Plasma Material Interactions : Institutional Overviews

Idaho National Laboratory

Masashi Shimada and Brad Merrill
Idaho National Laboratory

www.inl.gov

Idaho National Laboratory

U.S. DEPARTMENT OF ENERGY
Office of Science

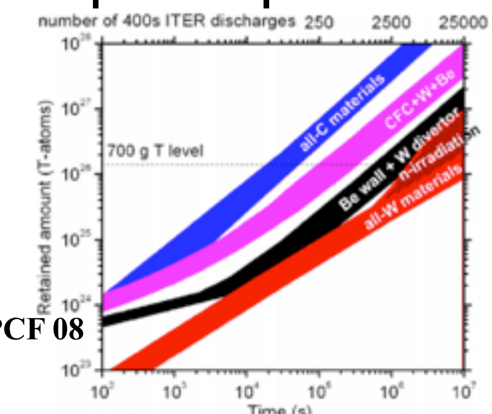
STI Number: INL/MIS-16-39668

Outlines

- **Motivation of PMI research at INL**
- **Upgrade in PMI research capabilities at STAR**
- **Recent research progress at STAR**
- **Future plans**

Tritium safety R&D: In-vessel tritium source

- **To minimize the uncertainty in in-vessel tritium source term assessment for ITER D-T and beyond.**
  - Our challenge is to understand synergy of multiple separate effects on tritium retention in D-T operation
    - **"hydrogen isotope loading"**
    - **"helium loading"** and
    - **"neutron-irradiation effects"**
      - **Radiation damage**
      - **Gas and solid transmutation by neutron**



Ref: J. Roth PPCF 08

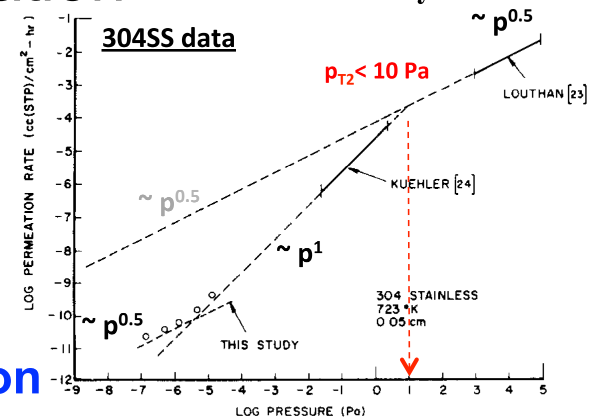
  - Our research approach is to perform sequential separate effect experiments.
  - International collaborations & programs on these topics:
    - US-Japan PHENIX program (Apr. 2013 – Mar. 2019)
    - IAEA Coordinated Research Program on irradiated tungsten (Nov. 2013 – Oct. 2018)
    - IEA IA Environmental, Safety and Economic Aspects of Fusion Power (ESEFP) Task 1.

Ref: J. Roth, PPCF 2008

Tritium safety R&D: Ex-vessel tritium release

- **To minimize the uncertainty in ex-vessel tritium release assessment for ITER D-T and beyond.**
  - Our challenge is to understand synergy of multiple separate effects on tritium permeation in D-T operation
    - **"low tritium partial pressure"**
    - **"hydrogen effects"**
    - **"surface effects" and**
    - **"neutron-irradiation effects"**
      - **Radiation damage**
      - **Gas and solid transmutation by neutron**

Ref: A.S. Zarchy JNM79



  - Our research approach is to perform sequential separate effects experiments.
  - International collaborations & programs on these topics:
    - US-Japan PHENIX program (Apr. 2013 – Mar. 2019)
    - KO NRFI-UCLA-INL collaboration Phase I (July 2013 – July 2016)
    - KO NRFI-UCLA-INL collaboration Phase II (July 2016 – July 2020)

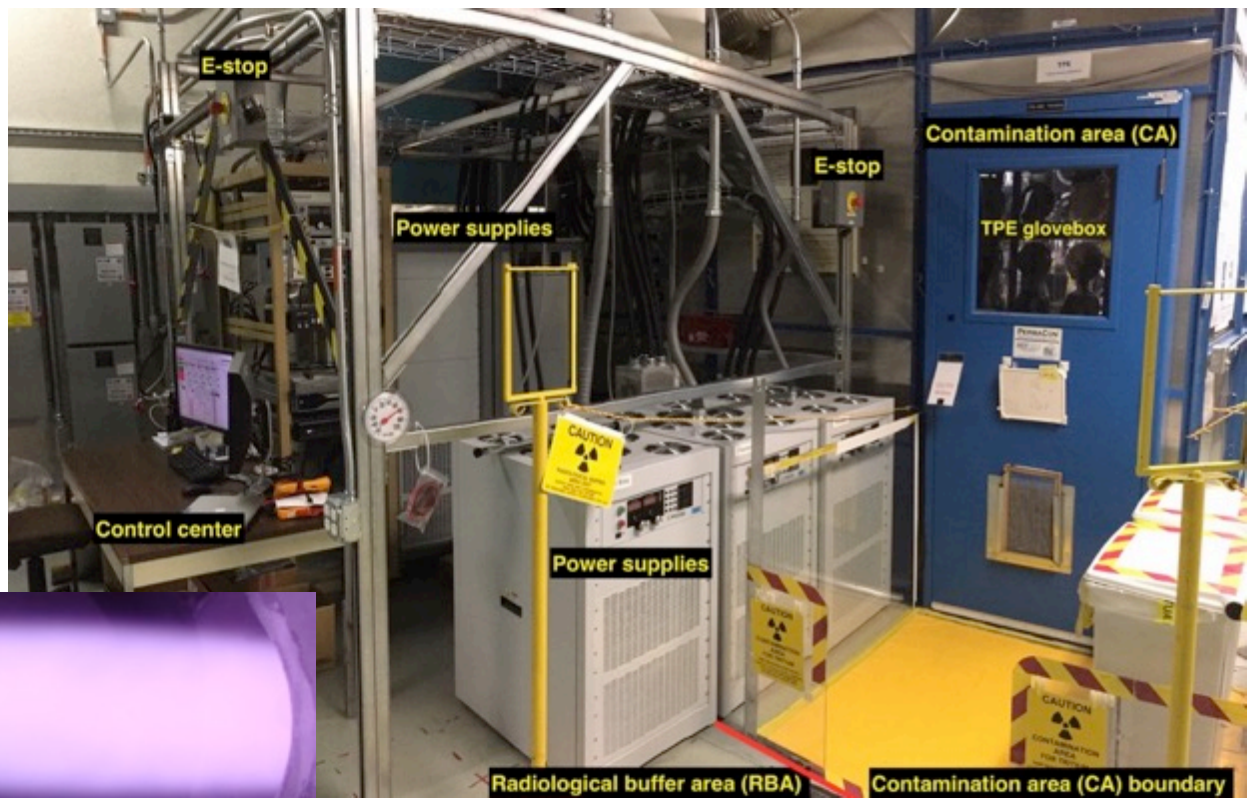
Ref: J. Roth, PPCF 2008

Outlines

- Motivation of PMI research at INL
- **Upgrade in PMI research capabilities at STAR**
- Recent research progress at STAR
- Future plans

