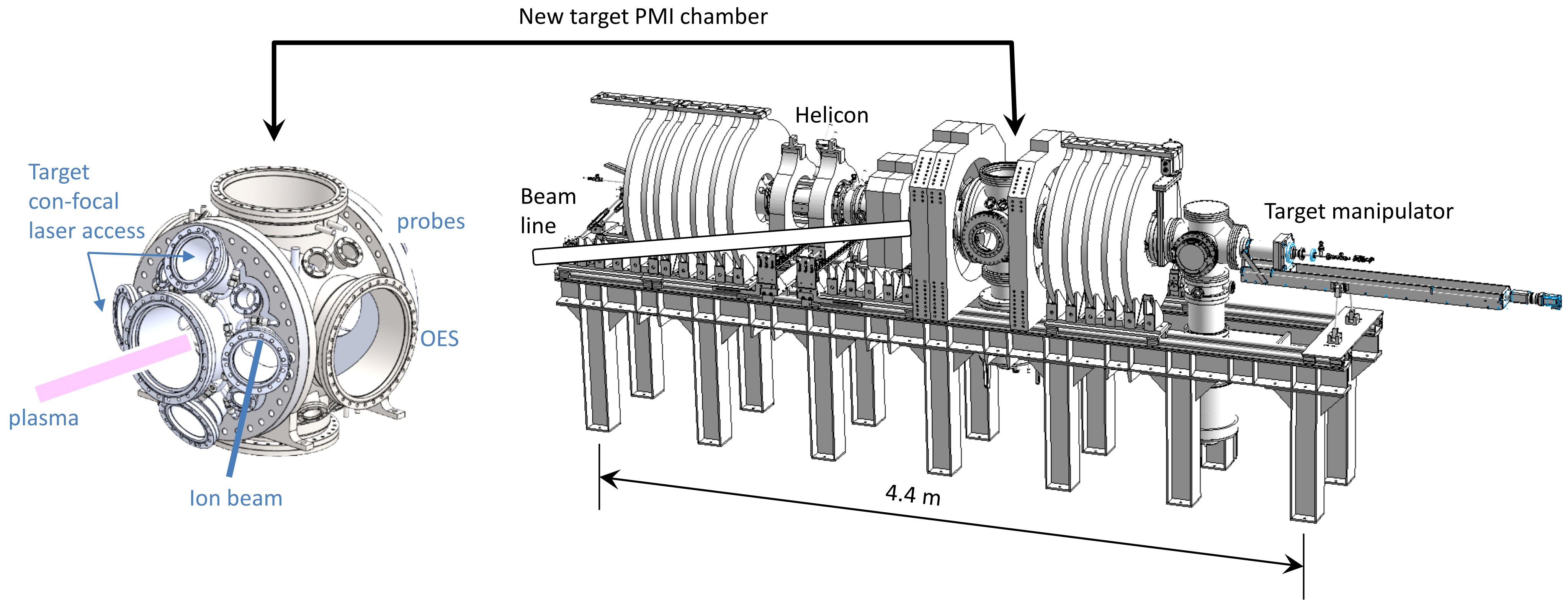
CAD model

At 20 kW, PISCES-rf produces D_2 & He plasmas ~10^{19} m^{-3}.



