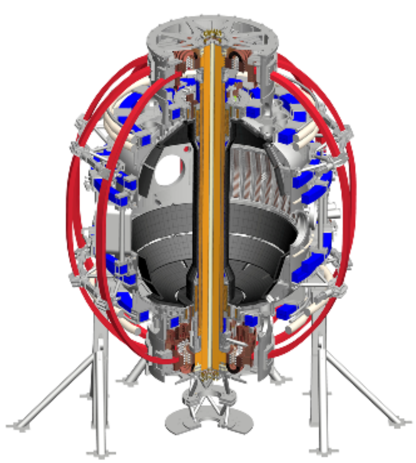
PPPL Institutional Overview

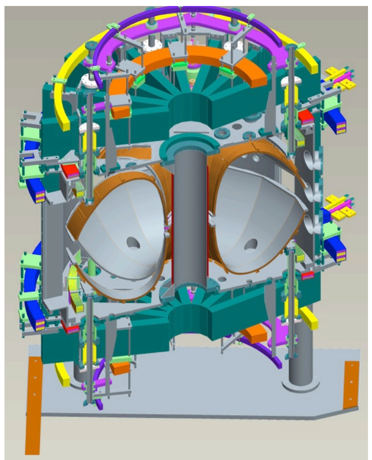
Charles Skinner, with contributions from

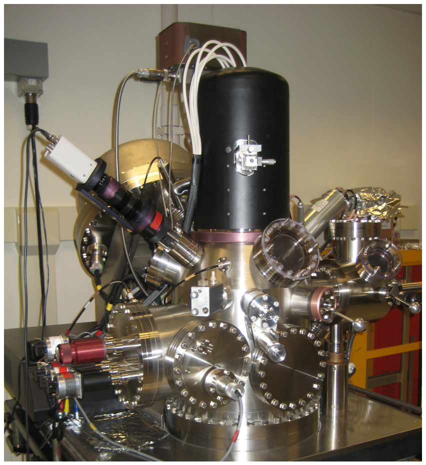
J.P. Allain, F. Bedoya, M. Jaworski, R. Kaita, B. Koel, E. Kolemen, R. Majeski,

R. Maingi, J. Menard, and the NSTX-U Team

Fusion Materials/Plasma Materials Interactions PI meeting
Oak Ridge National Laboratory
25-29th, July 2016







