Session II: Joint PFC/MASCO Special Topics Session on Tungsten

Recent result of PMI activity in STAR facility, INL

Recent results from the collaborative research of deuterium behavior in neutron-irradiated and ion-damaged tungsten

Masashi Shimada

Fusion Safety Program, Idaho National Laboratory

www.inl.gov

Idaho National Laboratory

August 10 2011

2011 PFC meeting, Oak Ridge National Laboratory

Outline:

1. Motivation of this study
2. Deuterium depth profile from neutron-irradiated tungsten at 100, 200, 500 C
3. Comparison of neutron-irradiated and ion-damaged W at 200 C
4. Summary and future plans

US collaborators: Guoping Cao[1], Mikhail Sokolov[2]

[1]University of Wisconsin-Madison

[2]Oak Ridge National Laboratory

International Collaborators: Yoshio Ueda[3], Yuji Hatano[4], Yasuhisa Oya[5], Takuji Oda[6], Masanori Hara[4], Makoto Kobayashi[6], Beata Tyburska-Puschel[7]

[3]Osaka University, Japan

[4]University of Toyama, Japan

[5]Shizuoka University, Japan

[6]The University of Tokyo, Japan

[7]Institute für Plasmaphysik, EURATOM Association, Garching, Germany

Motivation:

- *Plasma-facing components (PFCs) will be exposed to 14 MeV neutrons from deuterium-tritium (D-T) fusion reactions in ITER, FNSF and DEMO.*
- *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, and >10 dpa in FNSF and DEMO*
- *There is NO high flux 14 MeV fusion neutrons source available at this moments*

- *The 2007 FESAC "Priorities, Gaps and Opportunities: Towards A Long-Range Strategic Plan For Magnetic Fusion Energy" report identifies:*
  - *"Understanding and quantifying the fusion source term will be required for licensing activities. Two fusion source terms with greatest uncertainty are dust and tritium."*
  - *"Qualification of fusion components in the fusion DEMO environment will be required to validate the design and to demonstrate safety roles of key components"*
  - *"Separate effects and integral irradiation testing in a fusion component test facility, fission reactors, particles accelerators, combined with ITER, could provide a portfolio to high damage (> 10 dpa) performance testing data for licensing case to qualify DEMO components"*

- *Challenges arise for both PFC and safety communities to understand tritium behavior (retention, diffusion, permeation) in neutron-irradiated PFCs and to establish reliable model without the experimental data from 14MeV neutron source.*

High energy ion beam…

- Has been used to simulate displacement damages by 14 MeV fusion neutron
- Has provided us the knowledge about hydrogen isotope behavior in the damaged PFCs (mainly in tungsten).
- Indicated that the trap concentration will most likely saturate at > 1 dpa
  - Estimated ~ 1 at. % T/W at 0.7 dpa (the end of ITER operation) [1]
- Indicated also that T will most likely stay with in a few micro meter [1]
  - "No data is available that give D retention at displacement damage in tungsten from exposure to plasma at depths greater than a few microns."
- Resent studies(Tyburska09JMN&11JMN, Wright10JNM, Wampler09NF, Ogorodnikova11JNM) support
  - The saturation around 1 (0.5-1.5) at. % T/W using different ion species
  - Very small D retention from damaged W at high exposure temperature (> 500C= 773 K)
- QUESTION: ------> How similar is the high energy ion to neutron?

Reference:

[1] MIT report PSFC/RR-10-4, "An Assessment of the Current Data Affecting Tritium Retention and its Use to Project Towards T Retention in ITER", Lipschultz, B.et. al.,.1April 2010

Neutron vs. high energy ion

Species	Neutron	High energy ion
Damage profile	Uniform	Up to a few μm steep gradient at the end of ion range
Damage rate [dpa/s]	10^{-7}-10^{-8} (3.5×10^{-8} for ITER [2])	10^{-3}-10^{-4}
Transmutations	Yes (W => Ta, Re, Os, etc.)	No
Radiation	Yes (2.0 MeV β^- from ^{188}Re, 0.5 MeV γ from ^{185}W etc.)	No
Max. PKA energy [keV] in W	~ 50 (for 2.5 MeV n_{DD}) ~ 300 (for 14.1 MeV n_{DT})	2000-20000 (for 2.8-20 MeV Si^{2+}, Fe^{2+}, W^{4+}) 15- 60 (for 700~800 keV H^- and He^{2+})