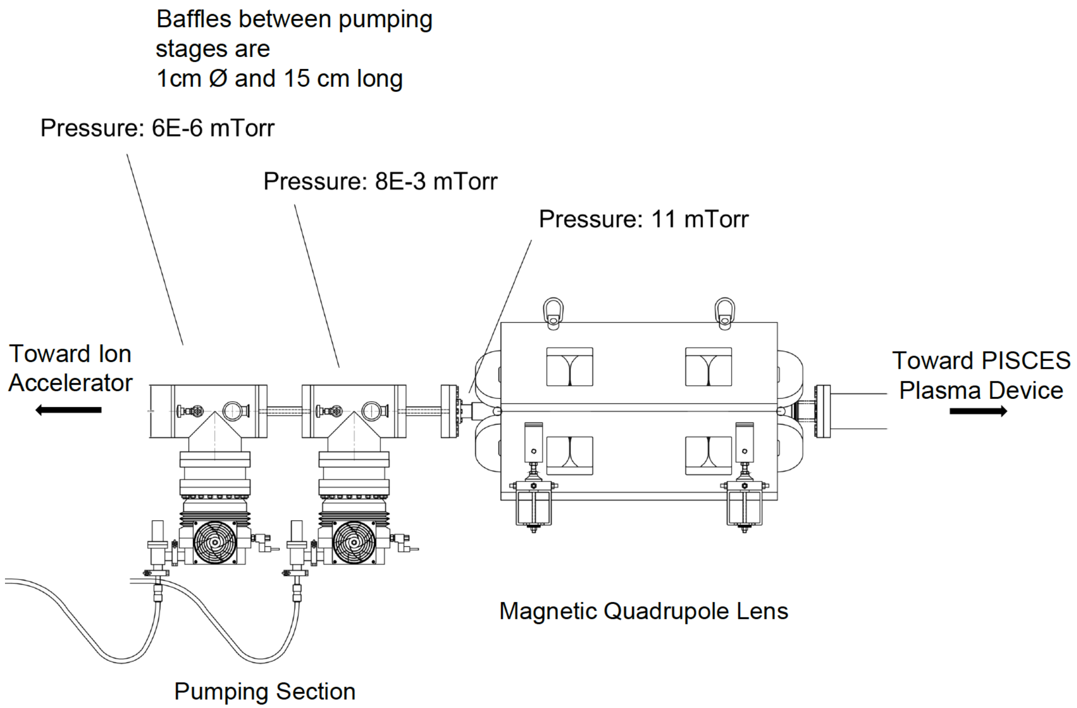


Will integrate 3 MeV accelerator w/ dual ion sources for **simultaneous plasma/displacement damage B-PMI** studies



PISCES Integrating 3 MeV Tandem-ion Accelerator for simultaneous plasma/displacement damage B-PMI Studies

9SDH-2 3 MV Pelletron for the production of simultaneous heavy ion damage in the first several microns of B-PMI targets



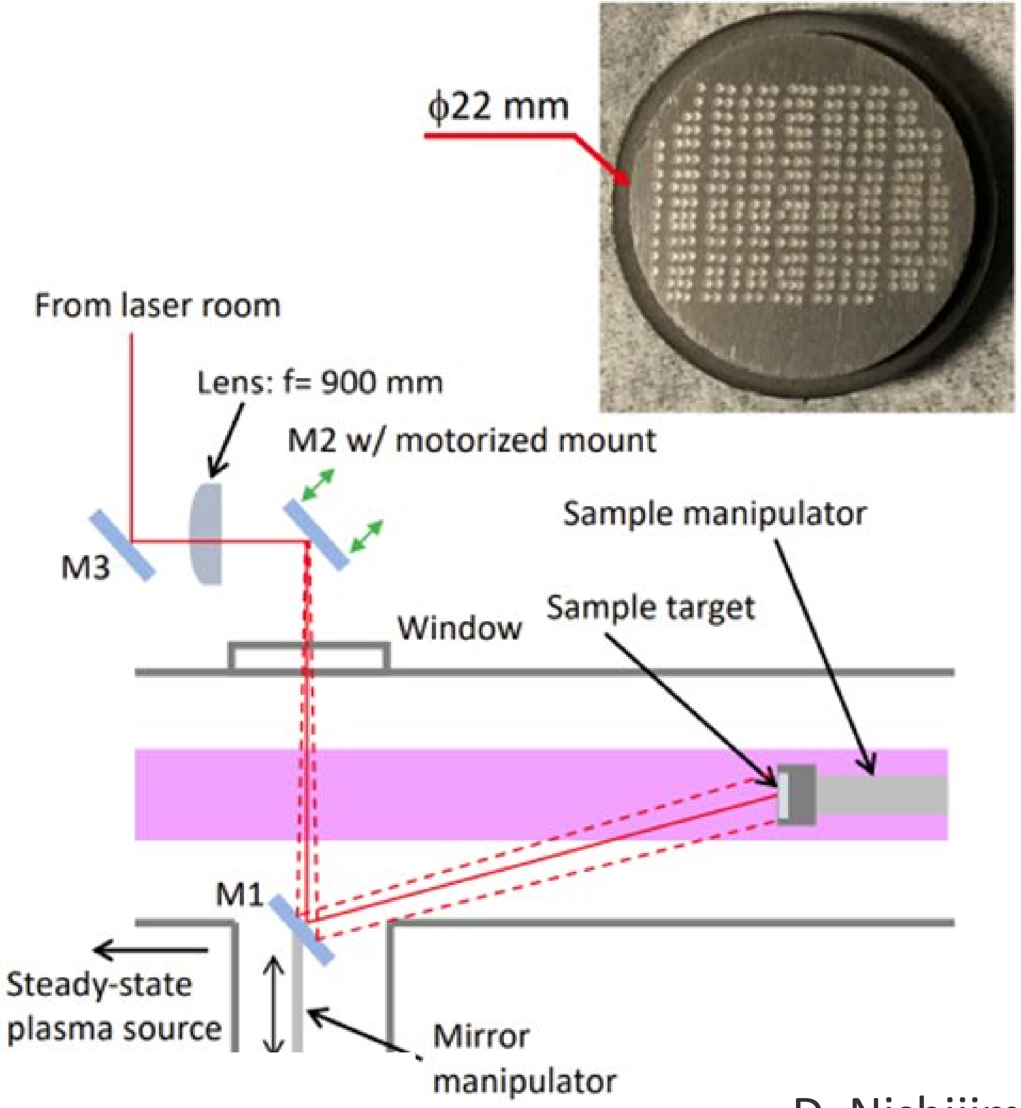
Differential pumping section and magnetic quadrupole focusing lens.