Outline

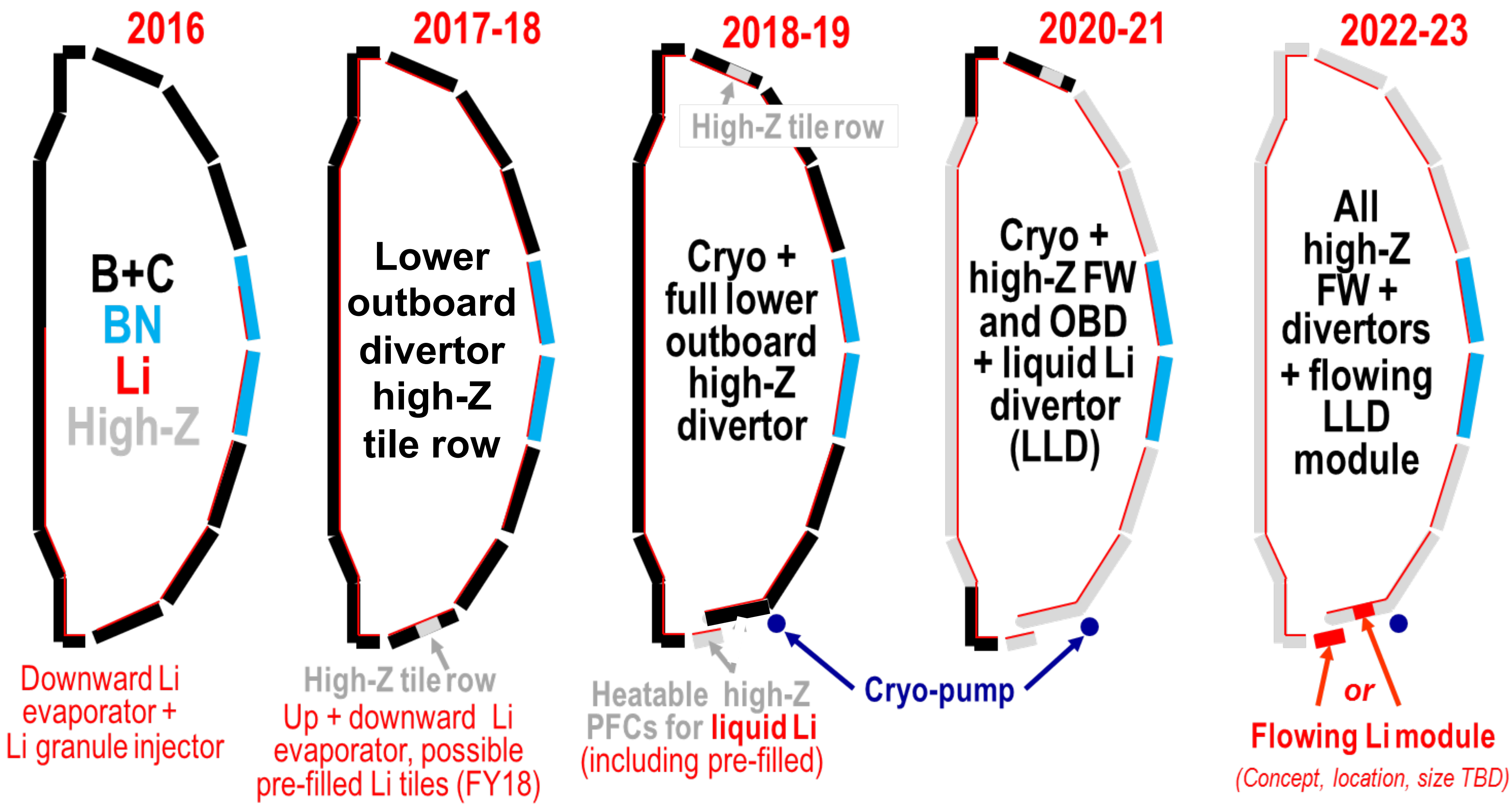
- NSTX-U PFC upgrade plan
  – Long term plan for high-Z and flowing liquid metal PFCs
- LTX program and plans
  – Neutral beam heating and fueling upgrade
- Surface Science program
  – Sample results of lithium surface physics

Viability of lithium as a plasma-facing material on NSTX-U cannot be assessed with graphite PFCs

- Lithium has improved plasma performance on NSTX, TFTR, EAST, TJ-II, RFX, LTX, and other machines
- Studies in NSTX and LTX have revealed complex chemistry in general as well as substrate dependence (i.e. C vs. metal)
- Evaporated films on graphite are not reactor relevant
- Importance of integrated scenarios *including the wall materials* recently demonstrated
  - e.g. JET with the Be wall and W divertor has lower energy confinement than with a carbon wall

NSTX-U staged conversion mitigates risk and enables comparative assessment of both high-Z and liquid Li

- Open divertor and flexible magnetic configuration enables studies of advanced divertors and materials.
- Single-variable experiment *in single campaign* enabled by conversion (i.e. high-Z vs. lithium PFCs)

