Lithium and Liquid Metal Program Update

Rajesh Maingi

PPPL Advisory Committee

May 2016

U.S. DEPARTMENT OF ENERGY

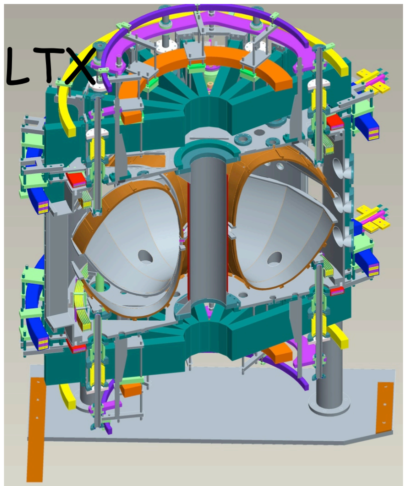
PRINCETON UNIVERSITY

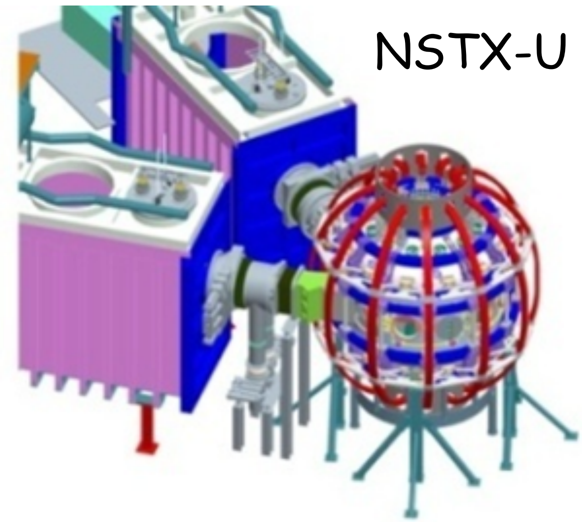
PPPL

Goal is to develop liquid metal PFC solutions for reactors

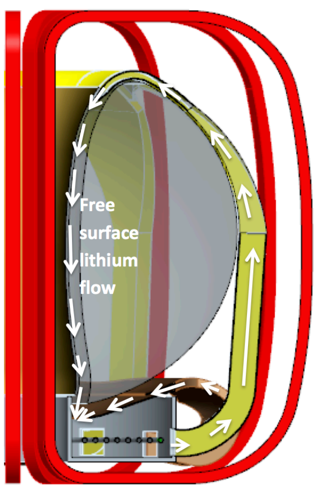
- **Problem:** it is unclear that a solid PFC solution exists for a long pulse D-T fusion reactor
- **Method**: develop liquid metal PFCs; gauge compatibility with compact, lower cost fusion reactors
- **Value to US**: large DEMOs are seen as unattractive, so this method aims at smaller DEMOs, as well providing at least one viable solution for any DEMO
- **Competitiveness**: other devices evaluate liquid metals in small scale facilities; we will evaluate in NSTX-U
- **Duration**: 10-15 years
- **Cost**: $10M per year for full program, but there are separable pieces

Lithium and Liquid Metal Program Elements

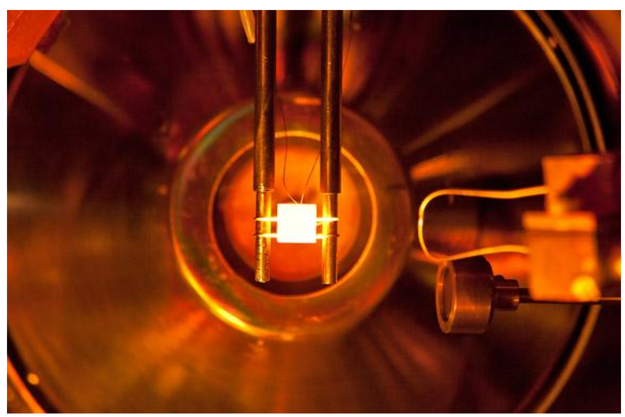




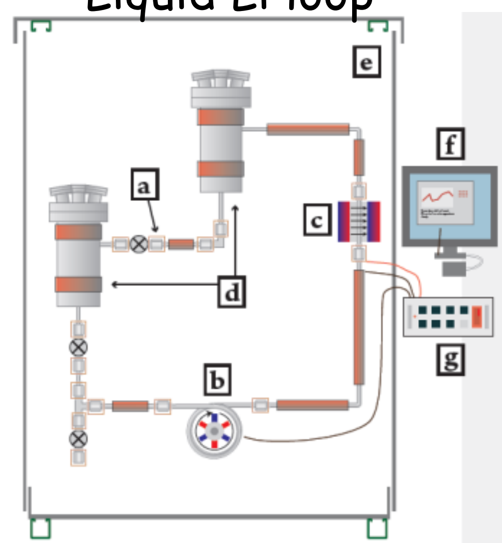
LM Flow with B_t



Surface Science



Liquid Li loop



Outline

Charge: We are evolving our strategy for a comprehensive study of liquid metals – from basic materials studies to tokamak experiments. Are our plans and advocacy for them effective?

- **Introduction**
  - Motivation, advantages and disadvantages
  - Science and Technology issues

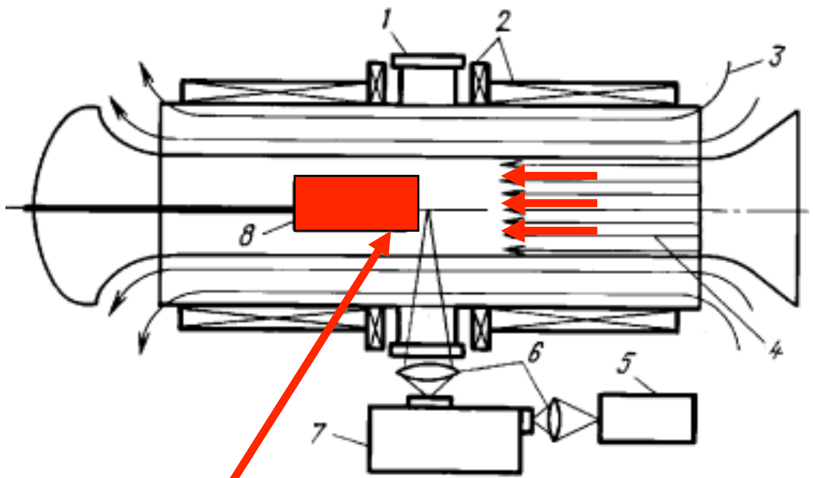
- Elements of existing program
  - NSTX-U lithium program and directions
  - LTX program and directions
  - EAST collaborative lithium program and directions
  - Liquid metal exposures in divertor simulators