New diagnostics will include:

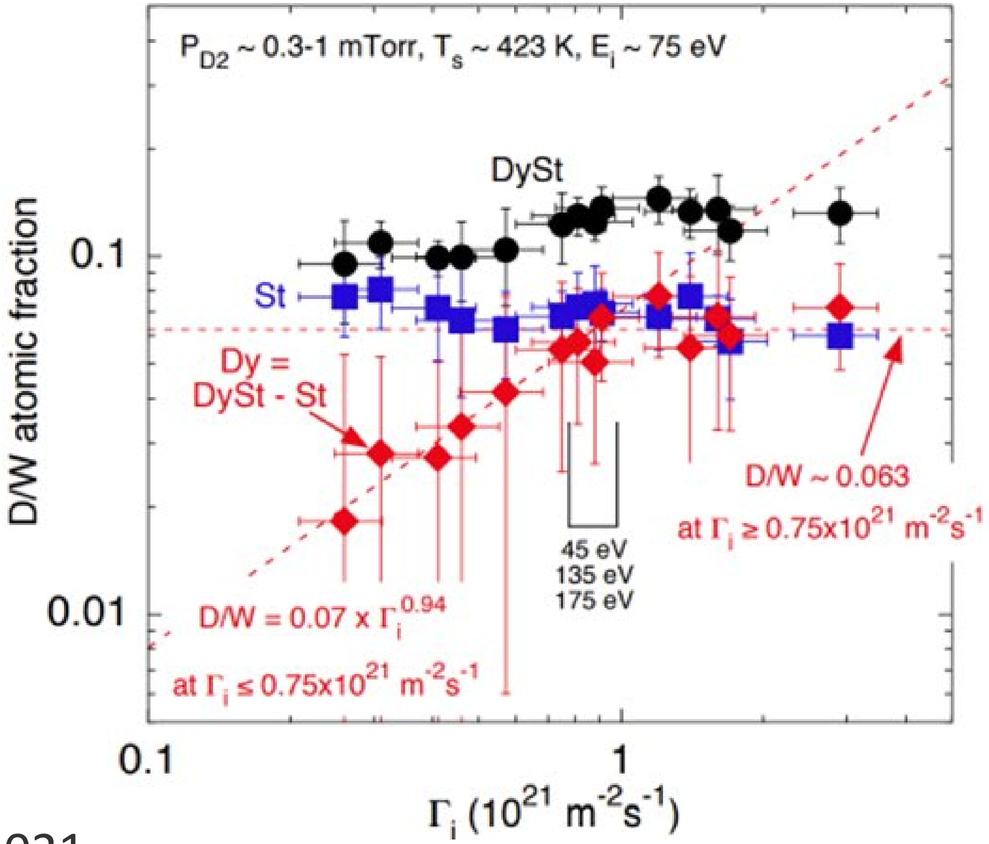
- LIBS-based In-situ In-operando Dynamic Gas Retention
- 2D Imaging Spectroscopy for In-situ In-operando Sheath/Pre-sheath & Erosion/Redeposition
- Transient Grating Spectroscopy (TGS) for In-situ In-operando Thermomechanical Properties
- Diffuse X-ray Scattering to Infer Defect Population & Density
- NRA for depth profiling, RBS for composition

In addition to existing tools: LP's, Vis. Spectroscopy, Witness Plates
Controlled Impurity Inj., SIMS, AES, SEM/TEM, ….

