Liquid Metal surface properties and plasma material interactions for plasma-facing component development in NSTX-U

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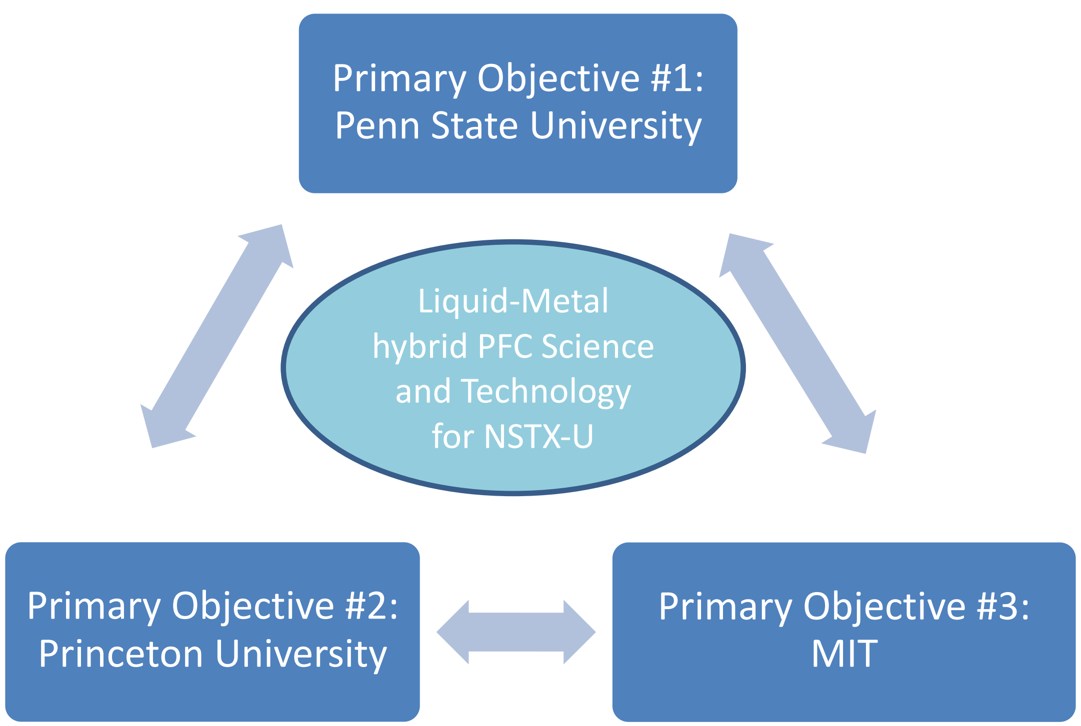
Project Summary

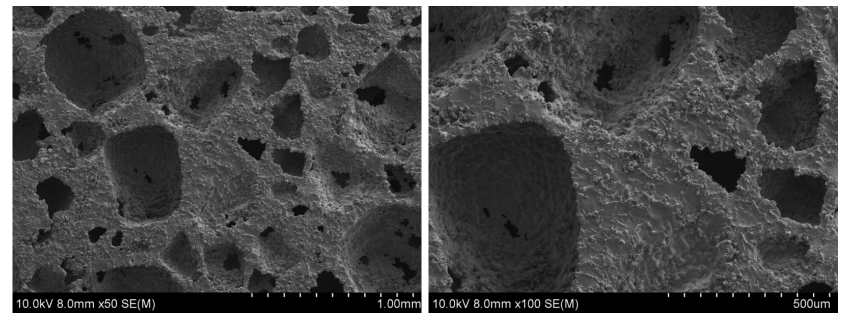
- This is a collaborative research proposal for surface science research and liquid metal (LM) plasma-facing component (PFC) development in the NSTX-U
- Our work seeks to establish the science and technology of functional W-based architected PFCs for liquid metal delivery and control (hybrid PFCs) to be deployed in NSTX-U in future 5-YR plans



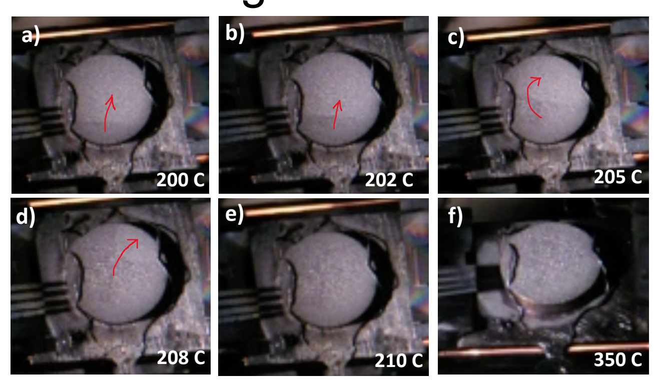
- *Project Objective #1: Fabrication and Development of architected PFCs, D retention and wettability studies*
- *Project Objective #2: Establish the surface science of hybrid PFCs*
- *Project Objective #3: Study the hydrogen compositional profiles of hybrid PFCs*