- ✓ Need to identify what the high energy ion can/can not simulate
  - We need ion bombardment simulation for DEMO type higher dose (>10 dpa) damage due to the high damage rate and no activation nature of ion beam simulation
  - The damage rate and irradiation temp. influence void swelling and dislocation loop density [3,4]

Reference

[2] H. Iida, V. Khripunov, L. Petrizzi and G. Federici, *2004 ITER Nuclear Analysis Report* G 73 DDD 2 W 0

[3] T. Muroga et.al., *Journal of Nuclear Materials*, v.155-157 (1988) 1290

[4] T. Muroga et.al., *Journal of Nuclear Materials*, v. 174 (1990) 282

Alternate approach….. Fission neutron

- Has been used for R&D of fission and fusion materials (mainly structural)
- Can provide the information that the high energy ion can not deliver
  - Displacement damages deep in bulk materials
  - Radiation (radiation enhanced phenomena)
  - Transmutation (W --> Re, Os, Ta, etc.)
  - Similar (but a little lower) PKA energy spectrum by fast neutrons
  - Similar damage rate (10^{-7}~10^{-8} dpa/s vs. 3.5×10^{-8} dpa/s for ITER [2])
- Fission reactor can have fairly large fraction of fast (>0.1 MeV) neutrons
  - ex.) ~20 % in HFIR vs. 65 % in DT ITER
- Of course there are drawbacks
  - Safety concern due to the high radiation (from especially tungsten)
  - Complex radiochemistry in the reactor (radiation enhanced phenomena, contaminations, aqueous environment)
  - Different transmutation and He production rate
  - Effects of high thermal neutron flux
  - Expensive and long cooling time
  - Hydrogen implantation experiments is typically not in hot cell --> risk of exposure to worker
- No tritium retention data from fission neutron-irradiated materials

Question:------> Don't we need data from actual neutrons?

Experiment

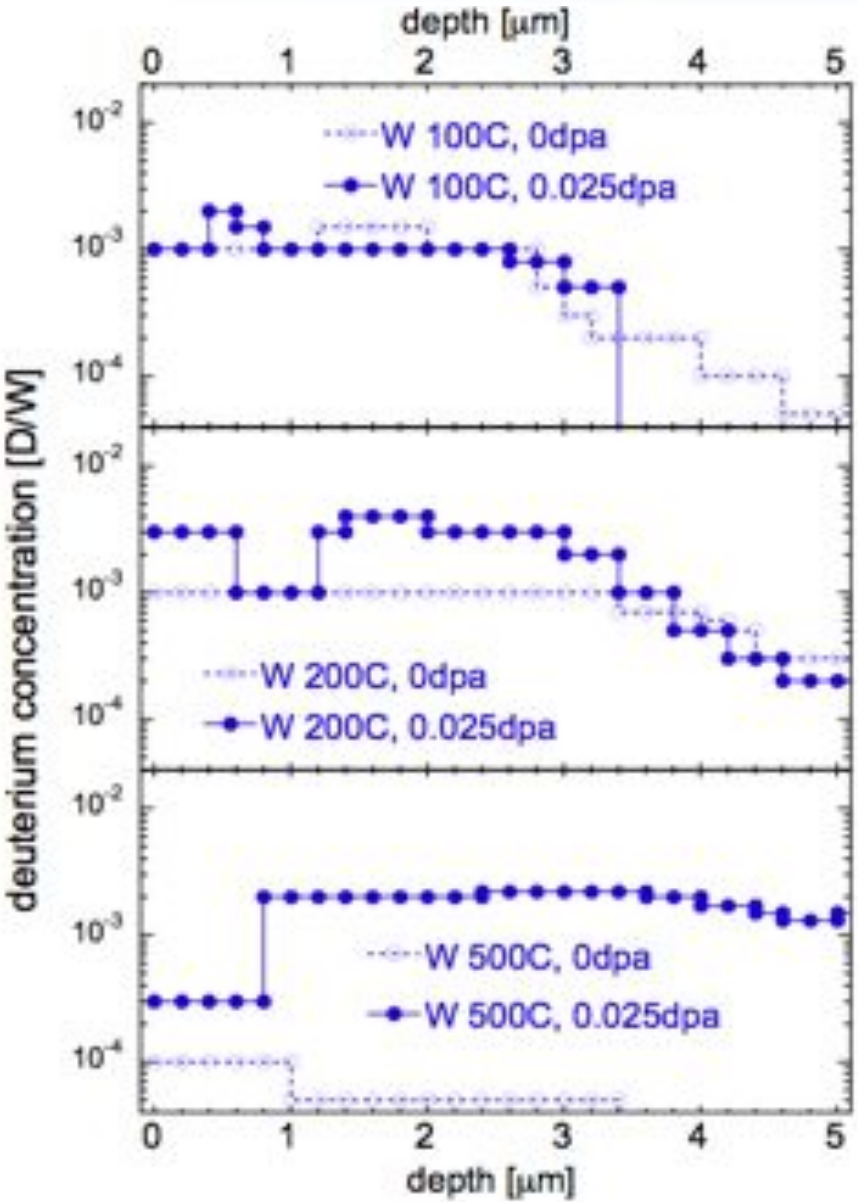
"Deuterium Depth Profiling in neutron-irradiated W"