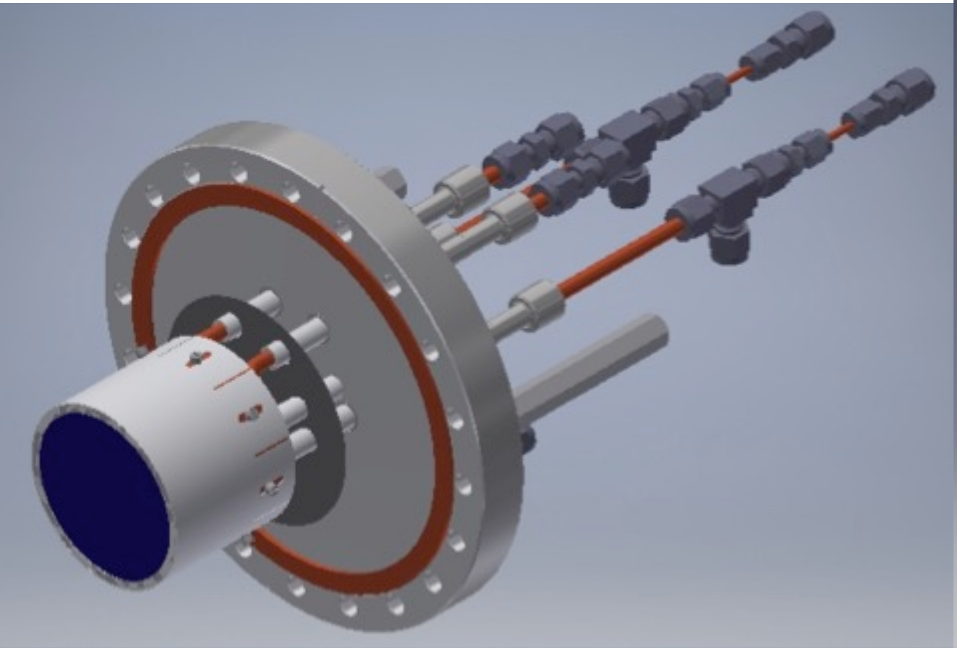
TPE upgrade

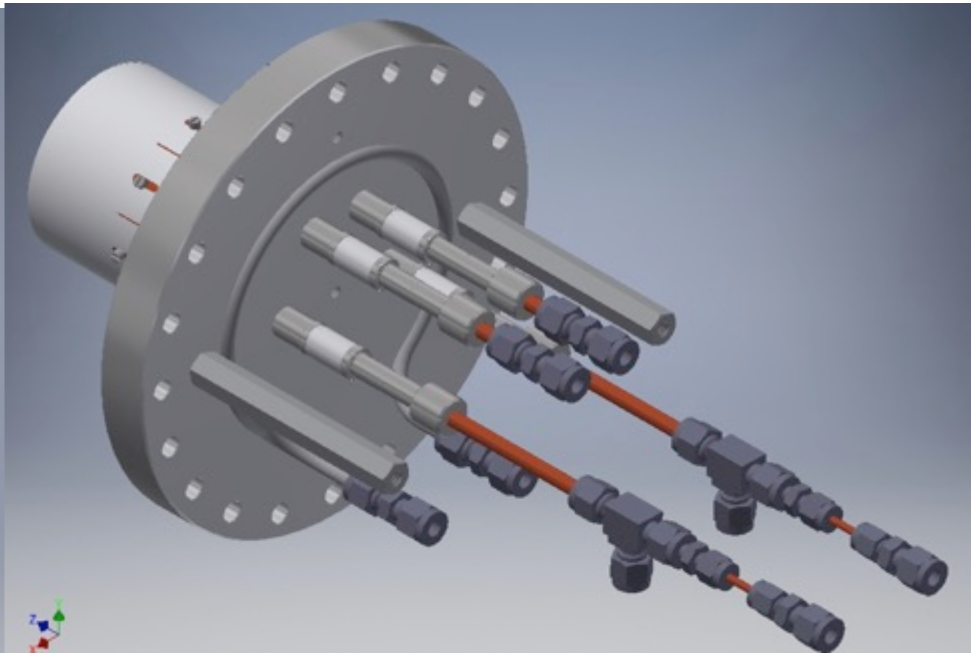
- A decision was made in FY2013 to set up new power supplies and the control room outside of PermaCon/CA in order to enhance operational worker safety.
- In November 2015, the TPE achieved its first deuterium plasma using the new control center outside of the CA after a significant three-year upgrade.



Development of new plasma source

- **A new plasma generator is being developed based on the UCSD PISCES plasma source**
- **The objective is to be able to meet ampacity requirements with the new power supply**
  - 125% x 750 A (maximum current of PS#1) =937.5 A
  - Utilize a water-cooled Cu bus conductor to minimize size





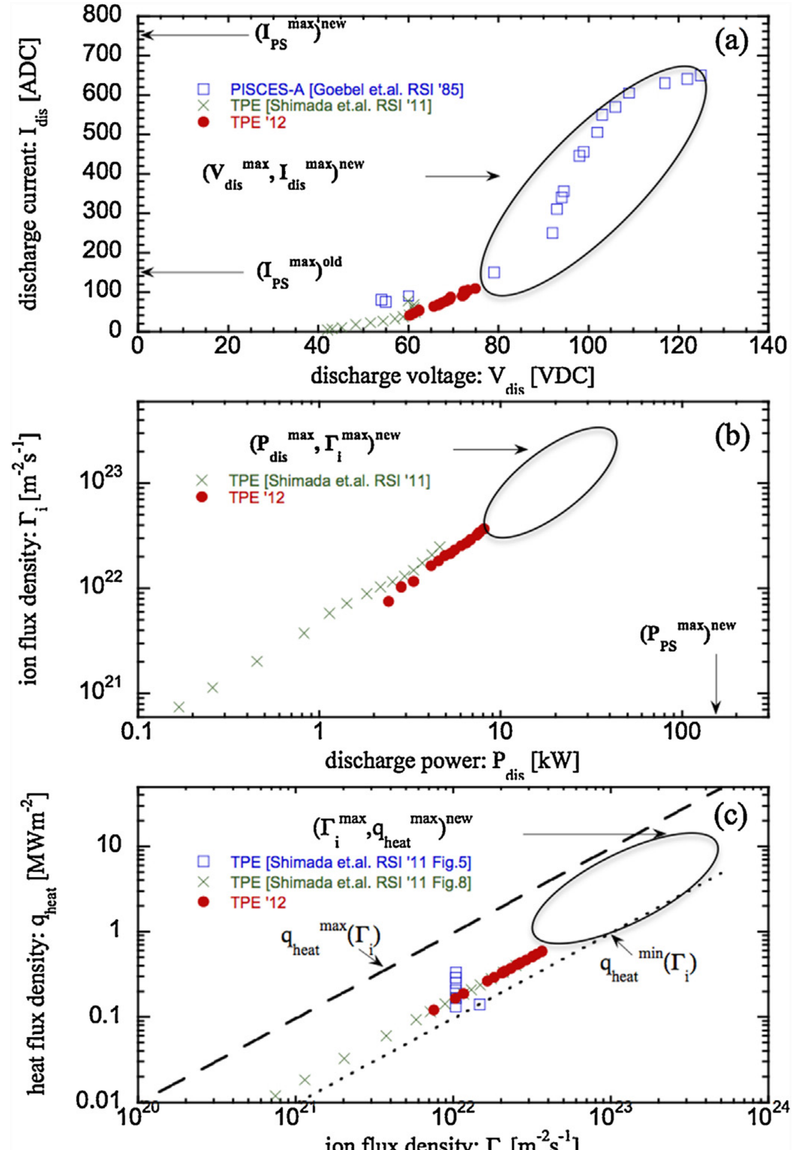
Simple estimate for expected ion flux density and heat flux after TPE upgrade