Primary Objective #1: Establish an understanding of the liquid/solid hybrid material interface and impact on PMI properties under prototypical plasma conditions (Years 1-5)

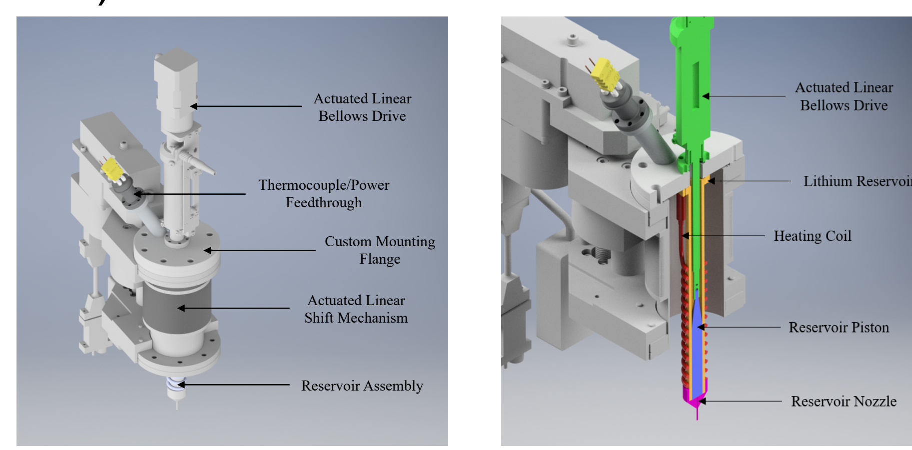
- Sub-Task #1.1: Material design of advanced nano and mesoporous tungsten (with Princeton)
  - Sample fabrication: SPS and VPS
  - Porous architectures
  - Surface preparation for wettability



- Sub-Task #1.2: Study liquid-metal wetting, percolation, and surface stability within hierarchical mesoporous tungsten PFC structures (with MIT, Princeton)
  - Building Lithium dropper in-vacuo with IGNIS-2 facility (XPS, LEISS)
  - Wettability tests feedback porous W designs in ST#1.1
  - Environmental glove box

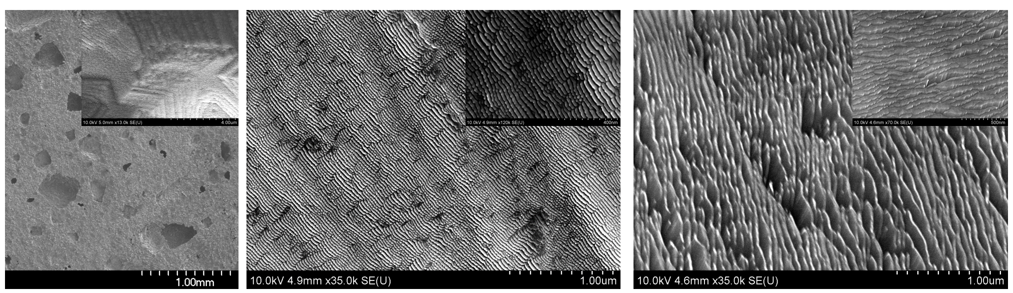


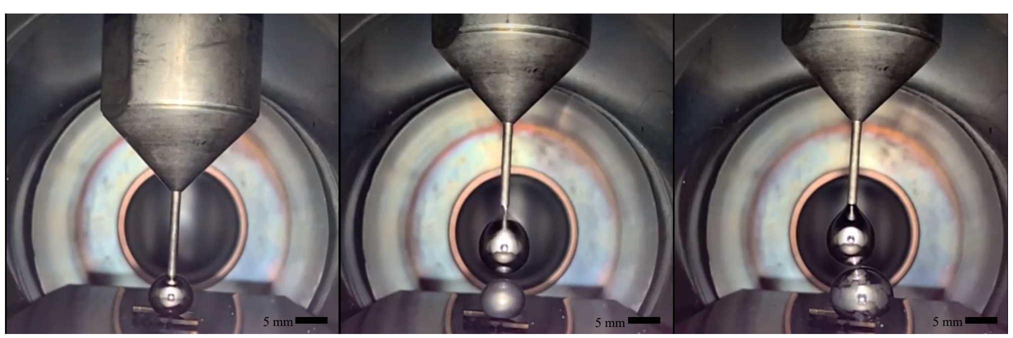
Li dropper on IGNIS-2 at Penn State



Primary Objective #1: Establish an understanding of the liquid/solid hybrid material interface and impact on PMI properties under prototypical plasma conditions (Years 1-5)