In-operando LIBS shows dynamic D retention increases with flux & saturates at high ion flux



- Dynamic retention is influenced by the sample temperature (348-573 K) and incident ion flux (0.26-2.9x10^{21} m^{-2}s^{-1}), while it does not depend on the incident ion energy (45-175 eV).



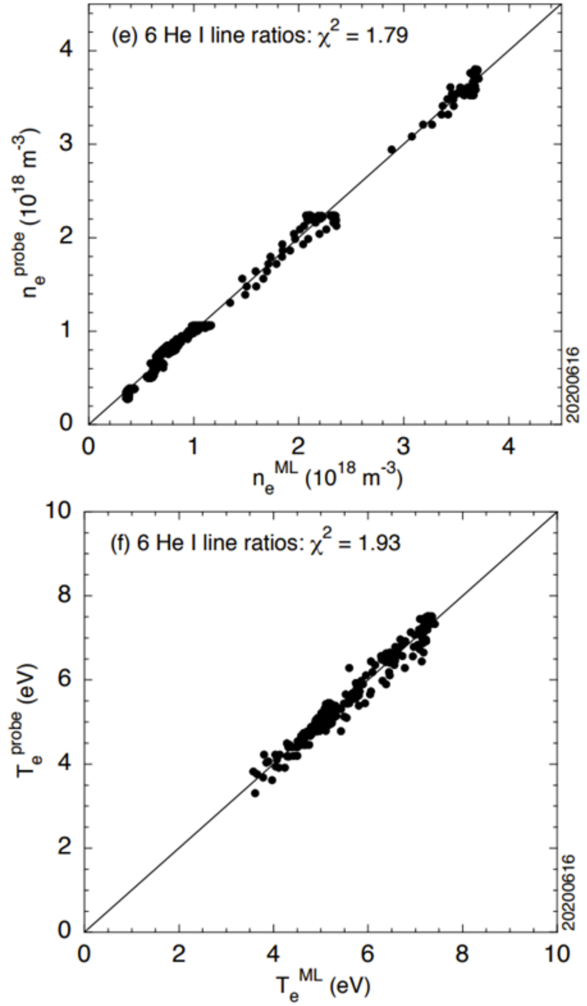
D. Nishijima *et al* NF 2021

2D spectroscopic imaging gives 2D plasma density N_e and temperature T_e for sheath/pre-sheath & erosion/redeposition studies

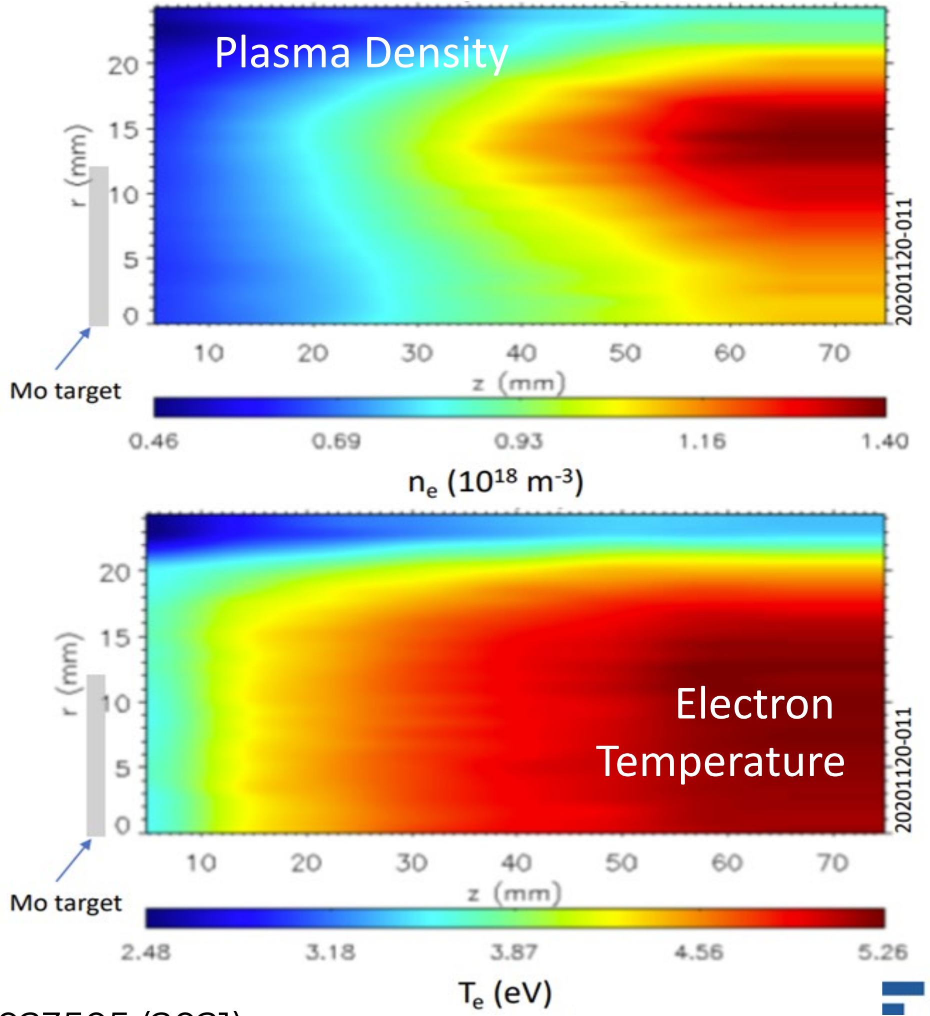
- **Training data**
  - Input: He I line ratios
  - Desired output: probe-n_e, probe-T_e