- With new power input capability, a simple linear scaling estimate showed that the TPE will be capable of reaching
  - $n_{e,max}$ $>1.0\times10^{19}\ m^{-3}$
  - Γ_{max} $>1.0\times10^{23}\ m^{-2}\ s^{-1}$
  - q_{heat} $>1\ MW\ m^{-2}$

Table 2
Summary of expected discharge performance, ion flux density, heat flux with new power supplies.

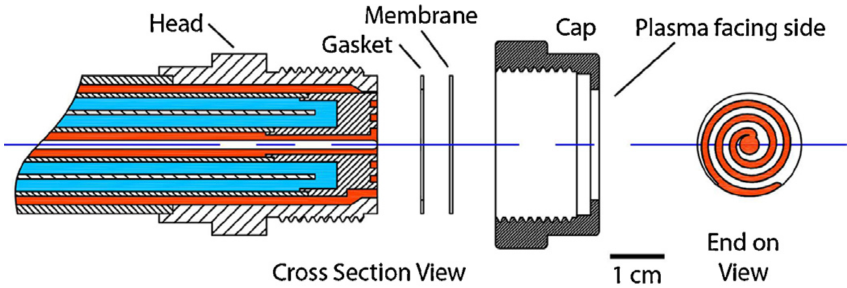
Parameters	TPE (old PS)	TPE upgrade (new PS)
I_{dis}^{max} [ADC]	100	>200
P_{dis}^{max} [kW]	10	>20
V_{bias}^{max} [VDC]	−200	−600
Γ_i^{max} [$m^{-2}\ s^{-1}$]	0.4×10^{23}	$>1.0\times10^{23}$
q_{heat}^{max} [$MW\ m^{-2}$]	0.6	>1

Ref: M. Shimada et.al., FED 2016

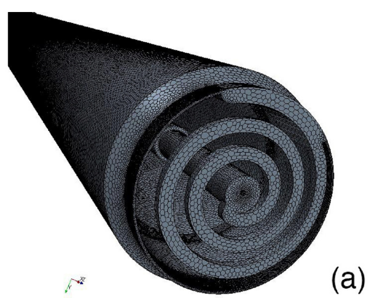


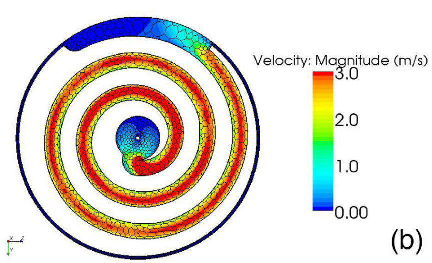
Improvement in plasma diagnostics in TPE

- **List of plasma and tritium diagnostics in TPE**



Diagnostics in the TPE	Tritium detection
Single probe Langmuir probe (ϕ=1 mm, L=2mm)	No[a]
Fixed range high-resolution spectrometer (Ocean Optics HR-4000, 580nm <λ< 680nm)	Yes
Czerny-Turner spectrometer (Andor Tech. Shamrock 750, 750mm, f/9.7) with 1024x255 pixels CCD (Andor Tech. DU420A-BV)	Yes
Tritium ion chambers (Tyne Engineering 10 cc and 1000 cc ion chamber)	Yes
Plasma-driven permeation system with 1000 cc ion chamber (Tyne Engineering 1000 cc ion chamber)	Yes

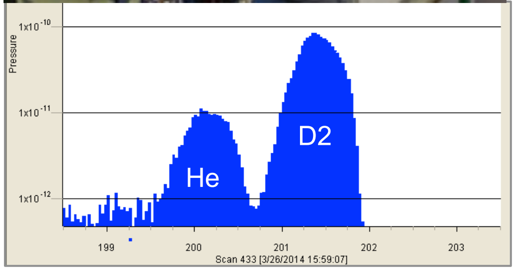




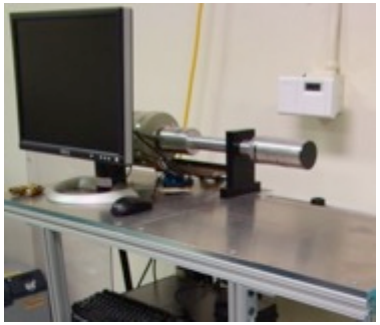
Ref: D.A. Buchenauer et.al., FED 89 (2014)

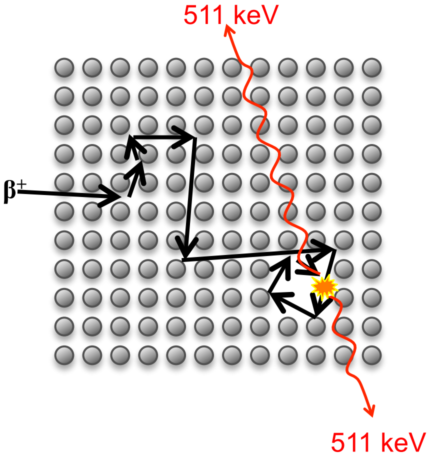
Improvement in surface diagnostics

- List of diagnostics for tritium and radioactive samples at STAR



Diagnostic at the STAR facility	Handling tritium exposed sample	Handling radioactive sample[f]
Thermal desorption spectroscopy with 1-100 amu and 1-6 amu quadrupole mass spectrometers (MKS eVision+ and IP Microvision)	Yes	Yes
Positron annihilation spectroscopy with a single high-purity germanium (HPGe) detector (Ortec GMX series)	Yes[a]	Yes
Optical microscope (Nikon Optiphot-100) with 2D CCD camera (PAXcam)	Yes	Yes
Liquid scintillation counter (Beckman LS6500)	Yes	No[b]
Imaging plate reader (Fujifilm FLA-7000)	Yes[c]	Yes[d]
Scanning Auger microscope (Perkin Elmer PHI 660)	Yes[a]	Yes
X-ray photoelectron spectroscopy (Perkin Elmer PHI 5400)	Yes[a]	Yes





- Improvement in plasma/surface diagnostics capabilities at STAR is currently one of FSP's focus areas to advance fusion nuclear science and to become a key facility to strengthen tritium science for DOE SC FES.