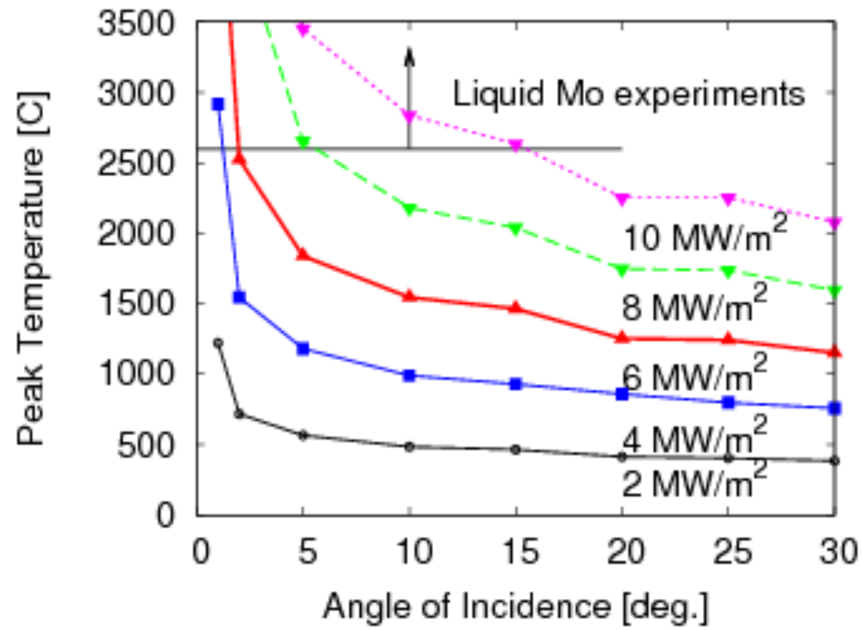


High-Z tile row will provide design and engineering assessments

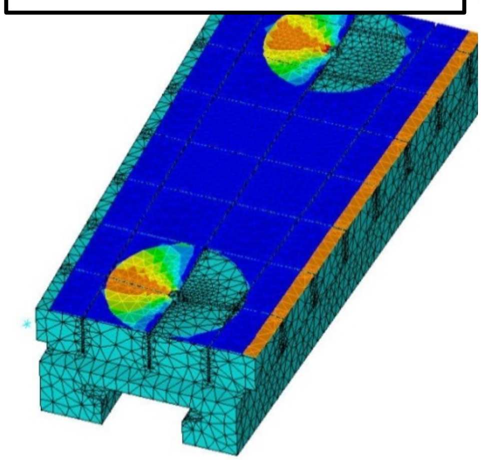
- Replace continuous row of graphite tiles with high-Z
  - Avoid Li substrate intercalation for longer-pulse experiments
  - Can low-Z coatings prevent high-Z influx and increase heat flux limit ?
- Provide operational experience and validate engineering design and analysis with an eye to future deployments of metallic PFCs
- Continue experiments on evaporated Li films on high-Z substrate in diverted configuration

High-Z design will enable broad temperature range and power handling capabilities for experiments

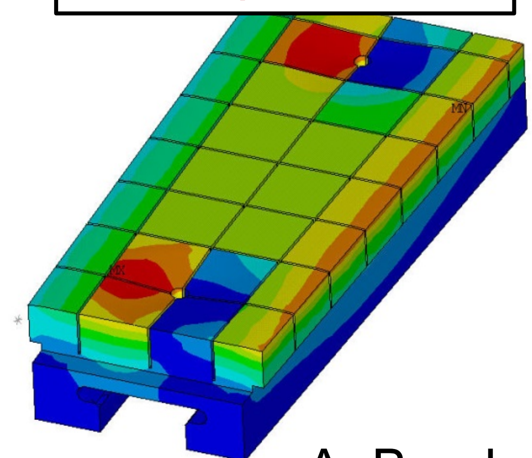
- Engineering design improves over graphite
- Geometric envelope lead to optimized, but stress-limited design
  -> good engineering tests
- Nominal transient heat-flux impact factor of 10 $MJ/(m^2\ s^{1/2})$
  - Leading edges mitigated with chamfering
  - Requires careful alignment



Surface heat flux



Temperature

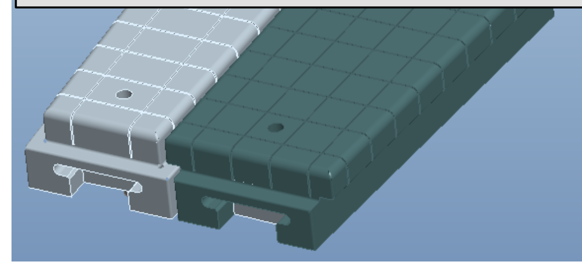


A. Brooks

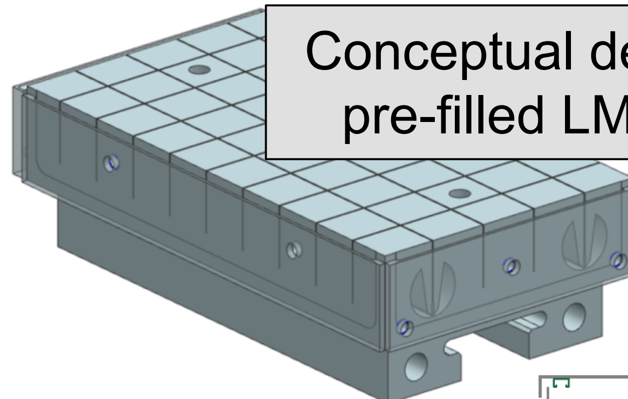
Three-step progression to flowing, liquid metal PFCs in NSTX-U