- Sub-Task #1.3: Investigate fundamental PMI properties of the Hybrid PFC systems (with MIT)
  - Single-effect high-flux ion irradiation of D_2+ at low energies (e.g. < 0.5 keV) sputtering and surface composition tests,
  - hydrogen retention mechanisms, and
  - In-vessel PMI properties in NSTX-U

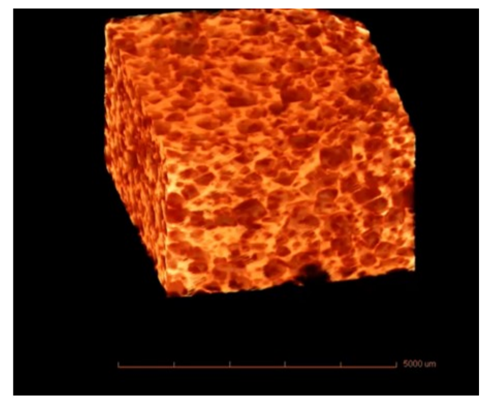


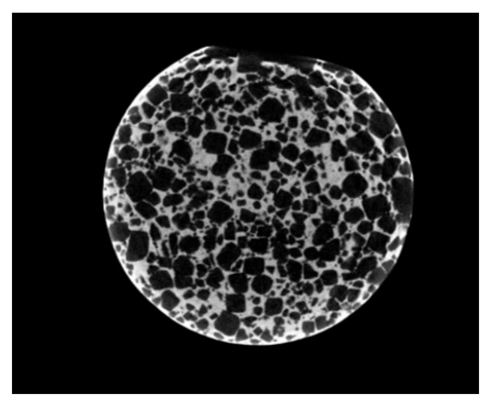


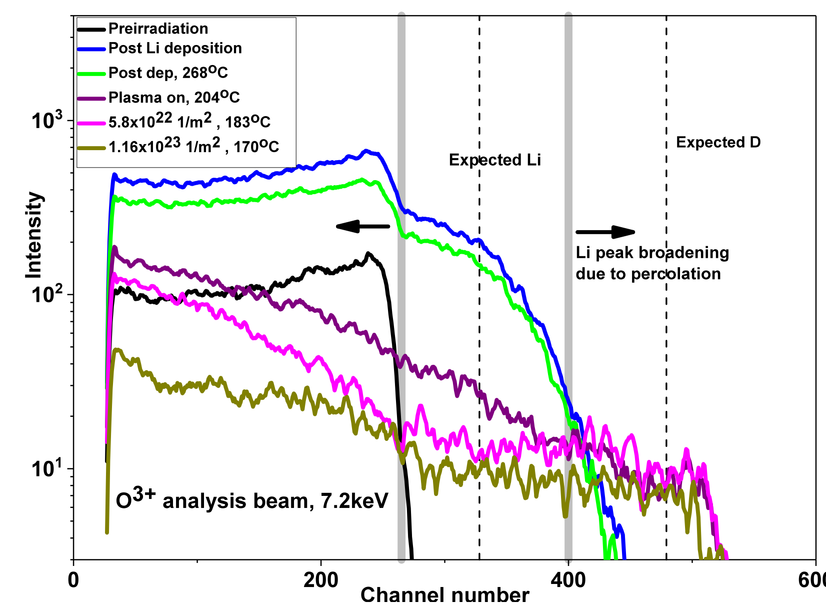
Droplet #1
7.15 mm

Droplet #2
7.91 mm

Droplet #3
7.56 mm







Primary Objective #2: Establish fundamental properties of LM PFCs including surface chemistry under various temperatures typically seen and foreseen in NSTX-U (Years 1-5)

Subtask #2.1: Thermal stability of Li on W substrates (with Penn State, MIT) (24 months)

- Conduct TPD studies for Li films on W substrates up to 2,000 K; simultaneous XPS, AES, and LEIS analysis will trace the development of surface species
- Studies will investigate effects of D and impurity (B, C, O) contamination, increasingly complex substrates

Subtask #2.2: Determination of D uptake and retention of Li and Li-Sn alloy on W substrates (with MIT) (36 months)

- Retained D is quantified by TPD
- Pure Li, impurity-contaminated Li, and Li-Sn alloys can be exposed to D atoms, D_x^+ ions, or D_2 molecules
- Direct measurement of ejected/reflected species during D ion irradiations using mass spec.