New surface diagnostics at STAR

- **Glow discharge optical emission spectroscopy**
  - Quantitative elemental depth profile analysis
  - Nanometer resolution
  - Can analyze 10s or even 100s μm sample depth
  - *Arriving late FY16*
- **X-ray photoelectron spectroscopy**
  - Surface sensitive chemical analysis
  - Excellent for quantification
  - Particularly useful for surface effects related to permeation
  - *Arriving FY17*
- **Scanning Auger electron spectroscopy**
  - AES provides elemental characterization
  - Scanning mode allows for microscopy
  - *Arriving FY17*

NOTE: all three diagnostics will be capable of handling low activation and tritium-exposed materials.

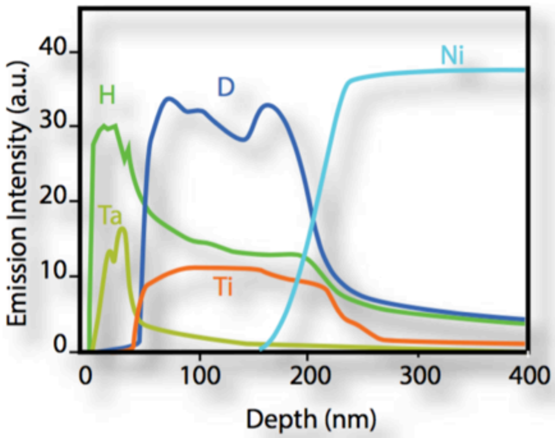
Glow discharge optical emission spectroscopy

Hydrogen

GD is one of the rare surface techniques capable of measuring H

The excellent optical resolution of the instrument even allows simultaneous measurements of H, and its isotope Deuterium, which is of great interest for nuclear research.

Ref: Fusion Engineering and Design 87 (2012) 1091– 1094



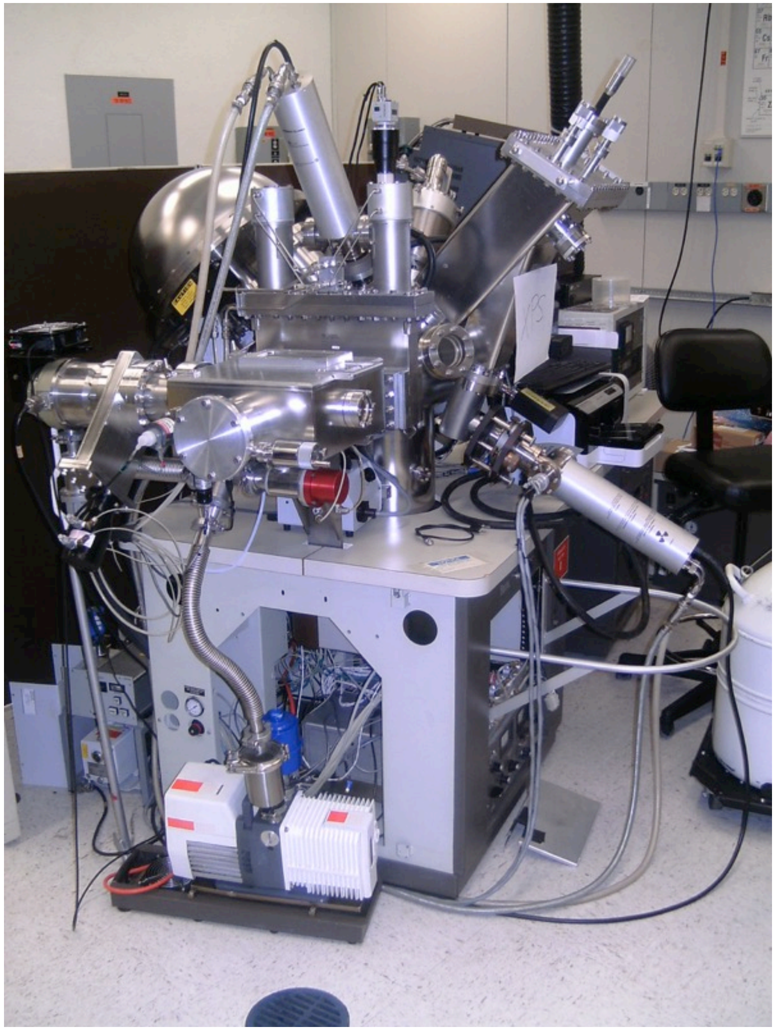
Will be delivered to STAR by Sept. 2016

GD-PROFILER 2

Made possible by generous support from INL Nuclear Science & Technology (NS&T) directorate

X-ray photoelectron microscopy

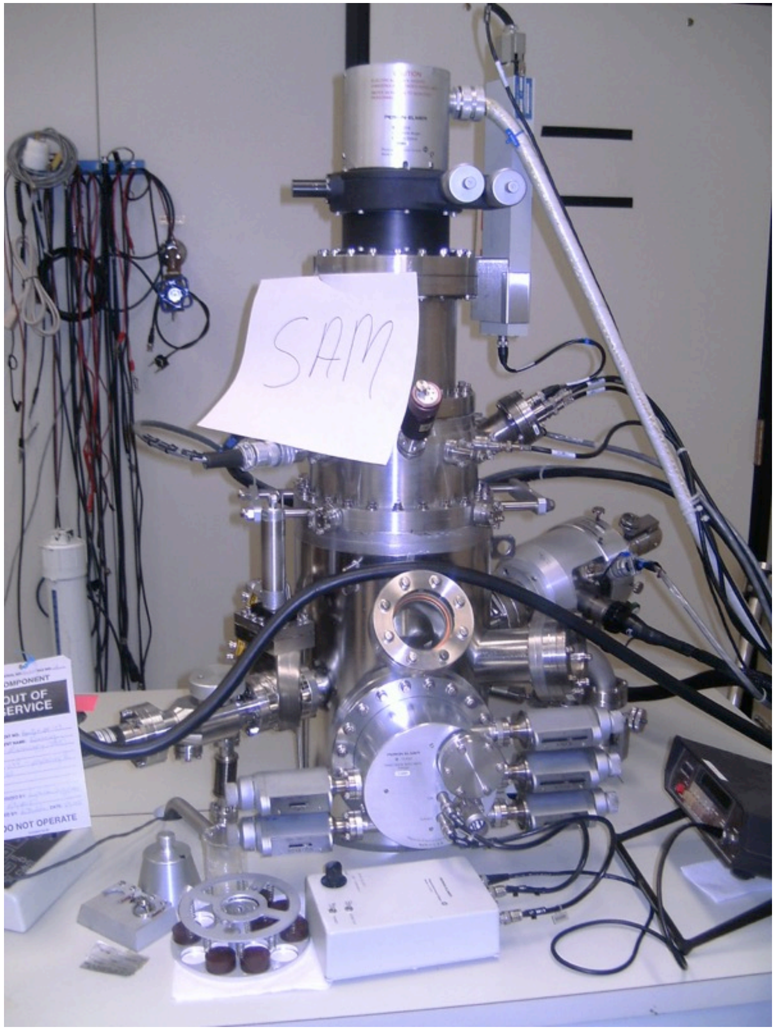
- **Technique**
  - Excellent chemical sensitivity.
  - Expansive libraries.
  - Capable of detecting elements, Li and larger.
- **Specifications**
  - X-ray monochromator for high resolution XPS scans.
  - Multiple x-ray sources.
  - Sputtering ion gun for depth profiling.