1. High-Z divertor tiles & LITER (2017)
2. Pre-filled liquid-metal target (2018)
3. Flowing LM PFC
(element in 2019-2023 proposall)

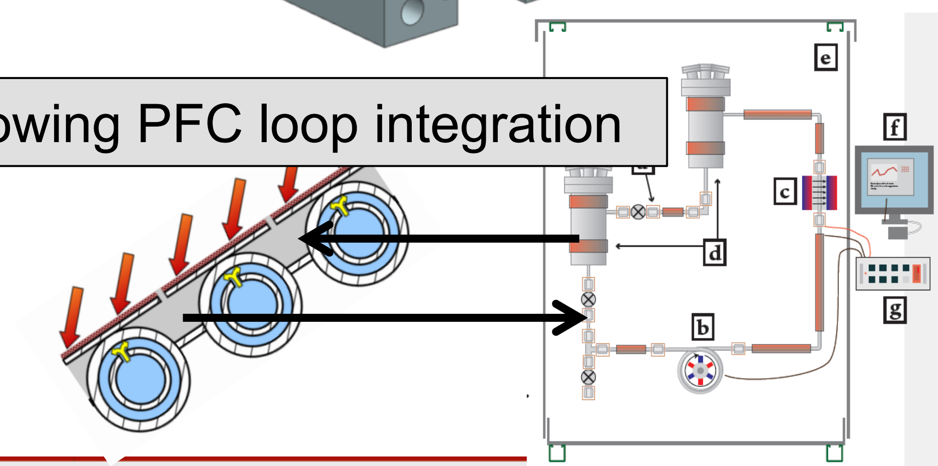
NSTX-U High-Z Divertor Upgrade 1



Conceptual design for pre-filled LM target



Flowing PFC loop integration

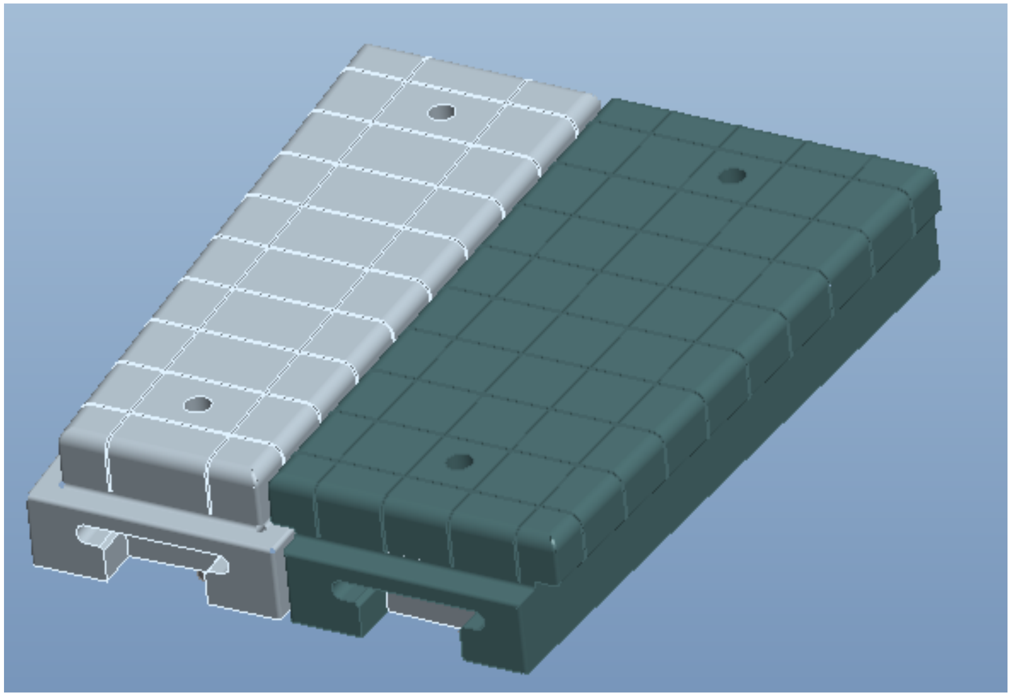


1.High-Z divertor tiles & Li evaporated coatings provide divertor analogue of Magnum-PSI experiments

– Technical goals:
  - Establish non-intercalating substrate for evaporated Li
  - Provide high-heat flux substrate for Li experiments

– Scientific goals:
  - Quantify maintenance of Li on high-temperature substrate and protection of substrate
  - Re-examine suppression of erosion in high-flux divertor
  - Understand impact and core-edge compatibility of high-temp. target with limited inventory of Li