Subtask #2.3: Study atomistic scale liquid metal wetting and surface stability on smooth and nanotextured tungsten PFC structures (with Penn State) (18 months)

- To be characterized by 2D (elemental) maps using SAM, SEM, EDS, TEM analysis available in PPPL and PU campus labs

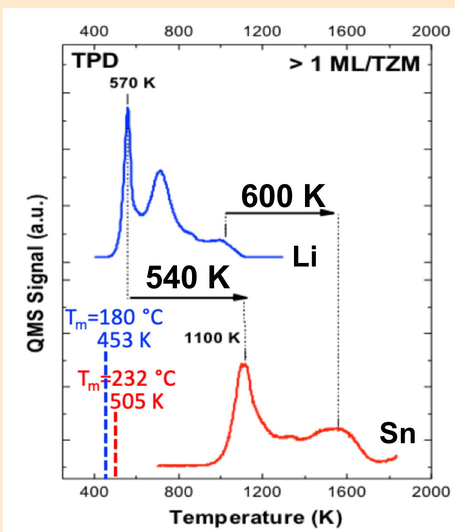
Progress towards subtasks:

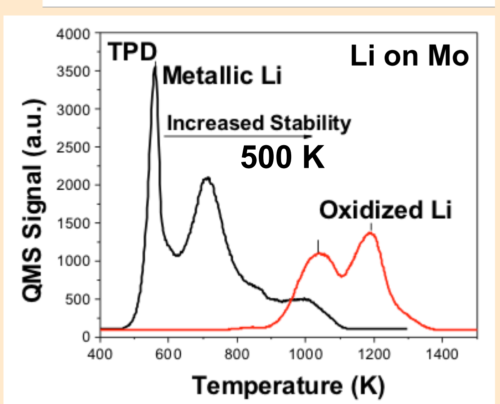
- HR-XPS analysis of boronized graphite from RFX-mod
- Studies performed on thermal stability of Sn, SnO_x
- Preparation of HR-XPS system on PU campus
- Monte Carlo code (MPR by A. Lasa [UTK]) to understand erosion and reflection behaviors for micro-structured surface

Additional on-site resources required:
Fraction of PPPL engineer, technician time

Primary Objective #2: Establish fundamental properties of LM PFCs including surface chemistry under various temperatures typically seen and foreseen in NSTX-U (Years 1-5)

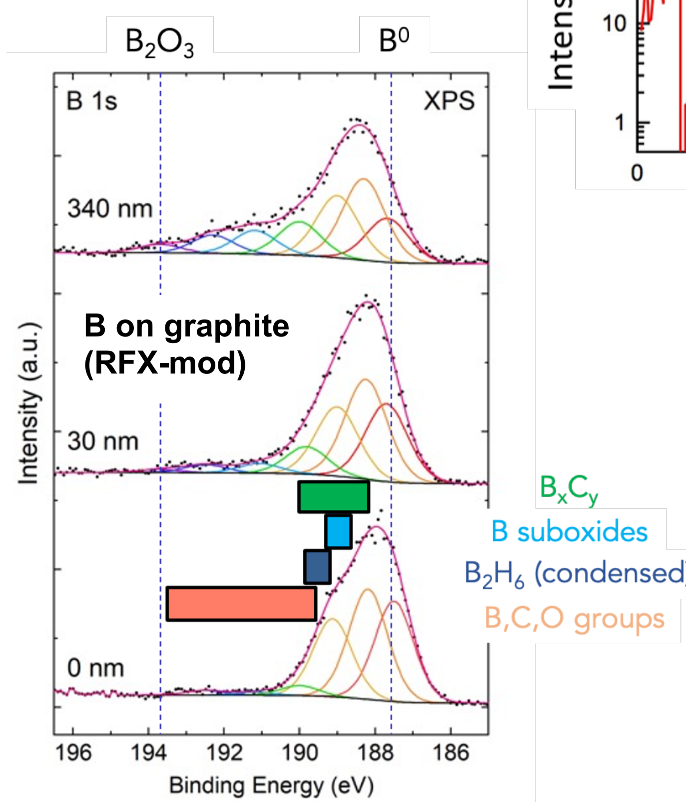
Subtask #2.1:
Thermal stability of Li & Li-Sn