Currently located at the INL Research Center, and being relocated to the STAR facility

Scanning Auger electron spectro/microscopy

- **Technique: AES**
  - Excellent elemental sensitivity.
  - Limited quantification.
- **Technique: SAM**
  - Rastering electron beam +
  - Secondary electron detector =
  - SEM
- **Specifications**
  - LaB_6 filament.
  - Sputtering ion gun for depth profiling.



Currently located at the INL Research Center, and being relocated to the STAR facility

Outlines

- Motivation of PMI research at INL
- Recent modification/improvement at STAR
- **Recent research progress at STAR**
- Future plans

Recent progress in In-vessel tritium source study

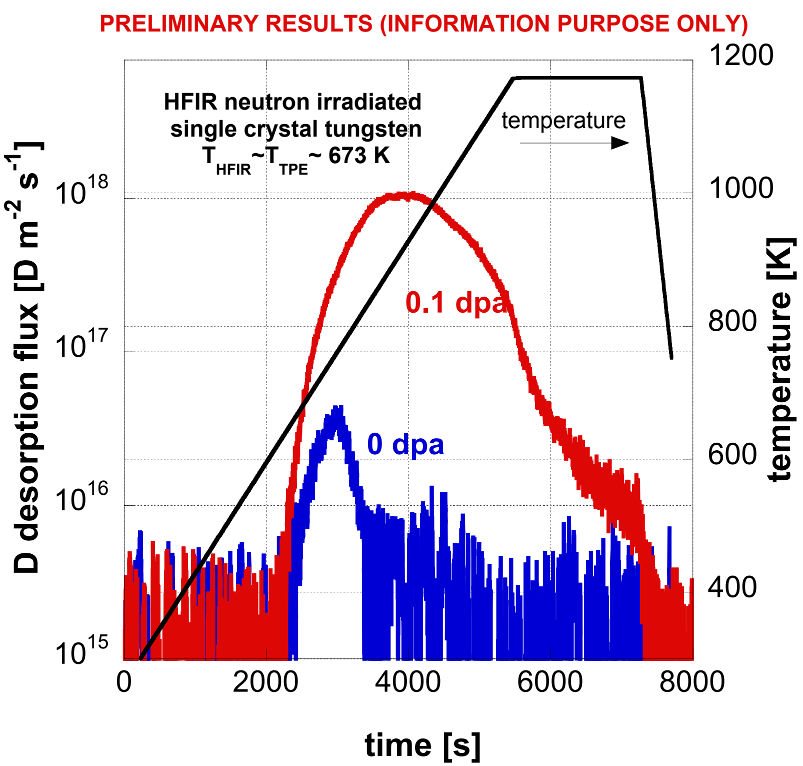
- **1st TPE plasma exposure to single crystal tungsten (SCW)**
  - **HFIR irradiation conditions for sample ID: W53**
    - Estimated irradiation temperature: **400 °C (673K)**
    - Fast neutron flux: 0.52×10^{25} n/m^2 (E > 0.1 MeV)
    - Displacement damage: **0.1 dpa**
    - Orientation (100)

  - **TPE plasma condition of 0 dpa and 0.1 dpa SCW (100) sample**
    - Sample size: $4.0 \times 4.0 \times 0.5$ mm^3
    - Hydrogen isotope: deuterium
    - Plasma exposed area: $\pi(3.88)^2$ mm^2
    - Plasma exposure temperature: **400 (±10) °C (673K)**
    - Ion flux density : **$7.2 (\pm 0.1) \times 10^{21}$ D/m^2-s^1**
    - Ion fluence: **$5.2 (\pm 0.1) \times 10^{25}$ D/m^2**
    - Plasma duration: 2 hr (7200 sec)

  - TPE plasma exposure temperature was kept similar to HFIR irradiation temperature
  - Ion flux and plasma duration (consequently ion fluence) were determined by recent experience with new TPE power supply system.

1^{st} thermal desorption from SCW

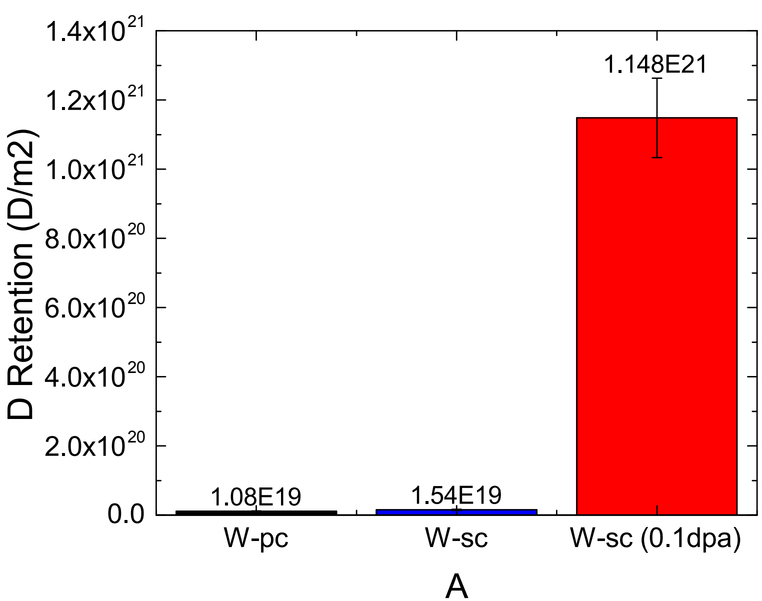
- 1^{st} TDS measurement from single crystal tungsten (SCW)
  - Thermal desorption spectroscopy (TDS) conditions:
    - Ramp rate: 10 °C/min (0.166K/sec)
    - Maximum temperature: 900 °C (1173 K)
    - Holding duration at max. temp.: 30 min (1800 sec)