- New initiatives & Summary

Development of liquid metal PFCs for FNSF and reactors is a *potentially transformative area*

- Motivation 1: power exhaust challenge harder than thought
  - Heat flux footprint decreases with I_p; no increase with R
    - ➢ Both steady and transient loads can exceed solid PFC limits
- Motivation 2: Confinement difficult with bare high-Z PFCs
  - Good confinement is challenging with high-Z walls in e.g. JET
- Evidence that liquid metal PFCs can exhaust higher power than solids, *and* lithium PFCs (liquid or solid) provide access to high confinement

Liquid metals can exhaust high heat flux and lithium can provide access to high confinement

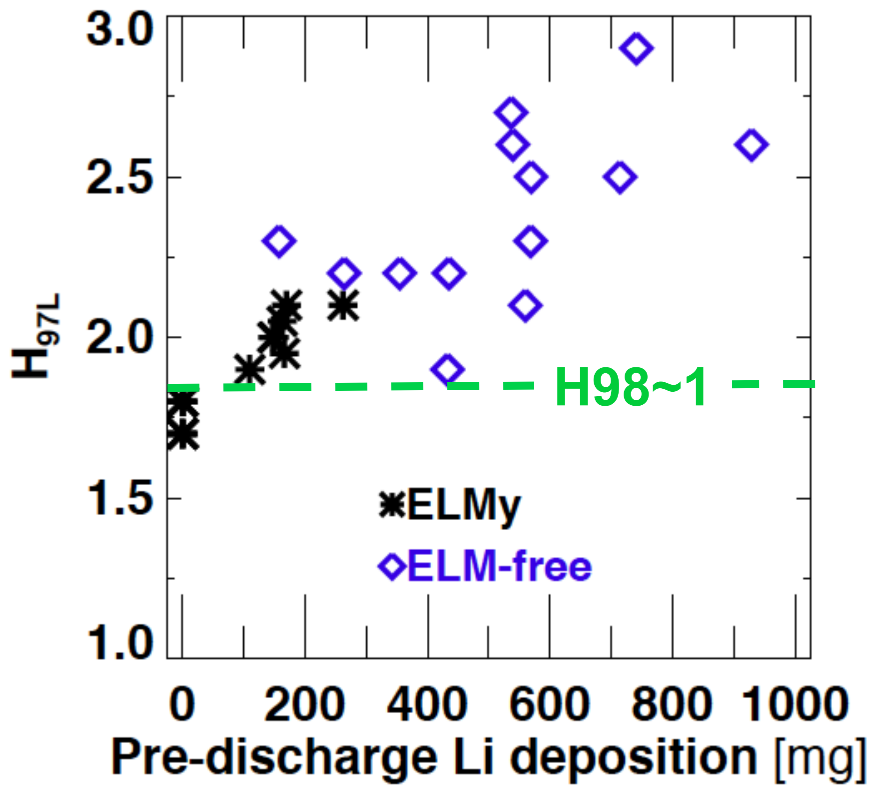


Lithium Capillary Porous System (CPS) targets

- Steady: 1-11 MW/m^2 for 3 hours
- Heat loads ≤ 25 MW/m^2 withstood with Li targets (5-10 minutes, limited by Li inventory)
- Transients ≤ 50 MW/m^2 with Li targets without cooling for ≤15 s

IAEA Technical Meeting on Assessment of Atomic and Molecular Data Priorities Vienna, Austria, 04 - 05 December 2006

NSTX (coatings)



D.P. Boyle, *J. Nucl. Mater.* **438** (2013) S979

- H_{H98y2} increased from 0.8 -> 1.4
- Pedestal broadens, pressure peaking drops, ELMs eliminated

Liquid metal PFCs are alternatives to solid PFCs, but have substantial R&D needs to assess viability

- Advantages
  - ✓ Very high steady, and transient heat exhaust in plasma gun tests
  - ✓ Liquid (and solid) lithium offer access to low recycling, high confinement regimes under proper conditions
  - – Erosion tolerable from PFC view: self-healing surface
  - – Main chamber material and tritium transported to divertor could be removed via flow outside of tokamak
  - – Liquid metal protects substrate from PMI
- Disadvantages and associated R&D needs
  - ➢ **Need stable surface & flows to maintain a fresh surface**
  - ➢ **Liquid metal chemistry needs to be controlled, including tritium retention**
  - ➢ **Temperature windows need optimization**

* *Most of experience in fusion is with Li, but Sn and Sn-Li offer broader temperature windows; FTU will test Sn in 2016*

Liquid metals can be used in several ways to address part or all of the particle and power exhaust challenge

- Provide particle exhaust
  - **‘Slow flow’ (cm/s)**, **low recycling**, high confinement with Li
  - Low PFC temperature $\leq$ 450 ^{o}C required
- Provide power exhaust
  - **‘Slow flow’ (cm/s), high recycling**; e.g. vapor-box
  - Multiple liquid metal candidates at high PFC temperature
  - *High confinement, low recycling with Li in low PFC temp. regions?*
- Provide particle and power exhaust
  - **‘Fast flow’ (m/s), low recycling**, high confinement with Li
  - Low PFC temperature < 450 ^{o}C required
  - Significant MHD forces try to hinder flow

Goal: assess the viability of liquid metal PFCs for power producing reactors in 10-15 years

- Which liquid metal is best for which mission, e.g. Lithium, Tin, Tin-Lithium?
  - Is Lithium the only LM to improve confinement, and both core and edge stability limits? Do these effects saturate with ‘dose’?
  - What substrate materials should be used in a reactor? What are the chemical compatibility issues?
  - How do the acceptable operating temperature ranges vary by liquid metal?
  - What are the hydrogen retention characteristics? Can flowing liquids remove hydrogen and helium away from plasma for reprocessing?
- What is the best way to drive a steady flow of the liquid metal in a magnetic field, because the field hinders flow?
- *Safety requirements integral to program conduct*

New capabilities needed to develop a liquid metal solution for reactors

- Test concepts for flowing liquid metal PFCs*
- Evaluate plasma-liquid interactions to optimize designs*

➢ *Important step: deploy and evaluate liquid metal divertor in NSTX-U (possible focus of 2019-2024 five-year plan)*
  - *Steps: high-Z row, pre-filled Li plugs; flowing Liquid Li divertor*

- Design flowing liquid metal system for reactor
- Develop liquid metal concepts for stellarators*