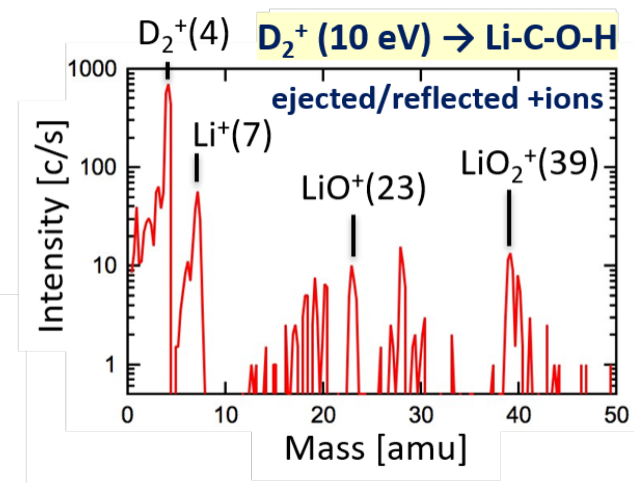




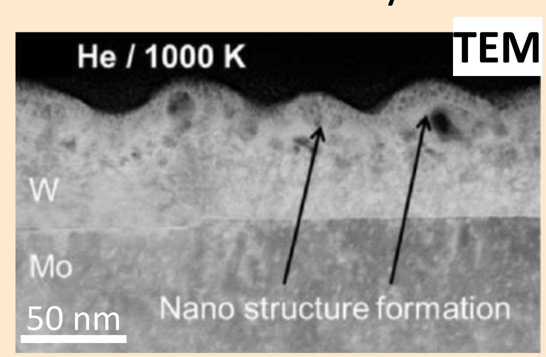
Fasoranti, *JNM* (2021)

Subtask #2.2:
Determination of D uptake and retention of Li and Li-Sn alloy



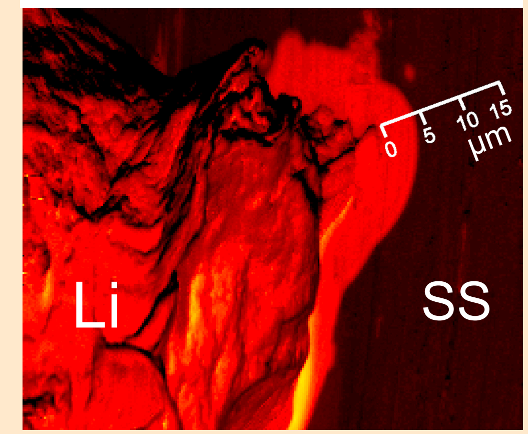


Subtask #2.3: Atomistic scale liquid metal wetting and surface stability on W



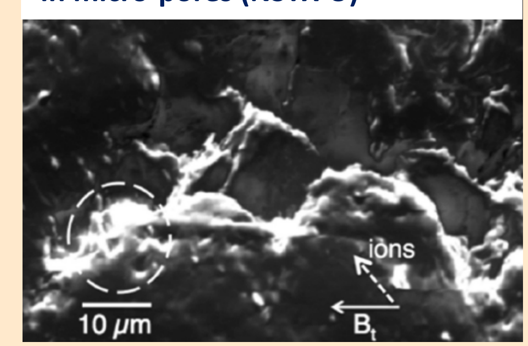
Buzi, *NME* (2019)

Wetting observation by scanning Auger microscopy (SAM) in PPPL



Skinner, *JNM* (2016)

Boron SAM intensity concentrated in micro-pores (NSTX-U)



Skinner, *NME* (2019)

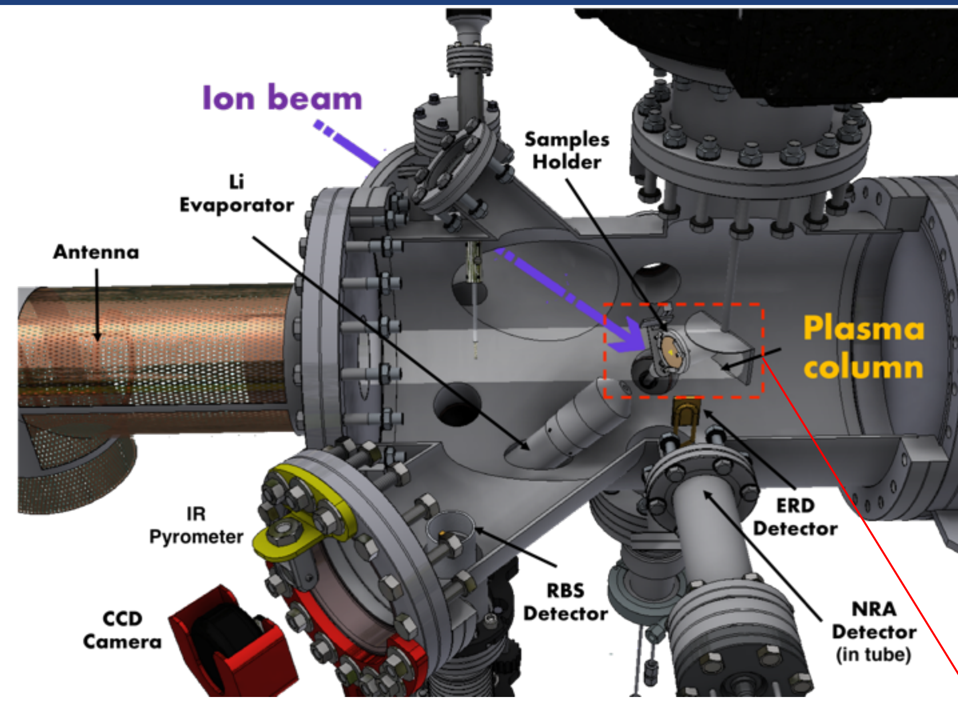
Tasks #1.2, #1.3, #2.1, and #2.2 complemented with ion beam analysis for increased range in depth profiling of Li in W and D in Hierarchical structures