Machine learning (SVM regression analysis)

- **Predictive model**
  - n_e = f(He I line ratios)
  - T_e = f(He I line ratios)



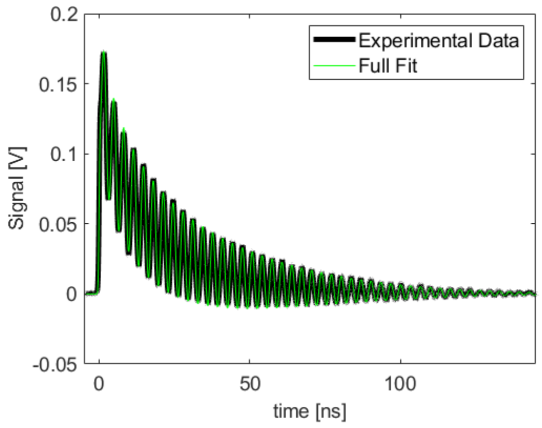
ML converted HSI - PISCES-A He plasma

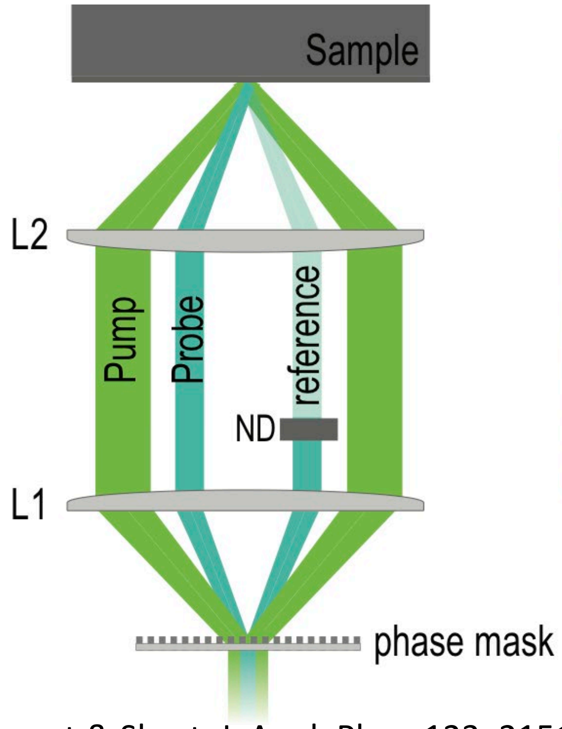


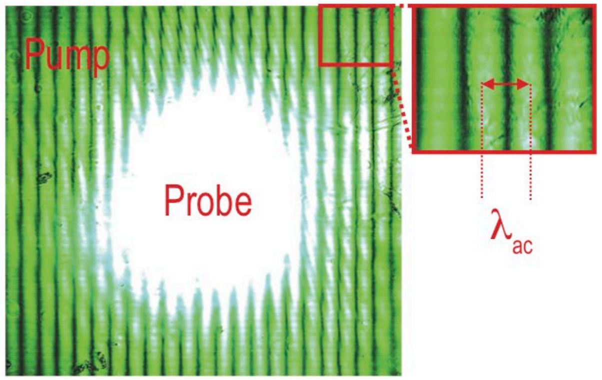
Nishijima *et al.*, Review of Scientific Instruments **92**, 023505 (2021)