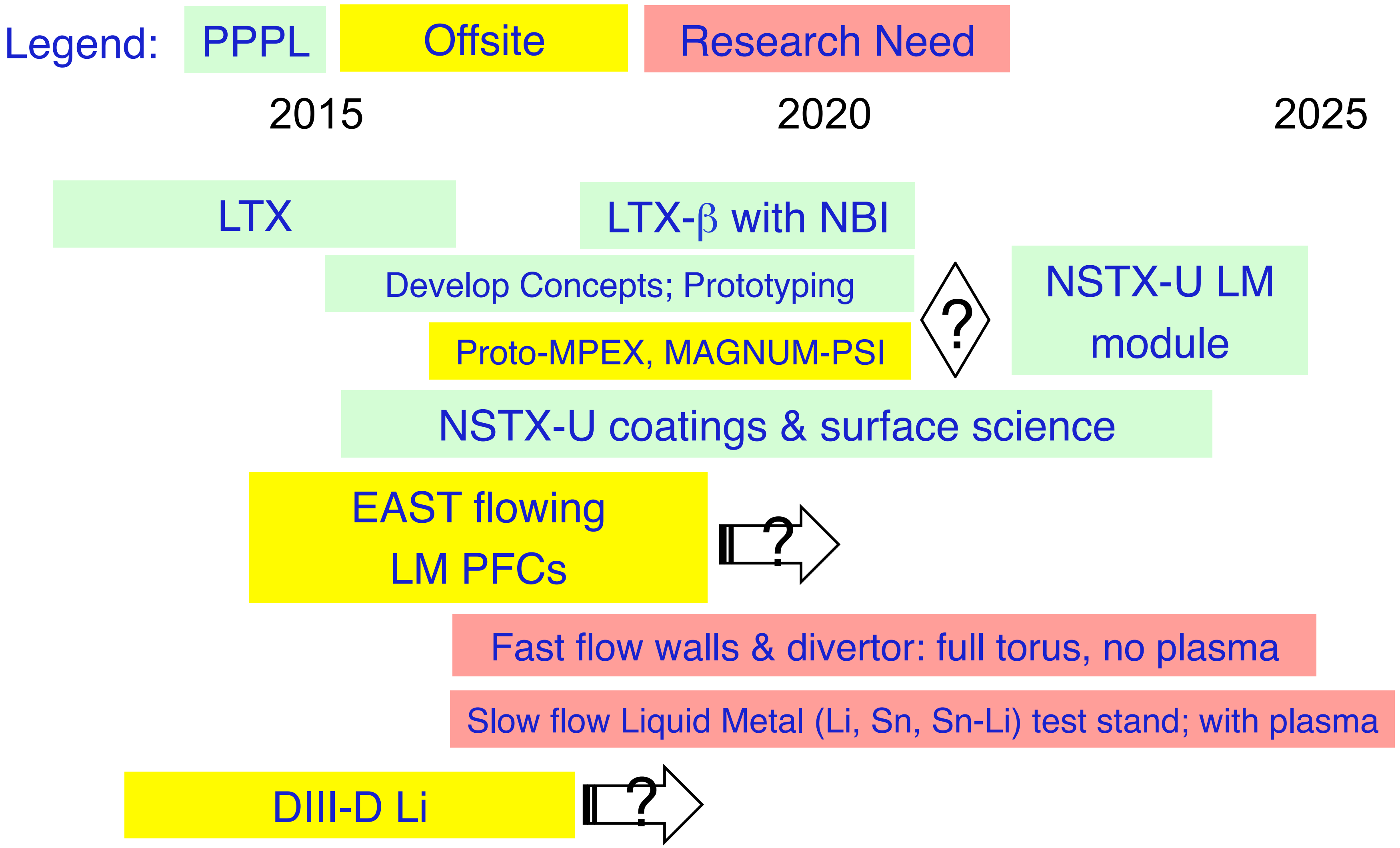
* need new experimental capability

Outline

- Introduction
  - Motivation, advantages and disadvantages
  - Science and Technology issues
- **Elements of existing program**
  - NSTX-U lithium program and directions
  - LTX program and directions
  - EAST collaborative lithium program and directions
  - Liquid metal exposures in divertor simulators
- New initiatives & Summary

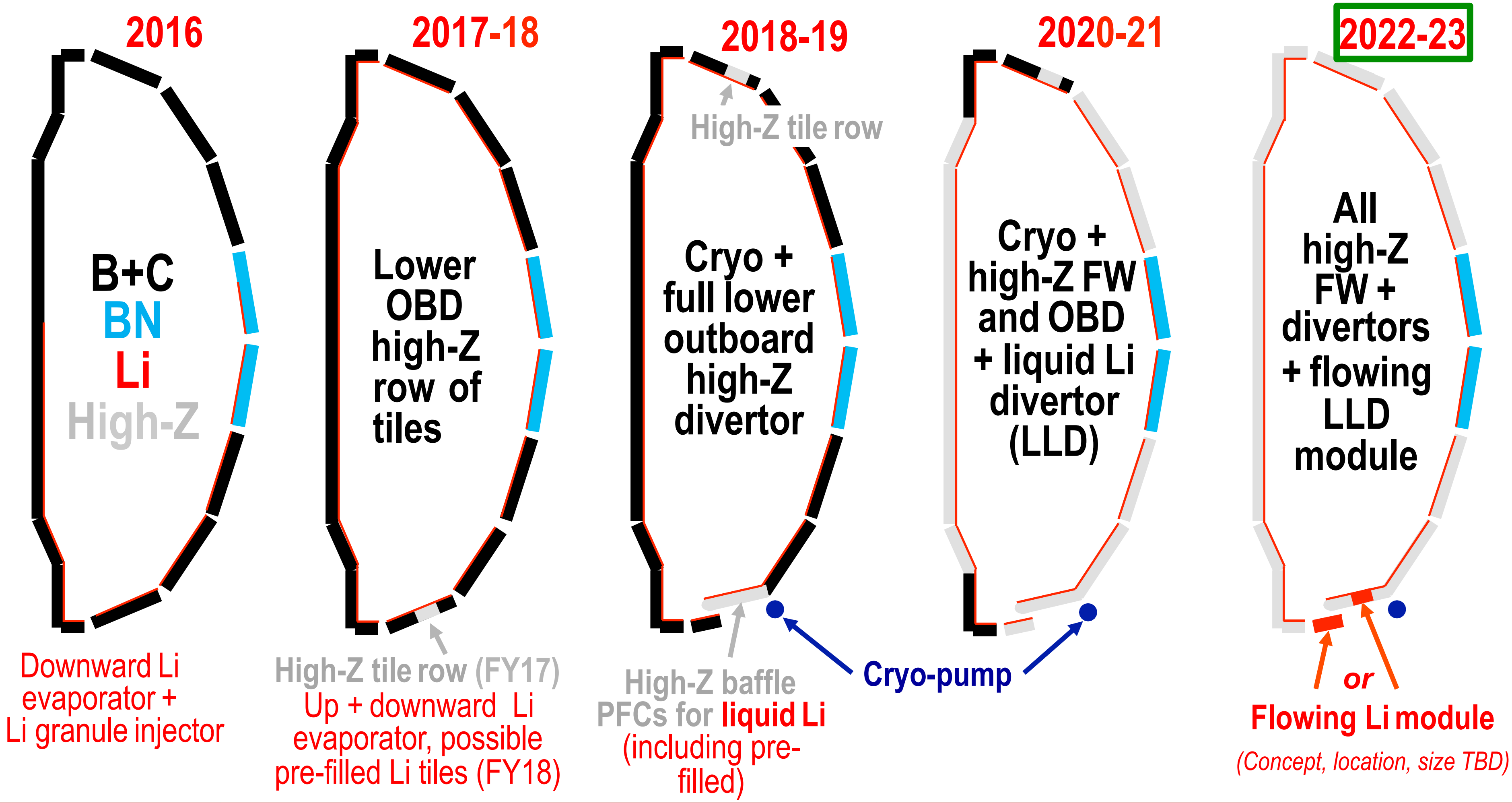
Elements of PPPL lithium and liquid metal program