NSTX-U High-Z Divertor Upgrade 1

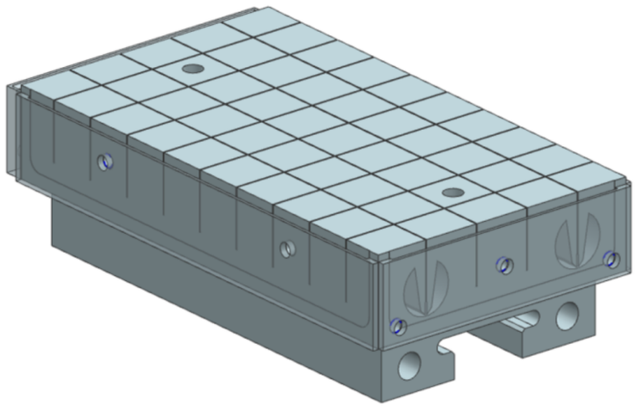


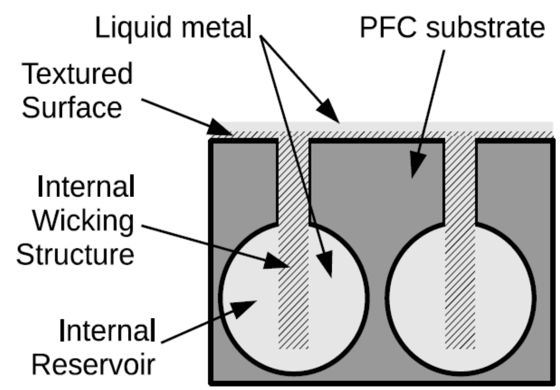
2. Pre-filled targets test LM coverage, resupply and impact of significant Li source

– Technical goals:
  - Achieve introduction of Li in NSTX-U without evaporation
  - Realize complex target production as high-heat flux target

– Scientific goals:
  - Test models of maintenance of LM wetting and coverage
  - Understand limits of LM passive resupply
  - Understand impact and core-edge compatibility of high-temp. target with **larger** inventory of Li