Contributions to Tasks #1.2 and #2.1

- Depth profiling of deposited Li film percolation into porous W substrate studied with **E**lastic **R**ecoil **D**etection (**ERD**)
  - Challenges (Opportunities): Mixed surface, roughness effects

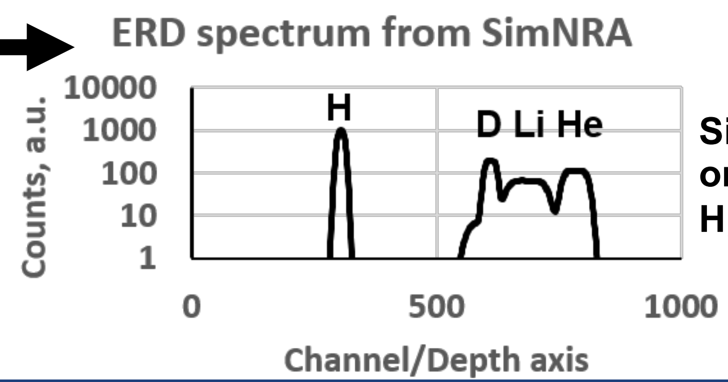
Contributions to Tasks #1.3 and #2.2

- D retention by ^{3}He **N**uclear **R**eaction **A**nalysis (**NRA**) and **ERD**
  - Advantages: Mass separation and simultaneous H, D, He, and Li
- Exploration of Sn and Li-Sn deposition



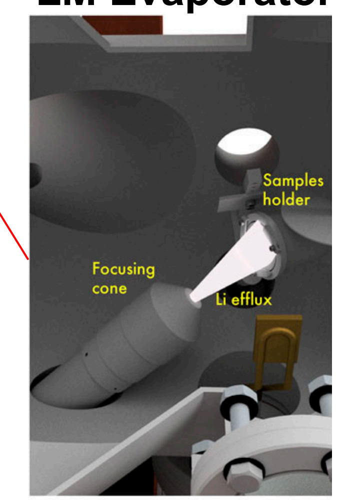
DIONISOS exposure chamber at MIT

Combines <10^{21} D/m^{2}s plasma exposure with in situ Li deposition and ion beam analysis



Simulated 200 nm Li on W with implanted H, D, and He

LM Evaporator



Bedoya et al. RSI 2018

Sub-Task #3.1: Study compositional depth profiles of Hybrid PFCs coupled with plasma exposure and radiation damage (with Penn State, Princeton) (60 months)

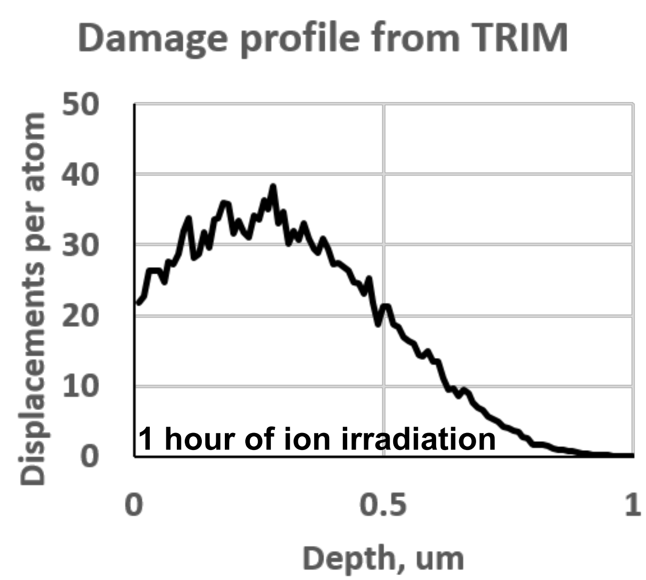
Separating hydrogenic contributions while monitoring with ion beam analysis