NSTX-U: Flowing Liquid Metal in 2022-23, possible accelerated decision ~2020



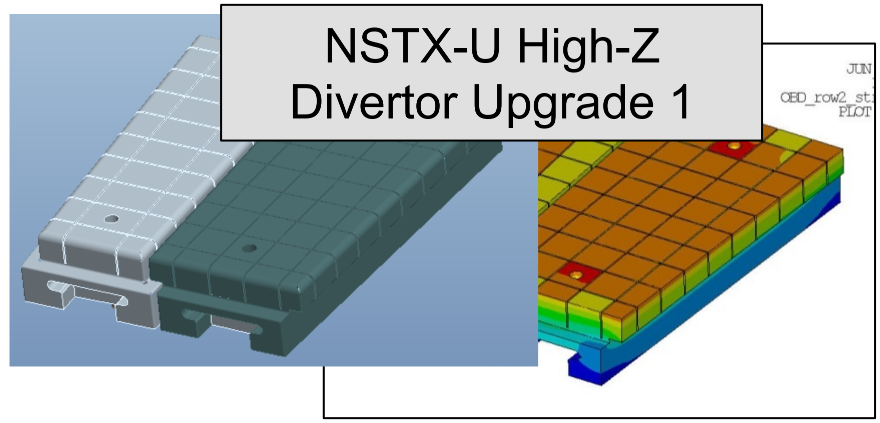
NSTX-U boundary / PFC plan: add divertor cryo-pump, transition to high-Z wall, study flowing liquid metal PFCs

- **5yr goal: Integrate high τ_E and β_T with 100% non-inductive**
- **10yr goal: Assess compatibility with high-Z and liquid lithium PFCs**



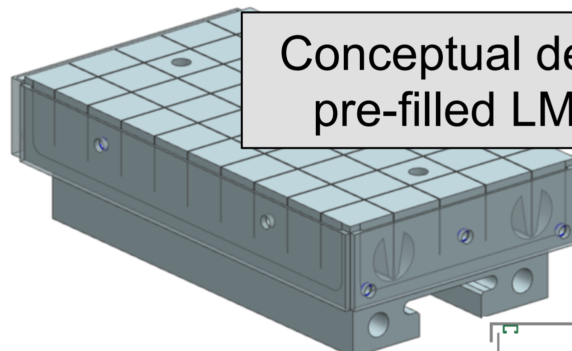
A three-step progression can achieve flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER (FY17)



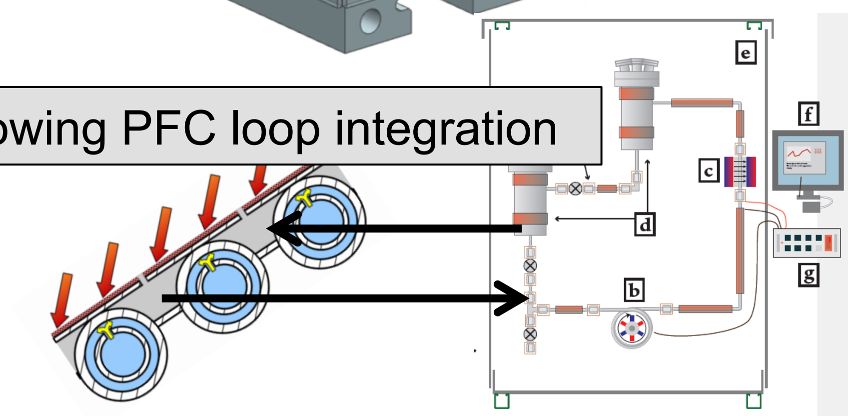
NSTX-U High-Z Divertor Upgrade 1

2. Pre-filled liquid-metal target (FY18)



Conceptual design for pre-filled LM target

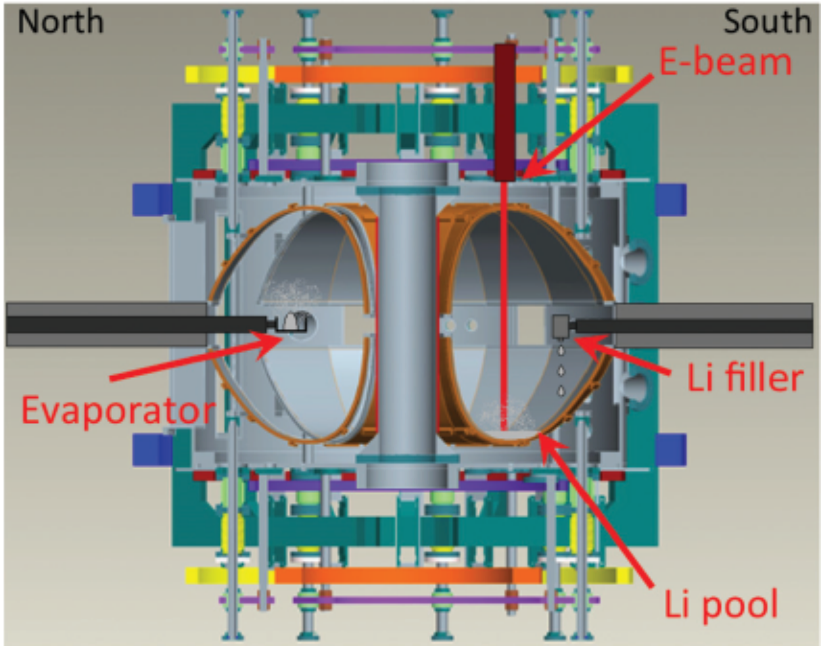
3. Flowing LM PFC (FY22-23)