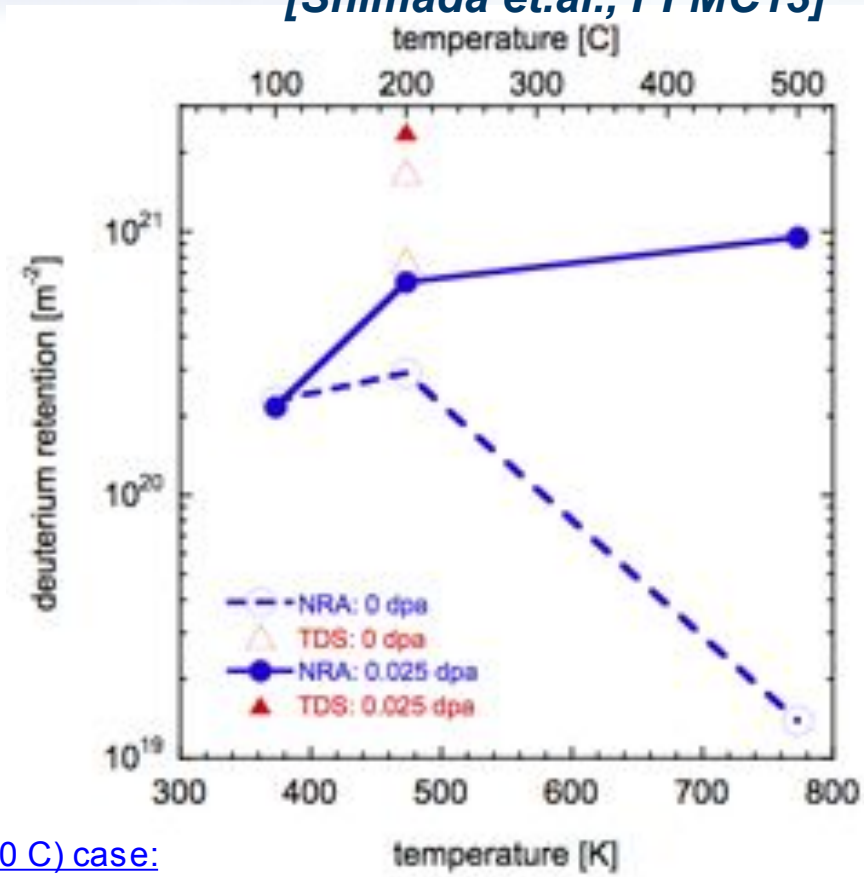
[Shimada et al., JNM'11 (article in press), Shimada et.al., PFMC13]