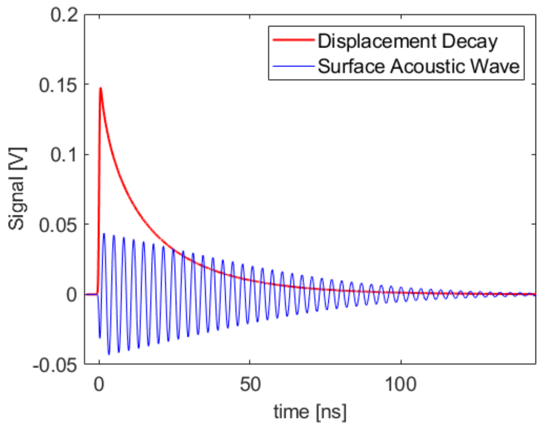
Transient Grating Spectroscopy (TGS): *in-situ real-time* nondestructive thermo-mechanical assessment of PFCs

- Phase Mask Splits Pulsed Laser
- Focused Pulsed Laser Interference Creates Transient Thermal Wave on Surface
- Probe Beam Measures Propagation & Decay of Surface Thermal Wave









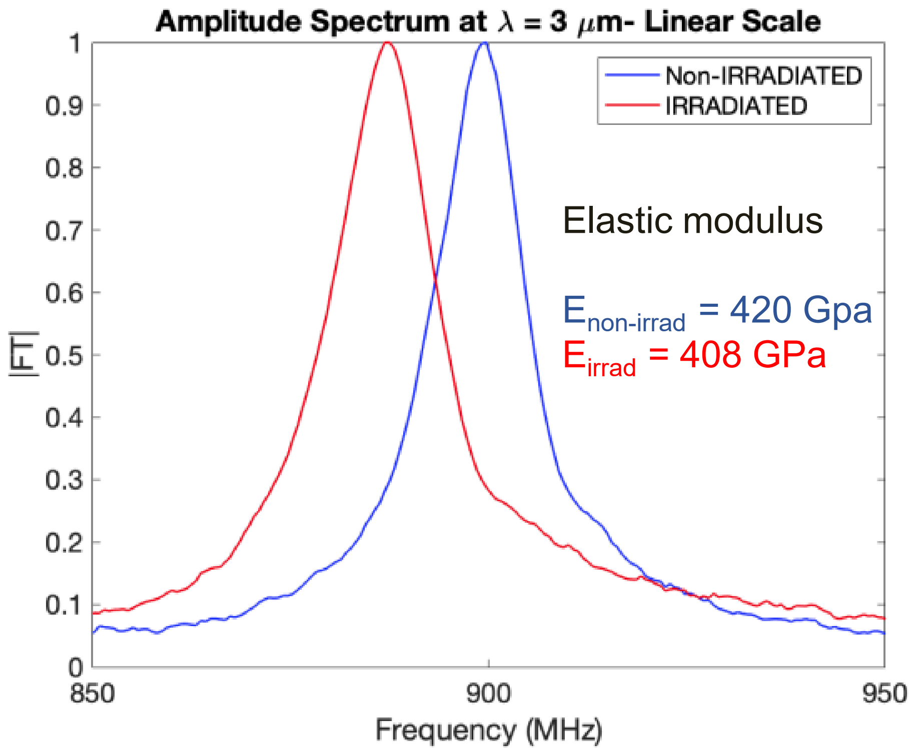
Dennet & Short, J. Appl. Phys. 123, 215109 (2018)

Near surface thermal diffusivity & elastic modulus from probe beam decay.