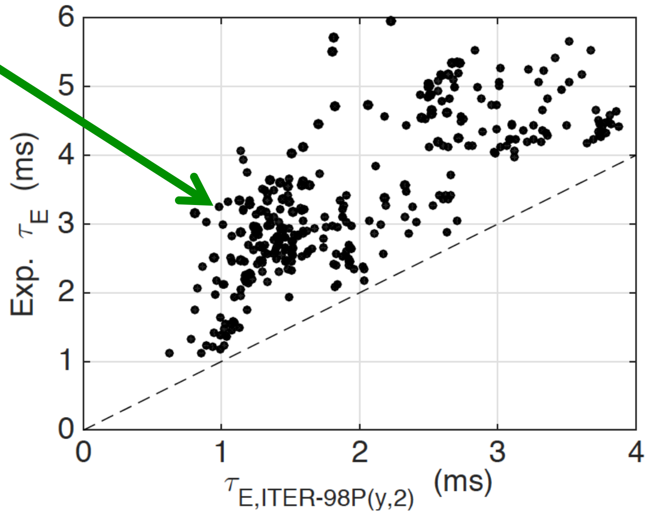


Flowing PFC loop integration

The Lithium Tokamak Experiment (LTX) is a small ohmic device to study how low recycling Li PFCs affect transport

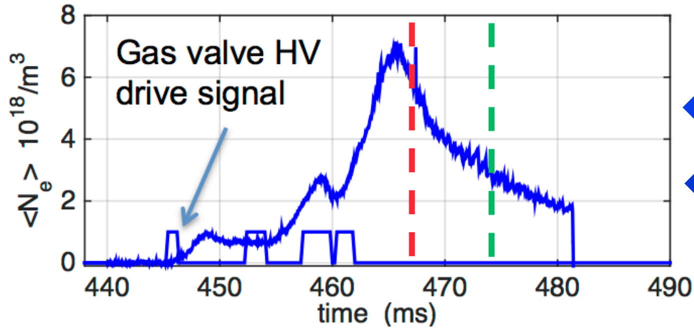
- R=40cm, a=26cm, κ=1.6
- Hot, high-Z shell in a limiter geometry
- Electron-beam based Li deposition technique
- Substantial confinement improvement with solid or liquid Li!
  - Can you achieve 'flat' profiles if you remove the particle source/ energy sink at edge?
- Commencing NB upgrade
  - 10x higher W_{MHD} w/I_p, B_t, NBI



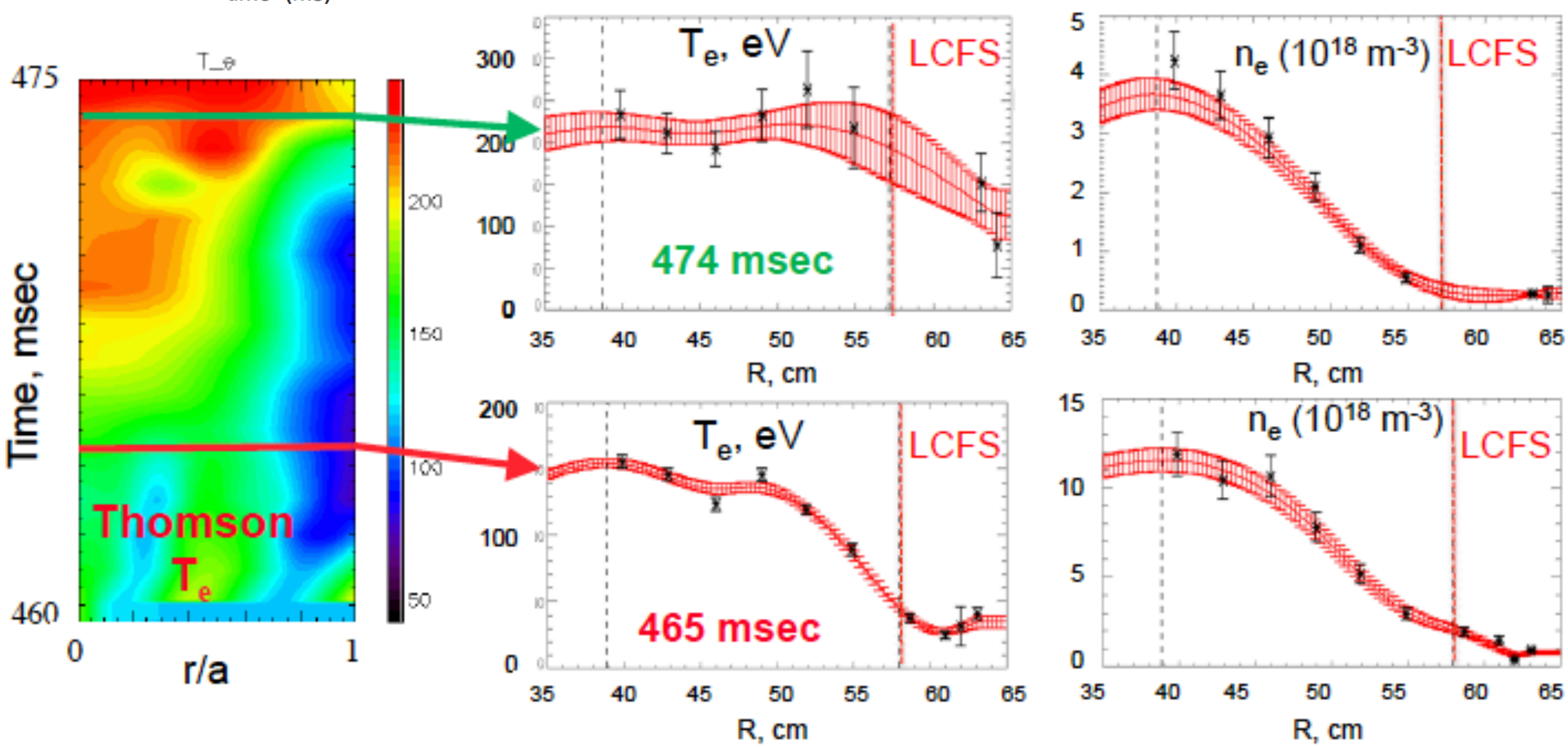


 J.C. Schmitt, *PoP* **22** (2015) 056112

Flat electron temperature profile develops in LTX when edge neutral pressure drops