- Material tested:
  - Tungsten (A.L.M.T. SR: ϕ 6mm x 0.2mm, mirror-polished on both side)
- Methodology:
  - Samples preparation:
    - W samples were sealed in Mo envelope ,and Al capsule/rabbit
  - Neutron-irradiation at HFIR, ORNL:
    - T9A1 rabbit at cycle 419, Hydraulic tube facility (location:B3-5)
    - 33 hour at 323°K (50C) to reach the damage creation of 0.025 dpa
    - Thermal neutron flux/fluence:
      - ~2.5×10^{19} n/m^{2}s /~ 3.0×10^{24} n/m^2
    - Fast neutron (>0.1MeV) flux/fluence:
      - ~8.9×10^{18} n/m^{2}s /~ 1.1×10^{24} n/m^2
  - Deuterium plasma exposure at TPE, INL, subsequently TDS or NRA
- TPE conditions:
  - Ion flux: (5-7)x10^{21} m^{-2}s^{-1}, ion fluence: (5-7)x10^{25} m^{-2}, bias: -100V
  - Sample temperature: ~ 100C (373K), 200C (473K), and 500C (773K)

Deuterium Depth Profiling in neutron-irradiated W

[Shimada et.al., PFMC13]





373K (100 C) case:

- D is trapped to 3 μm and (0.1-0.2) at.% D/W in 0.025 dpa
- Similar D/W concentration from 0 dpa to 0.025 dpa

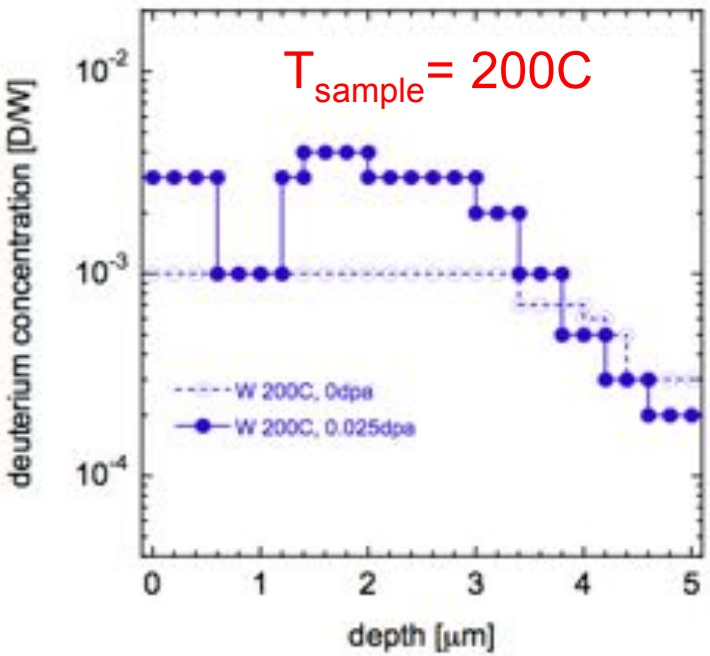
473K (200 C) case:

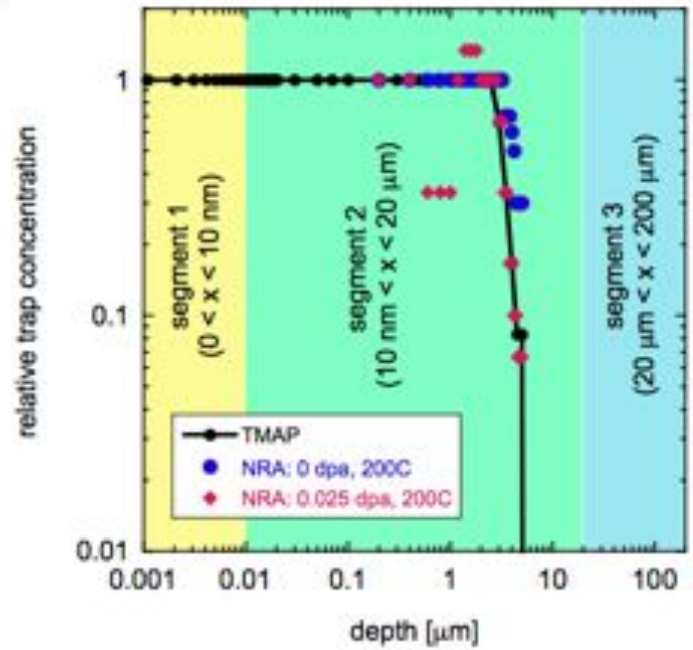
- D is trapped to 3 μm and (0.2-0.4) at.% D/W in 0.025 dpa
- (x2~4) higher D/W concentration in 0.025 dpa

773K (500C) case:

- D is trapped to >5 μm and (0.1-0.3) at.% D/W in 0.025 dpa

TMAP7 simulation of TDS spectrum at 200C





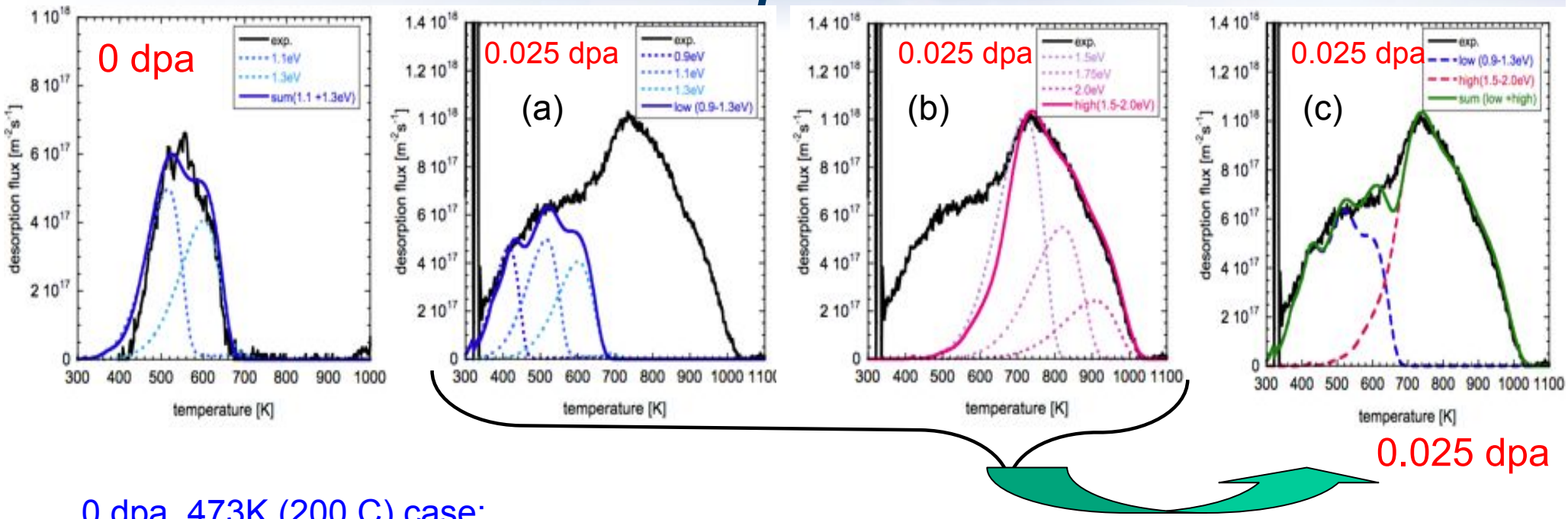
Assumptions:

- Use the experimentally obtained deuterium depth profile
- Set very low trap concentration (D/W=10^{-5}) in deeper bulk (x > 5 μm)
- Frauenfelder's Diffusivity
- R. Anderl's Recombination Coefficient
- Traps are fully filled with deuterium from surface (saturable traps only)