- Measure sticking coefficient of atomic H and D on liquid Lithium surfaces
- 1000-2000 K thermal H or D in addition to molecular H_2 or D_2 or ion sticking

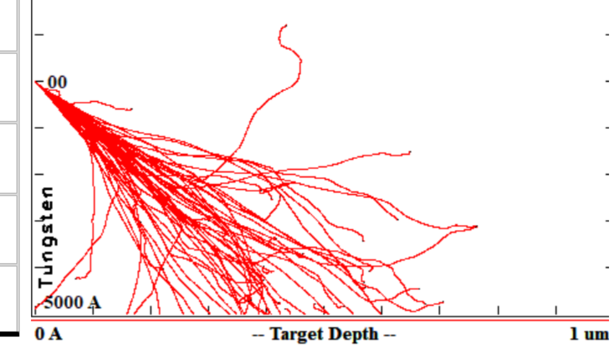
Understanding for LM Hybrid PFCs as well as LLD, LVB

Understanding impact of radiation damage on retention, shown to increase

- Use heavy ion beam to damage material and expose to Li and plasma
- Heavy ion beams or self ion beams (Li, C, O, Ti, Mo, W, etc) are used to induce damage comparable to neutron damage

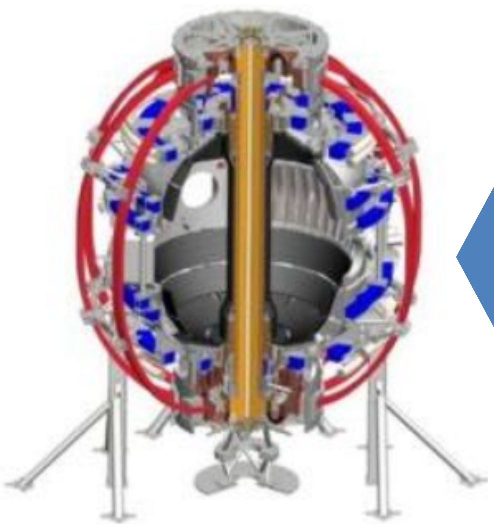


Simulated 8.9 MeV W^{3+} incident at 45 degrees

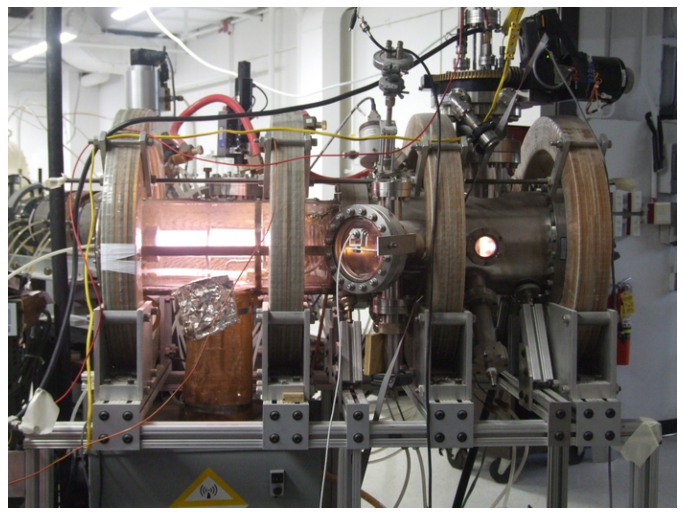


Sub-Task #3.2: Study effects of mixed wall conditioning practices of NSTX-U in DIONISOS (with Princeton, Penn State) (24 months)

NSTX-U



DIONISOS



- Intended to be complementary to MAPP
- Transition to smaller study of representative material conditions from NSTX-U
- Explore alternative diagnostic coverage of material conditions in NSTX-U

NSTX-U planning for initial Boronization, then subsequent Lithium provides opportunity to study the impact of the different conditioning materials

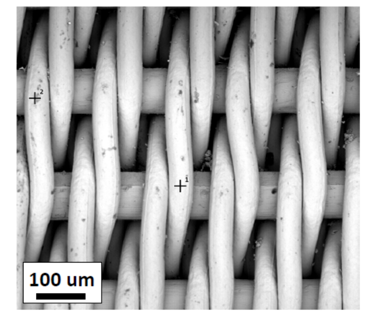
- Previous work at MIT focused on Li-C-O system in DIONISOS, new effort on B-C-O and Li-B-C system
- Retention studies of Li on B, B on Li, etc.
- Also, then on porous W substrates

Sub-Task #3.3: Development of permeating LM-solid Hybrid PFC (with Penn State) (42 months)

Objective: Prototype LM Hybrid PFCs with separate chamber and DIONISOS for plasma exposure