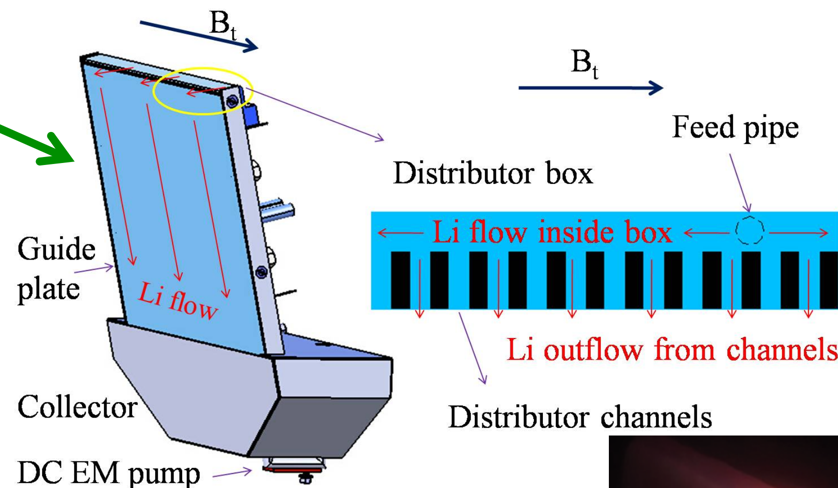


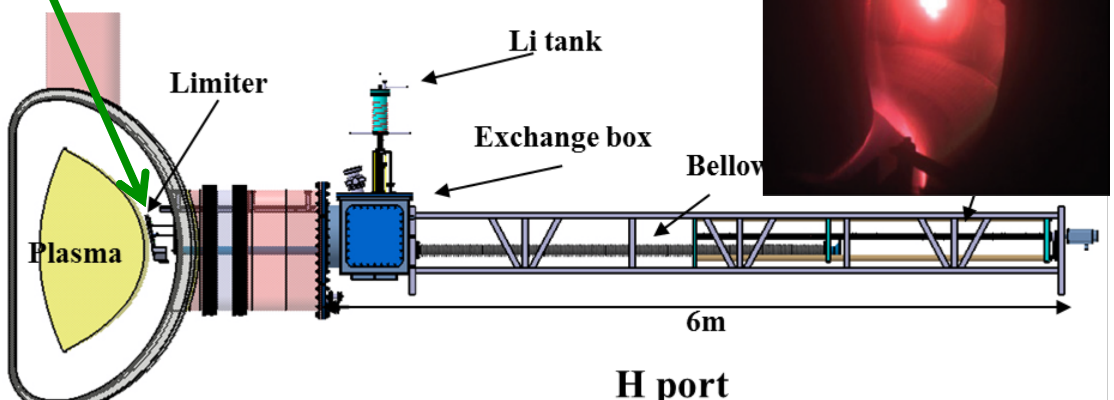
- Fueling terminated at 462 msec
- Thomson scattering time stepped through time during sequence of 60 identical discharges

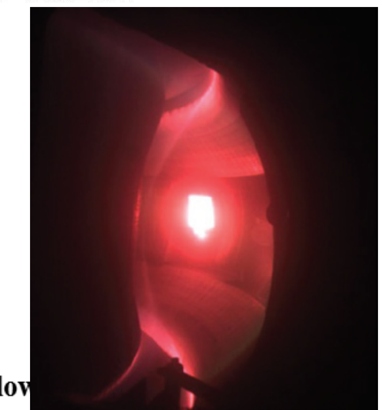


EAST: Liquid lithium limiter collaboration between ASIPP and PPPL, and inserted via midplane port

- Designed and fabricated at PPPL
  - Cu heat sink
  - SS protective coating
- Used a DC EM pump, with B_T of EAST, for steady-state recirculation
- First experiments in 10/2014; *new NF paper*
- *H-modes and ohmic discharges compatible with flowing Li limiter*
  - $q_{peak}^{limiter} \sim 2\ MW/m^2$
- Also active injection with Li dropper that eliminated ELMs (not shown)







J. Ren et al., *Rev. Sci. Instrum*. **86** (2015) 023504
J.S. Hu et al., *Nucl. Fusion* **56** (2016) 046011

PPPL liquid metal program includes collaborations throughout the community

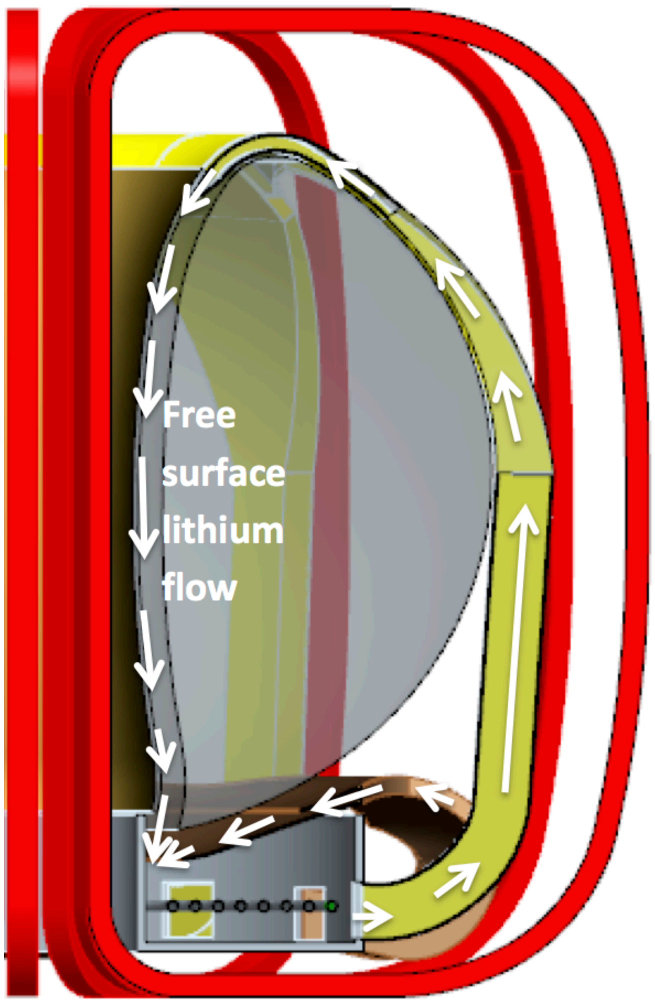
- Experiments on MAGNUM-PSI for pre-filled targets
  - Will be restarted once MAGNUM resumes ops in 2016, in conjunction with Eindhoven Univ. (EU)
- Experiments on Proto-MPEX under discussion
  - Using pre-filled liquid metal (e.g. Sn) targets, for droplet physics
- Experiments at UI-UC facilities on pre-filled Li targets: 8/16
  - To test NSTX-U pre-filled target concept
  - Additional interest on testing flowing Li and vapor box concepts
- Discussion with ORNL materials division initiated
  - Interest in collaboration with EU also: FTU, TJ-II
- *Advocate national liquid metal R&D needs workshop*