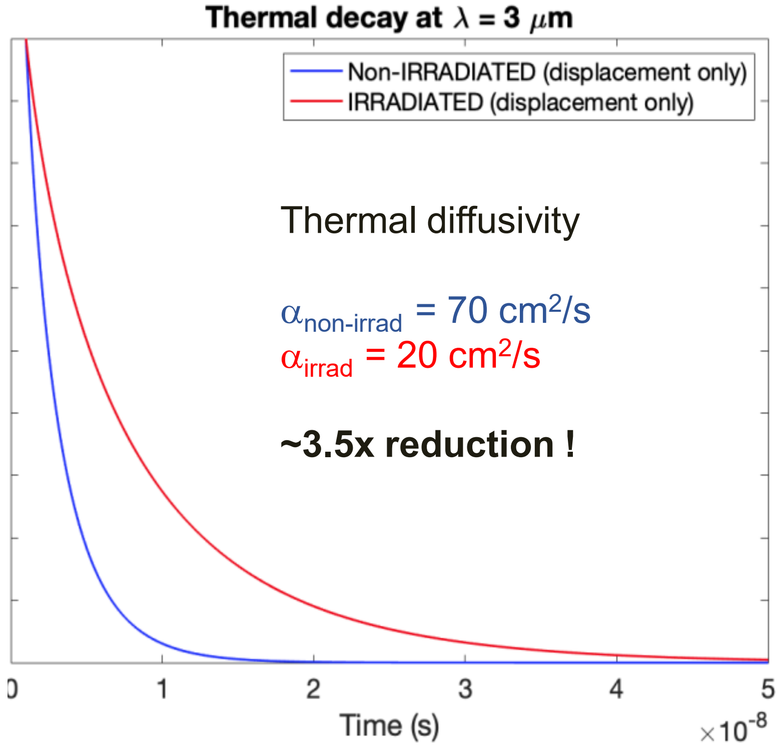
TGS shows changes in elastic modulus & thermal diffusivity in ion-beam damaged W samples

Elastic Modulus

- Fourier transform of the SAW.



Thermal Diffusivity

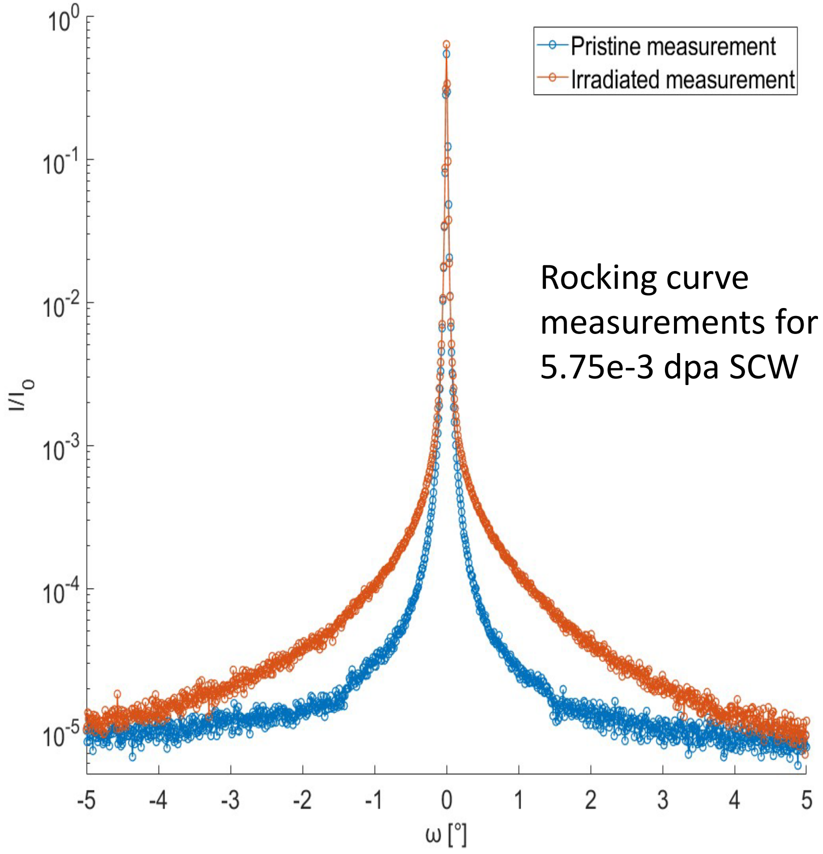


- Decay of phase grating

In-operando development on PISCES-RF will provide thermomechanical near-surface region measurements in a B-PMI conditions