Parameters in the simulation

- Vary the trap concentration (10^{-4}<D/W<10^{-1}) of the normalized profile(< 5 μm)
- 6 different detrapping energy traps are used (0.9, 1.1, 1.3, 1.5, 1.75, 2.0 eV)

TMAP7 simulation of TDS spectrum at 200C



0 dpa, 473K (200 C) case:

- Two traps (1.1 eV and 1.3 eV) with 0.17 and 0.15 at.% D/W give reasonable fit TDS
- Combined trap conc. (0.3 at.%) is higher than the D/W (0.1-0.2 at.%) by NRA

0.025 dpa, 473K (200C) case:

- Six traps (0.9 ~ 2.0 eV) with (0.14~0.45) at.% D/W are required to fit TDS
- Combined trap conc. (1.3 at.%) is higher than the D/W (0.2-0.4 at.%) by NRA
- Four (0.9, 1.5, 1.75, 2.0 eV) traps are induced by neutron-irradiation, indicating that different trapping mechanisms exist for neutron-irradiated and non neutron-irradiated tungsten. Further investigation is needed.

Comparison of ion-damaged with neutron-irradiated W

[Fe^{++} data: Y. Oya, M. Shimada, et.al., PFMC13]

UNPUBLISHED RESULTS: FOR YOUR EYES ONLY

INTENTIONALLY LEFT IN BLANK

- Identical tungsten sample were used.
  - Tungsten (A.L.M.T. SR: ϕ 6mm x 0.2mm, mirror-polished)
  - Similar to ITER grade: drawing direction perpendicular to the plasma exposed surface
- Exposed to the identical conditions in the same linear device
- Desorbed in the identical conditions (10K/min to 900C) in the same TDS system
- High energy ion-damaged samples
  - 2.8 MeV Fe^{2+} (0.027, 0.3, 3.0 dpa) provided by T. Oda, The Univ. of Tokyo
  - 20 MeV W^{4+} (0.3, 3.0 dpa) provided by B. Tyburska-Puschel, IPP
  - 700 keV H^- (0.48 dpa) provided by Y. Ueda, Osaka Univ.

Comparison of ion-damaged with neutron-irradiated W

UNPUBLISHED RESULTS: FOR YOUR EYES ONLY

INTENTIONALLY LEFT IN BLANK

- Comparison of ion-damaged with neutron-irradiated W shows:
  - HFIR neutron produces the broad TDS spectrum (300-1000 K)
  - Fe^{++} reproduces the lower temperature TDS peaks (300-700 K)
  - H^{-} and W^{++} reproduce the medium temperature TDS peaks (450-900 K)
- D retention from 0.025 dpa HFIR neutron is similar to that from 3.0 dpa Fe^{++} and W^{++}
  - Despite the 2 orders of magnitude difference in dpa

Summary and future work

Importance to NOTE that

- This is based on the only first set (0.025 dpa) of experimental data from neutron-irradiation tungsten in fission reactor.
- Therefore, NO conclusions should be drawn from this set of data. (especially estimate/implication for ITER)

- Further investigation is absolutely necessary, especially…
  - Need to test more neutron-irradiated tungsten
    - The second set (0.3 dpa) of neutron-irradiated W will begin in Sep. 2011
  - The effort to correlate various high ion energy simulations (H^-, He^{2+}, Si^{2+},Fe^{2+}, W^{2+}, W^{4+}) and identify what each ion can/cannot simulate.
  - Without 14 MeV fusion neutron source available at this moments, we need to even utilize any neutron source available to study tritium behavior in PFCs in higher (>10 dpa) dpa *for licensing case to qualify FNSF and DEMO components*.
- Conclusion:
  - The effort to correlate among high-energy ions, fission neutrons, and fusion neutrons (or whatever neutron source) is absolutely crucial for understanding tritium behavior (retention, diffusion, permeation) under a neutron-irradiation environment.

Thank you very much for your attention.