Outline

- Introduction
  - Motivation, advantages and disadvantages
  - Science and Technology issues
- Elements of existing program
  - NSTX-U lithium program and directions
  - LTX program and directions
  - EAST collaborative lithium program and directions
  - Liquid metal exposures in divertor simulators
- **New initiatives & Summary**
  - Evaluate fast flow concept: toroidal flowing system (new)
  - Liquid metal linear test stand for PMI evaluations, with full liquid lithium compatibility (new)
  - Expanded surface science capabilities

New (unfunded) element: torus with magnetic fields and full flowing liquid metal walls, mainly for reactor issues

Conceptual tokamak with LM wall & divertor



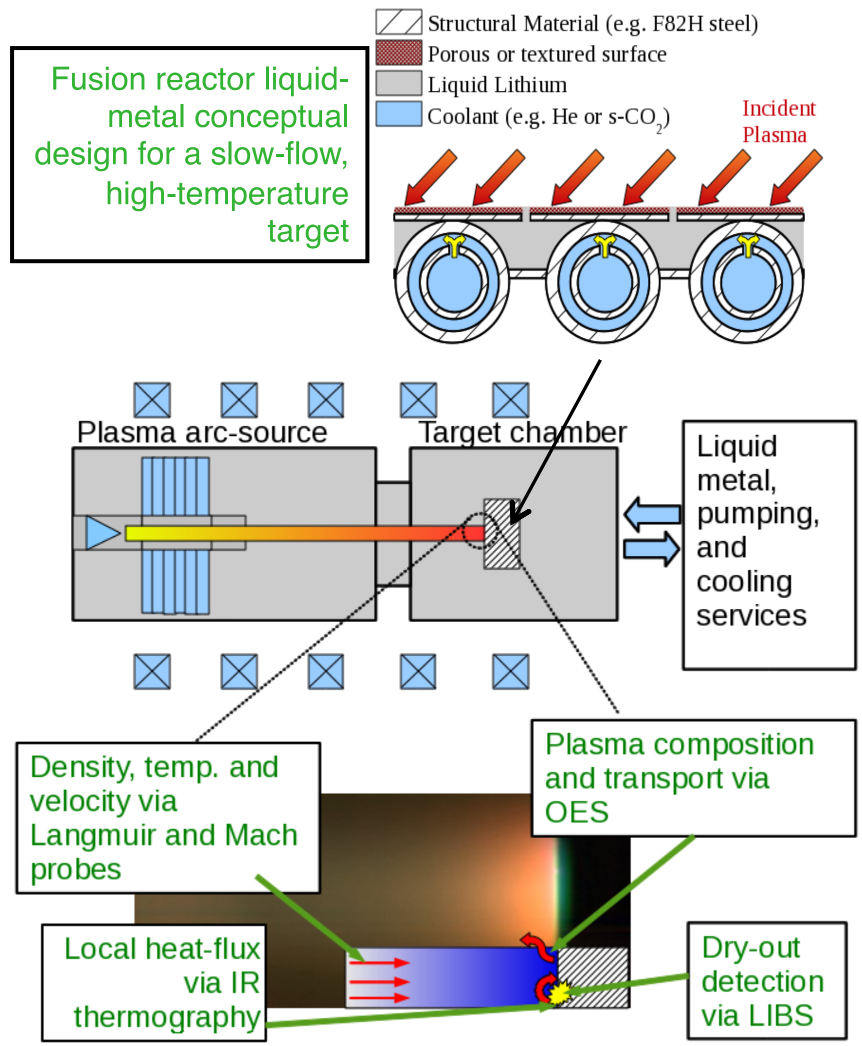
- Test stand with 1Tesla TF coils
  - **No plasma** for initial experiments
  - Lexan vessel in Ar atmosphere
  - Can add ring coil for poloidal field
- Demonstrate fast liquid metal flow
- Develop science and technology to *control* LM flows up to ~10 m/s
- Quantify and optimize heat transfer rates; evaluate convection
- Initial operation uses LM channel from existing device (LMX), using Galinstan (68.5% Ga, 21.5% In, 10% Sn)
- Future operations in Lithium

Possible need: a liquid metal linear test stand for PMI evaluations, with full liquid lithium compatibility

- Evaluate acceptable operating temperatures for liquid metals
- Evaluate fuel retention and removal from liquid stream
- Evaluate chemical compatibility with liquid metal and substrate

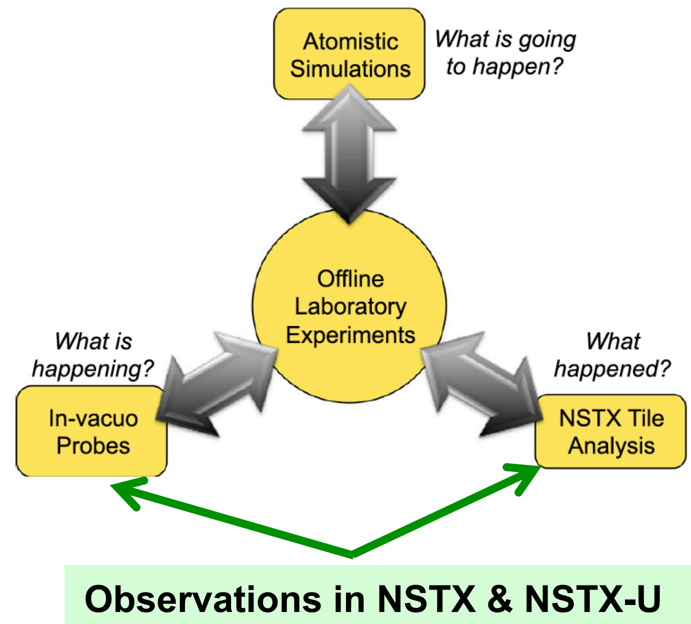
- Phase 1: liquid metal loop with high power plasma and H_2 separation (~3 years)

- Phase 2: High temperature liquid metal test (~5 years)