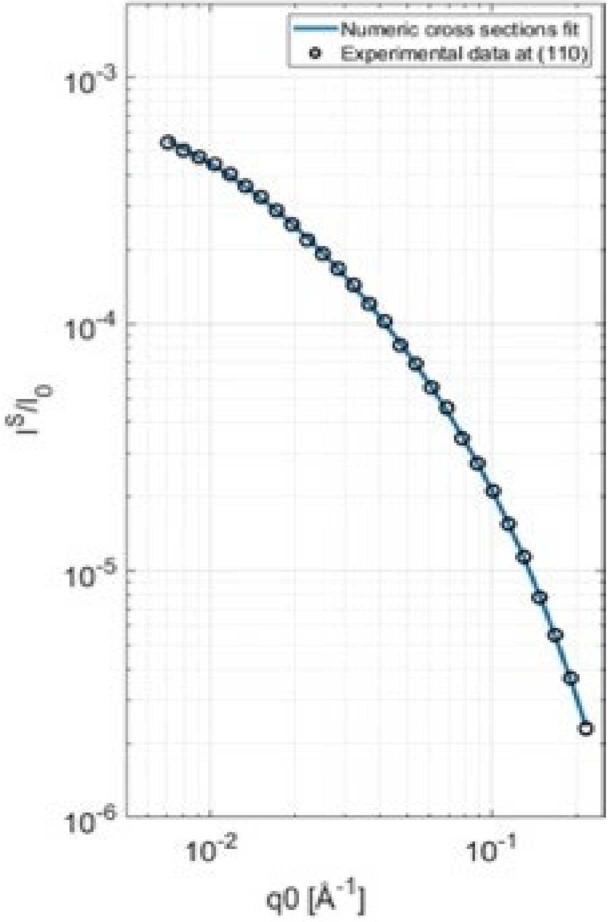
Diffuse XRD Gives Dislocation Loop Defect Population

Measured XRD Line Shapes

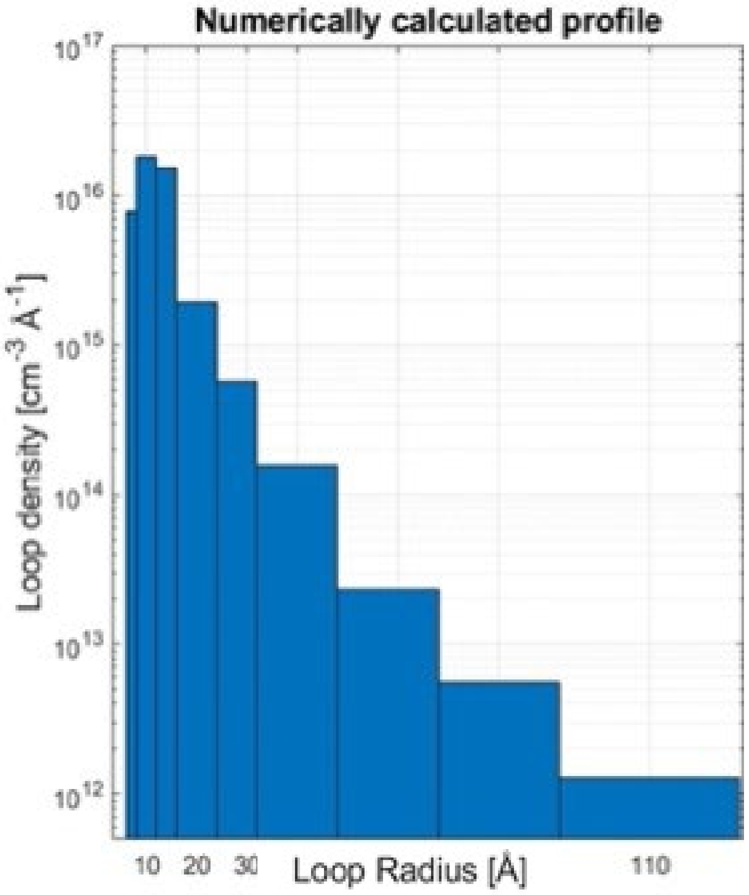


Rocking curve measurements for 5.75e-3 dpa SCW

Diff. Wavenumber Spectrum



Inferred Defect Population.



GOAL: Link atomistic-scale defects w/ retention & thermomechanical property evolution

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Thank you!