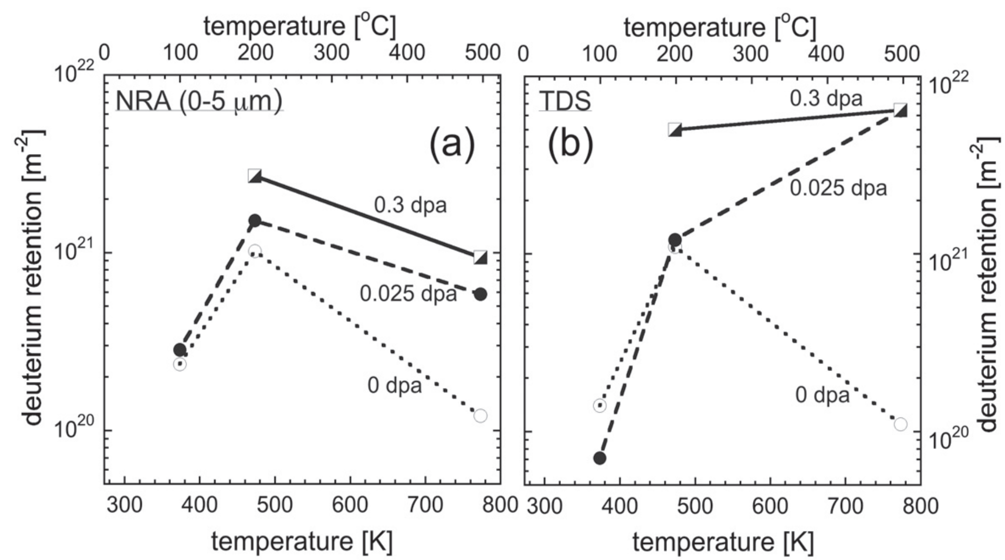


- Profound effect of neutron-irradiation on deuterium behavior in SCW

1^{st} thermal desorption from SCW

- **1^{st} TDS measurement from single crystal tungsten (SCW)**
  - **Thermal desorption spectroscopy (TDS) conditions:**
    - Ramp rate: 10 °C/min (0.166K/sec)
    - Maximum temperature: 900 °C (1173 K)
    - Holding duration at max. temp.: 30 min (1800 sec)





Ref: M. Shimada et.al., *Nucl. Fusion* 55 (2015)

- **Profound effect of neutron-irradiation on deuterium behavior in SCW**
- **NOTE: Experimental conditions (flux and temperature) were different**

Summary of in-vessel tritium source study

- INL has restarted the enhanced TPE to study tritium retention in neutron-irradiated tungsten under the US-Japan PHENIX program.
- There is a profound effect of neutron-irradiation on deuterium behavior noted in neutron-irradiated single crystal tungsten. TMAP modeling is under way to reveal de-trapping energy, deuterium penetration depth, and deuterium concentration.
- New surface diagnostics compatible with tritium and low activation material will help to reveal PMI mechanisms in fusion nuclear environments.
- US-Japan PHENIX program will provide > 100 neutron-irradiated tungsten samples to help understand tritium behavior in fusion nuclear environments.

Recent progress ex-vessel tritium release study

- **Tritium – (1000 ppm) hydrogen – helium gas from TSS**
  - Newly constructed Tritium Supply System (TSS) provided:
    - Similar hydrogen concentration in primary and secondary, and avoided counter permeation of hydrogen ($p_{H2}{}^{1} = p_{H2}{}^{2}$)
    - Capability to change tritium concentration by a factor of 250
  - Ion chamber provides $J_D{}^T$ and p_{HT} *since* $p_{H2} >> p_{HT} >> p_{T2}$
  - Then tritium partial pressure can be calculated for $H_2 + T_2 \leftrightarrow 2HT$
    - $p_{T2} = p_{HT}{}^{2} / (K_{HT} * p_{H2})$

- **Experimental conditions:**
  - Material: 20 mm OD KO Advanced Reduced Activation Alloy (ARAA)
  - Thickness: 0.5, 1.0, and 2.0 mm
  - Temperature: 400(± 5), 450(± 5), and 500(± 5) °C
  - Primary gas: (10^{-3} – 10^{-1} Pa) T_2 – (99Pa) H_2 – He at total pres. of 10^5 Pa
  - Primary flow rate: 50(± 1) sccm
  - Secondary gas: (97Pa) H_2 – He at total pres. of 10^5 Pa
  - Secondary flow rate: 200(± 2) sccm

Research under KO NRFI-UCLA-INL Phase I (July 2013 – July 2016)

Tritium permeation behavior at low p_{T2} and high p_{H2}

- **At low tritium partial pressure:** $10^{-3} < p_{HT}$ [Pa] $< 10^{-1}$
- **At high hydrogen partial pressure:** p_{H2} [Pa] $= 10^{3}$