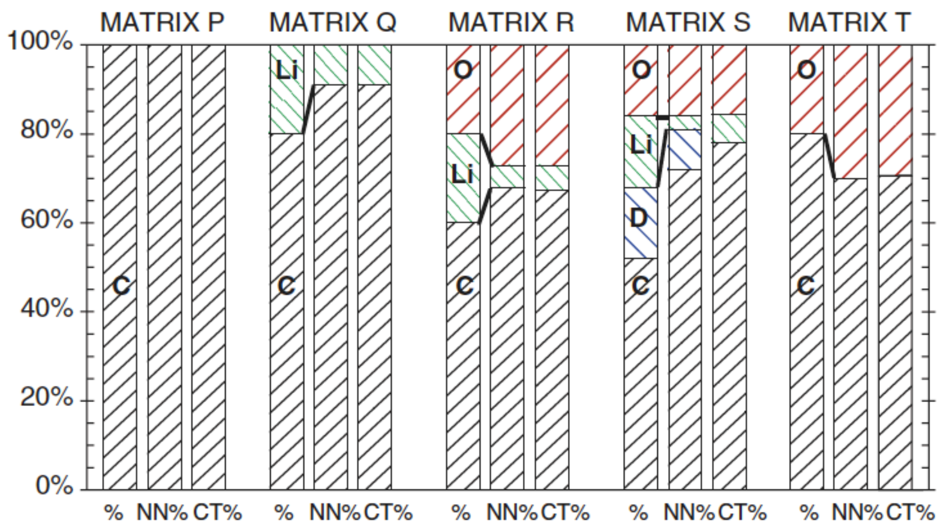


Surface Science studies aimed at fundamental understanding of surface physics via modeling and experiments

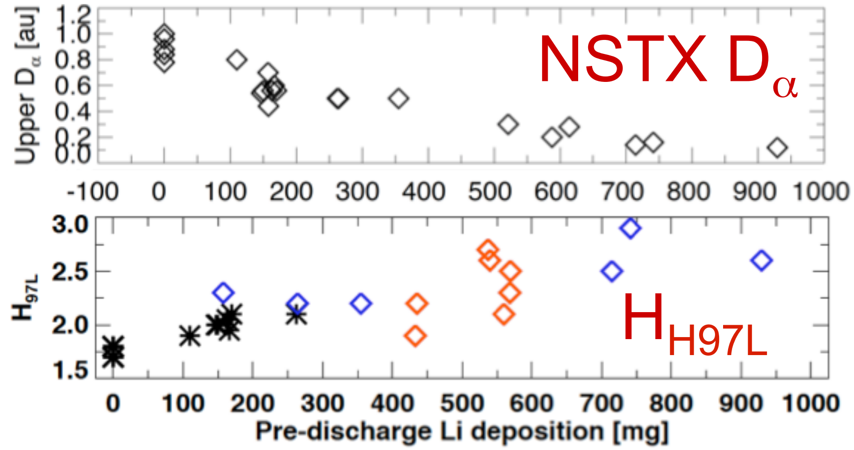
- Used to interpret observations of PFC and discharge performance
  - E.g. how Li-coated carbon PFCs reduce recycling and retain deuterium
- Can then be used to test liquid metal PFC designs
  - Experiments increase in complexity from single-variable to multi-variable as needed for fusion devices
  - Includes e.g. substrate optimization and wetting, D_2 retention…
  - Modeling integral for projections
- New resources needed to upgrade aging equipment and additional manpower



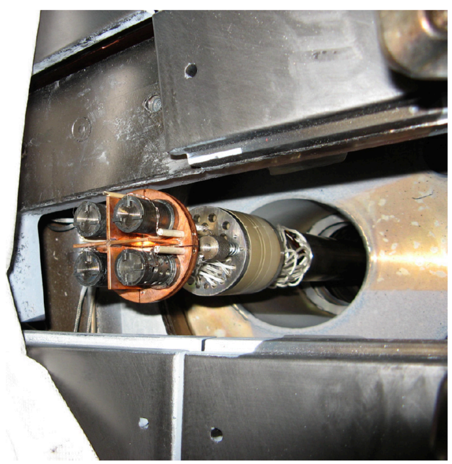
Surface science studies identified that oxygen is central to increasing D_2 retention with Li-coated carbon PFCs in NSTX-U

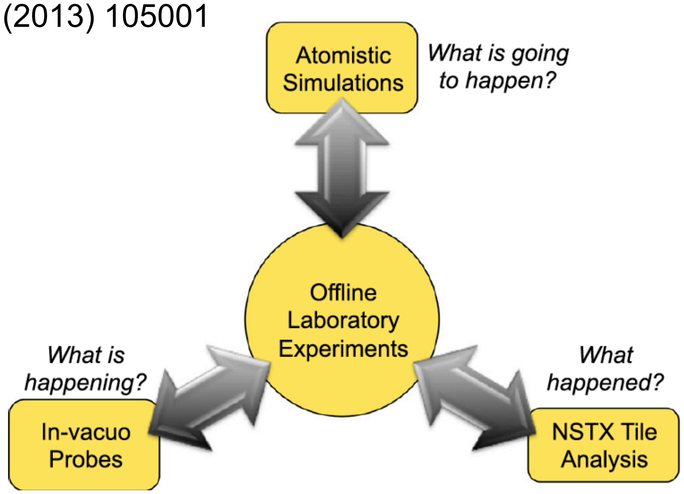


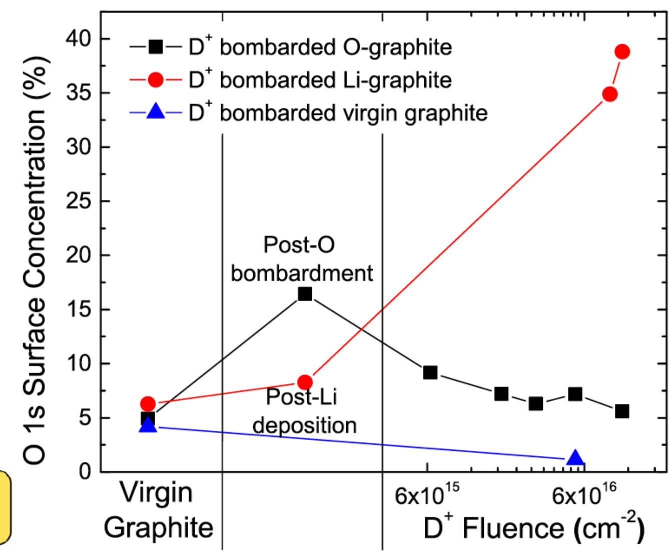
P. Krstic et al., PRL **110** (2013) 105001



R. Maingi et al., PRL **107** (2011) 145004







C. Taylor et al., PRL **21** (2014) 057101

Summary and Conclusions

- Goal is to assess the viability of liquid metal PFCs for power producing reactors in 10-15 years
- Continue emphasis on NSTX-U and LTX-β liquid metal programs, as well as EAST and domestic collaborations
- **Need**: Evaluate fast flow concept via torus with B_t, simulated plasma fields but no plasma
  - Test response of system to MHD instabilities
  - May be able to do some slow flow R&D; exposure to weak plasma…
- Collaborate on proto-MPEX and MAGNUM-PSI, but safety questions on compatibility with liquid lithium
  - **May need** to expand plasma exposure capabilities: linear plasma device fully compatible with flowing liquid metal targets
  - **Need** to upgrade surface science capabilities