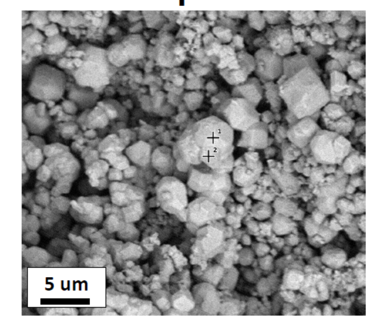
- Test bed for deployment in NSTX-U

Metal Filter Cloth



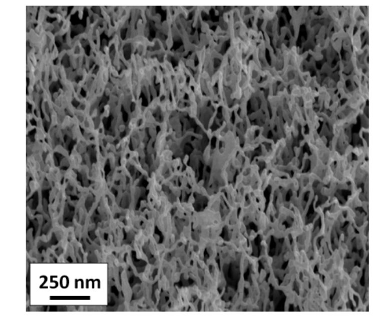
Unique Wire Weaving, Inc.

Sintered powder



UIUC

Tungsten Fuzz

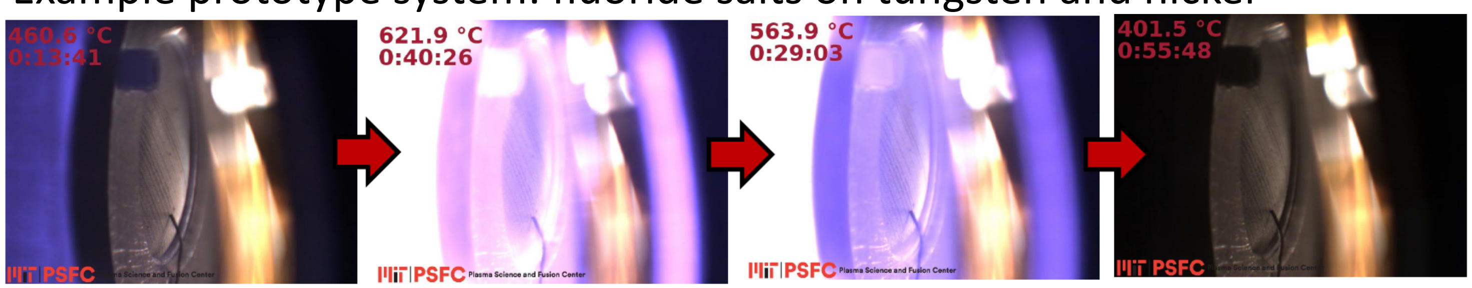


MIT

Porous materials

Surface treatment

Example prototype system: fluoride salts on tungsten and nickel

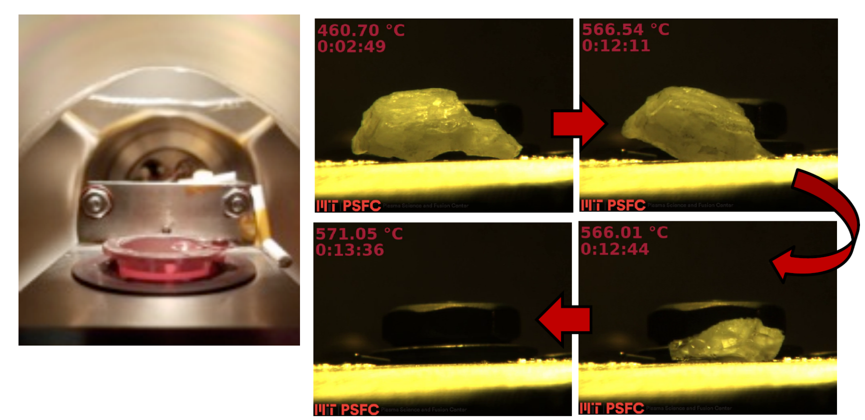


Gravity

- Successful percolation of fluoride salt (FLiNaK) through 10 um pore size nickel mesh
- No droplet formation

Woller et al. ICFRM 2019

Wetting and percolation of FLiNaK into SPS porous material



Bedoya et al. SOFE 2019

Timeline

Primary Objectives	Y1 Sep 2020 to Feb 2021	Mar 2021 to Aug 2021	Y2 Sep 2021 to Feb 2022	Mar 2022 to Aug 2022	Y3 Sep 2022 to Feb 2023	Mar 2023 to Aug 2023	Y4 Sep 2023 to Feb 2024	Mar 2024 to Aug 2024	Y5 Sep 2024 to Feb 2025	Mar 2025 to Aug 2025
Task 1.1										
Task 1.2										
Task 1.3										
Task 2.1										
Task 2.2										
Task 2.3										
Task 3.1										
Task 3.2										
Task 3.3										