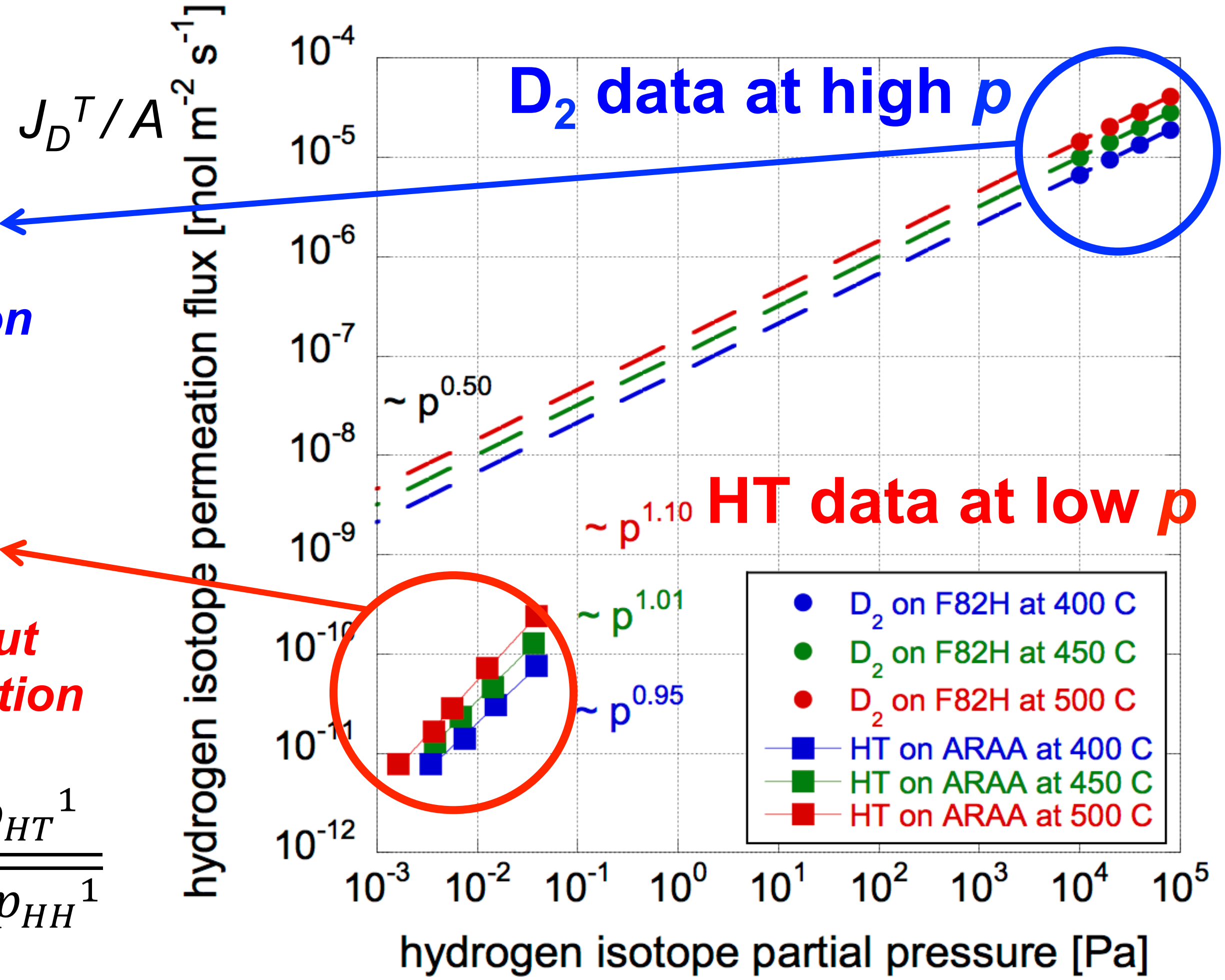
$J_D^D \sim (p_{D2})^{0.5}$

Diffusion-limited permeation

$J_D^T \sim (p_{HT})^{1}$

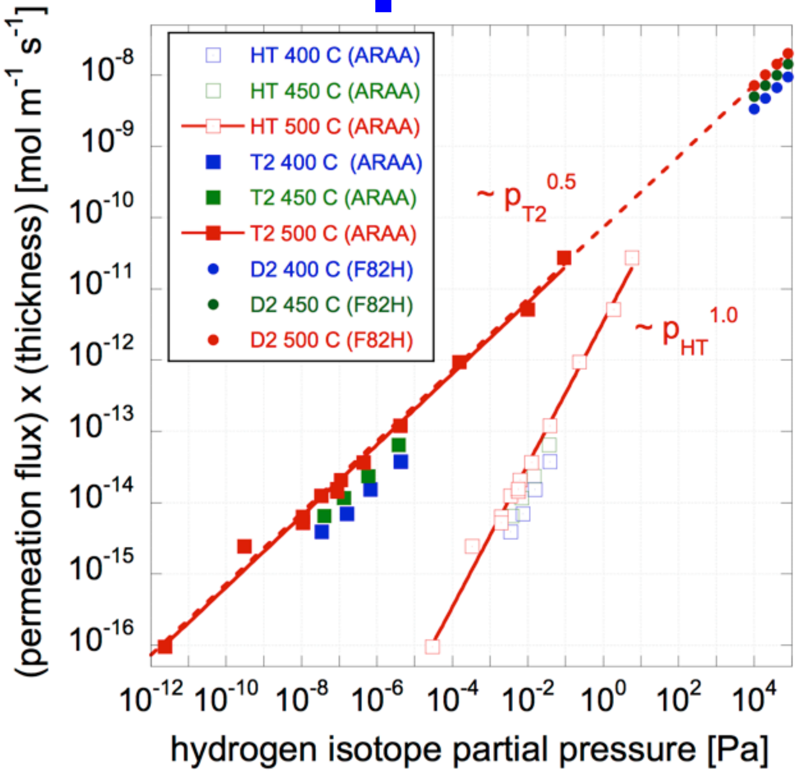
NOT surface-limited, but Diffusion-limited permeation

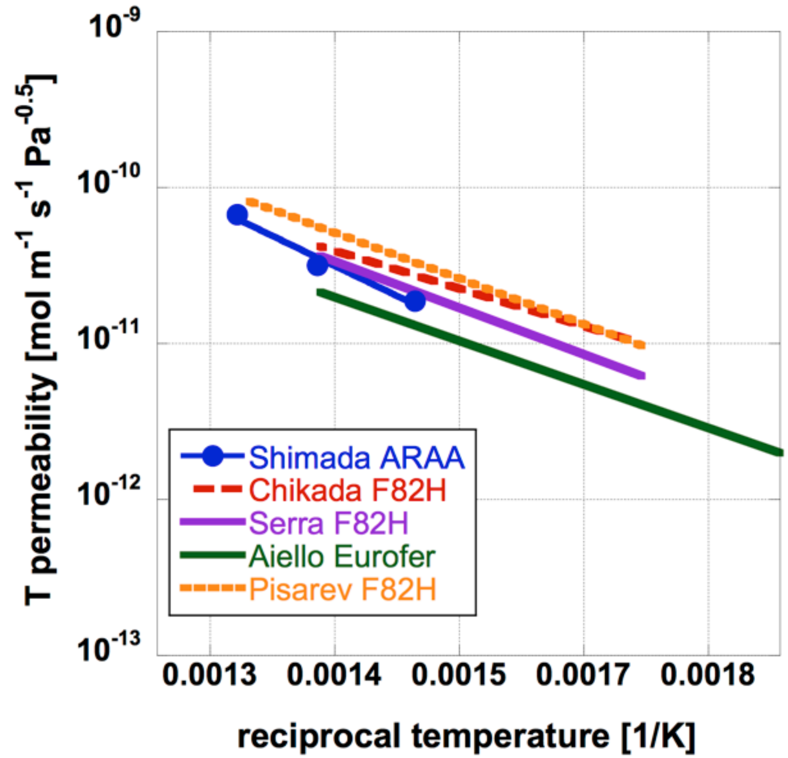
$$J_D^T \approx \frac{D_T\, K_T\, A}{\Delta x \sqrt{K_{HT}{}^{1}}} \frac{p_{HT}{}^{1}}{\sqrt{p_{HH}{}^{1}}} \propto \frac{p_{HT}{}^{1}}{\sqrt{p_{HH}{}^{1}}}$$



$p_{HT}{}^{1}$

Tritium permeation behavior in RAFM





$$J_D^T \approx \frac{D_T\ K_T\ A}{\Delta x \sqrt{K_{HT}}^{1}} \frac{p_{HT}{}^{1}}{\sqrt{p_{HH}}^{1}} \propto \frac{p_{HT}{}^{1}}{\sqrt{p_{HH}}^{1}}$$

$$P_T = D_T\ K_T \approx \frac{J_D^T\ \Delta x \sqrt{K_{HT}}^{1}}{A} \frac{\sqrt{p_{HH}}^{1}}{p_{HT}{}^{1}}$$

NOTE: All the D permeability data from the literature were adjusted for T by sqrt (mass2/mass3).

Summary of ex-vessel tritium release

- INL developed experimental capability to measure tritium permeation fluxes in a wide range
  - 6 orders of magnitude in HT partial pressure
  - 12 orders of magnitude in T_2 partial pressure
- The results experimentally revealed that tritium permeation behavior in low tritium partial pressure (< 10 Pa) with 1000 ppm (0.1 %) hydrogen-helium gas mixture still follows diffusion-limited, square root (n=0.5) with T_2 partial pressure
- Tritium permeation fluxes were significantly reduced by the presence of hydrogen, which is beneficial for blanket safety.
- This system is capable of measuring tritium permeability in low tritium partial pressure (< 10 Pa) with 1000 ppm (0.1 %) hydrogen-helium gas mixture.

Outlines

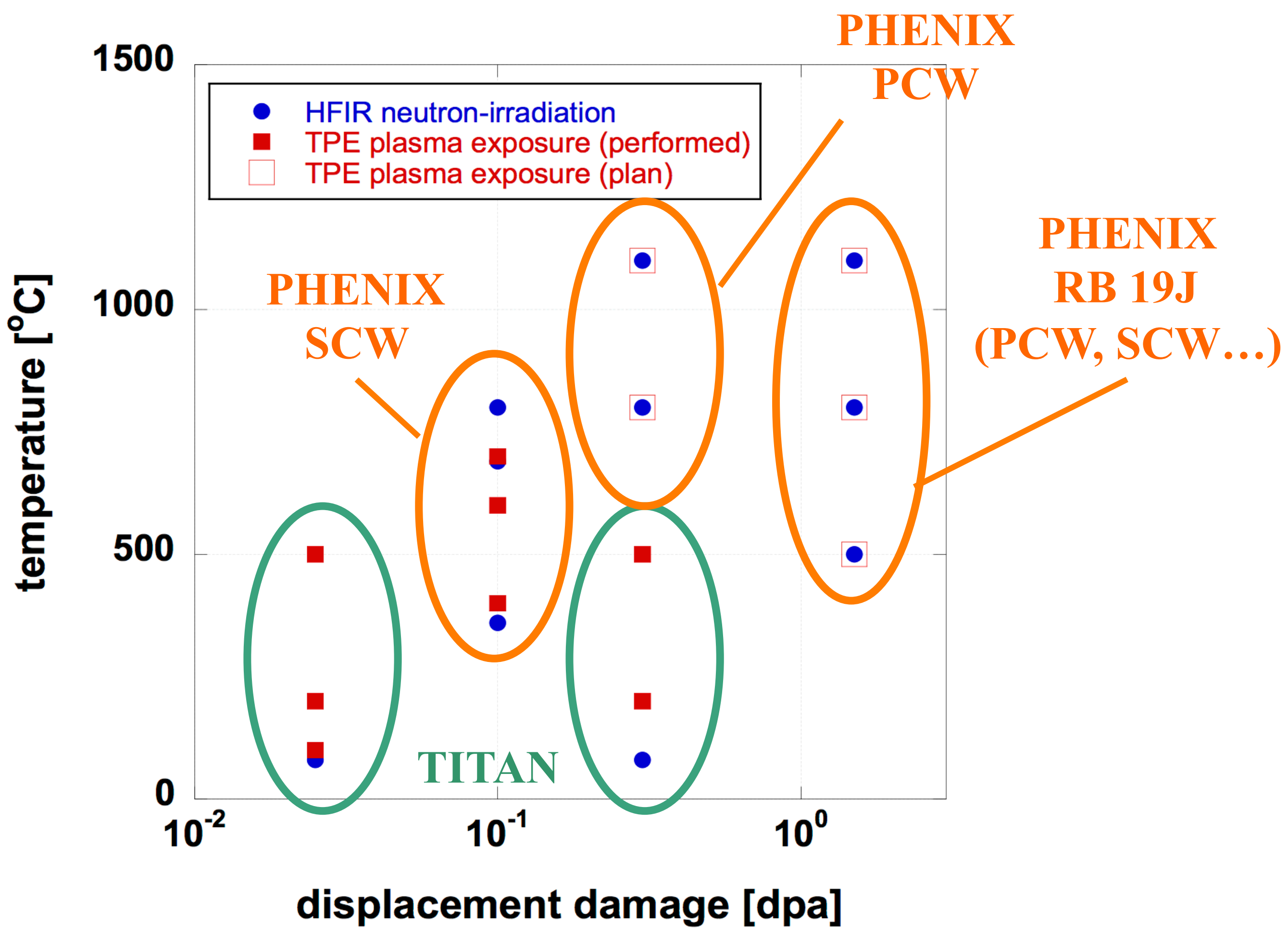
- Motivation of PMI research at INL
- Recent modification/improvement at STAR
- Recent research progress at STAR
- **Future plans**

Future plans for Fusion Material R&D

- **Tritium retention in neutron-irradiated tungsten**
  - PHENIX RB-19J irradiation conditions:
    - Three irradiation temperature zones: 500, 800, and 1100 C
    - High neutron dose: 1.5 dpa
    - Unique neutron irradiation with thermal neutron shielding to better simulate fusion neutron spectrum
  - TPE plasma exposure conditions:
    - Plasma exposure temperature similar to irradiation temperature: 500, 800, and 1100 C
    - Mixed plasma condition: D, T, and He plasma
    - High ion flux density for DEMO condition: 10^{22} – 10^{23} D/m^2-s^1
    - High ion fluence for DEMO condition: > 10^{26} D/m^2-s^1
    - Focus on bulk and surface measurement to reveal key physics issues in a fusion nuclear environment.

Status of neutron-irradiated tungsten study

- **Irradiation dose vs. irradiation temperature**
  - PHENIX program will focus on high temperature, high dose



Plans for neutron-irradiated tungsten study

- **Questions to be answered by PHENIX program:**
  1. Tritium retention in neutron-irradiated tungsten under mixed plasma (D, T, He)
     - Especially if helium can reduce tritium migration and trapping in neutron-irradiated tungsten or not.
  2. Trap density saturation above 1 dpa
     - If trap density saturates ~ 1 at.% T/W above 1 dpa or not
  3. Defect annealing at high irradiation and high plasma exposure temperature
     - How much are defect/trap sites reduced at high temp.?
  4. Microstructural changes and its effects on tritium behavior
     - Tritium trapping mechanisms in different microstructures

INL

Idaho National Laboratory

The National Nuclear Laboratory