Conceptual design for pre-filled LM target





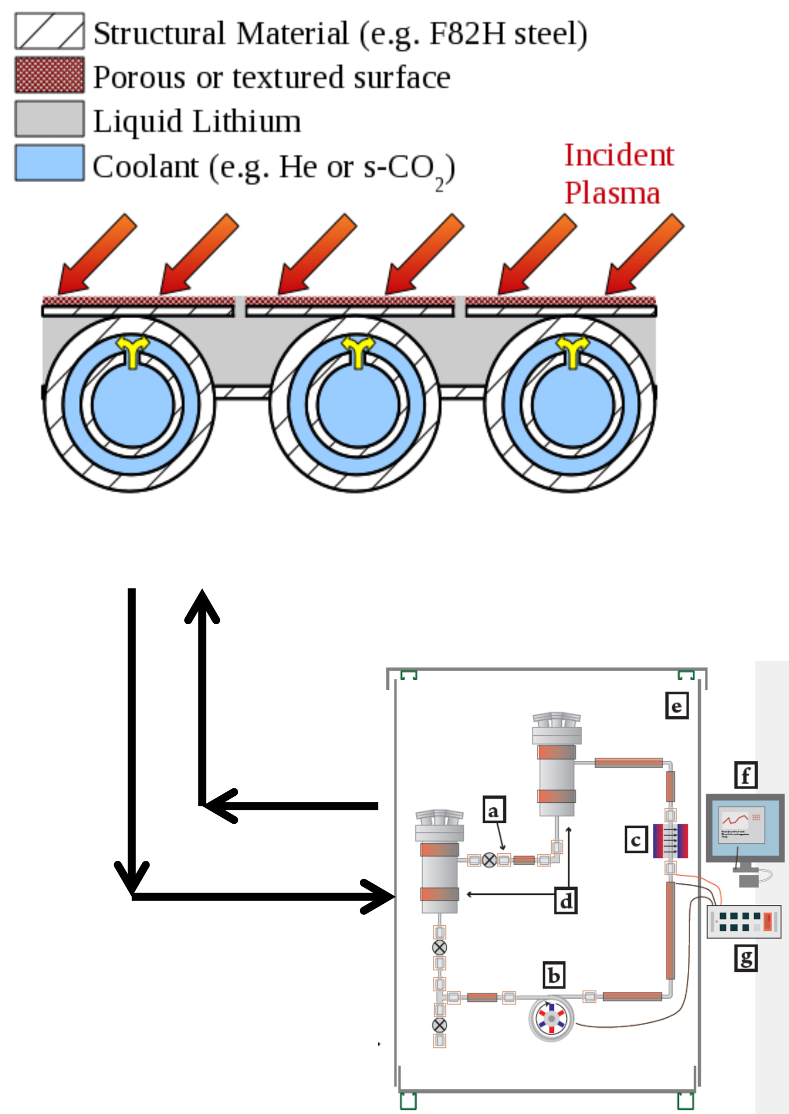
Trials begun at UIUC

3. Flowing LM PFC to demonstrate LM introduction/ extraction and inventory control

– Technical goals:
  - Integrate parallel effort on loop technology with confinement experiment
  - Achieve active introduction and extraction from exp.

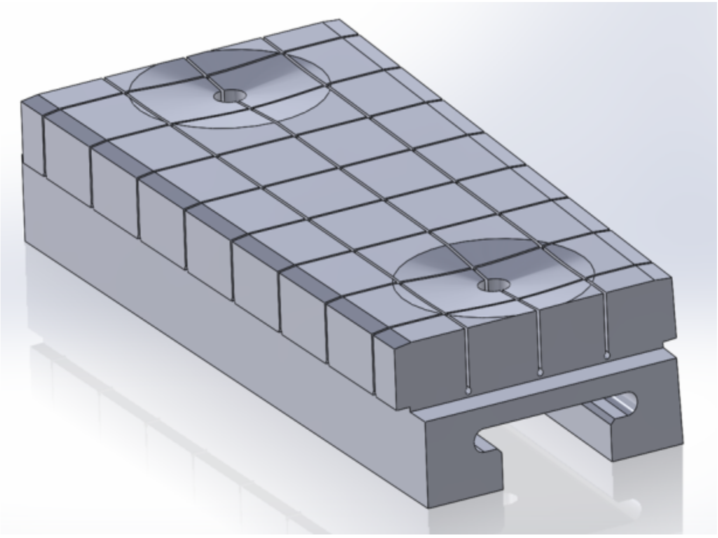
– Scientific goals:
  - Assess material inventory control from LM target
  - Understand performance of passive + active replenishment techniques
  - Understand impact and core-edge compatibility of <u>high-temp. target</u>

Flowing PFC loop integration

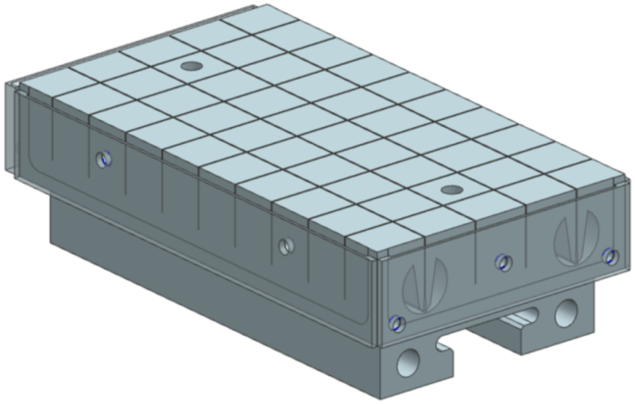


Most mature technologies emphasized in current development path for NSTX-U

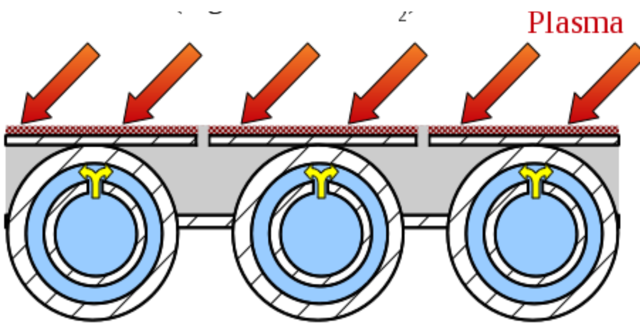
- Capillary-restrained PFCs demonstrated in numerous machines – nearest technology
- Pre-filled targets build on high-Z substrate design
- External Li feed into reservoir region with inertial cooling provides nearest target technology for NSTX-U



High-Z PFC design

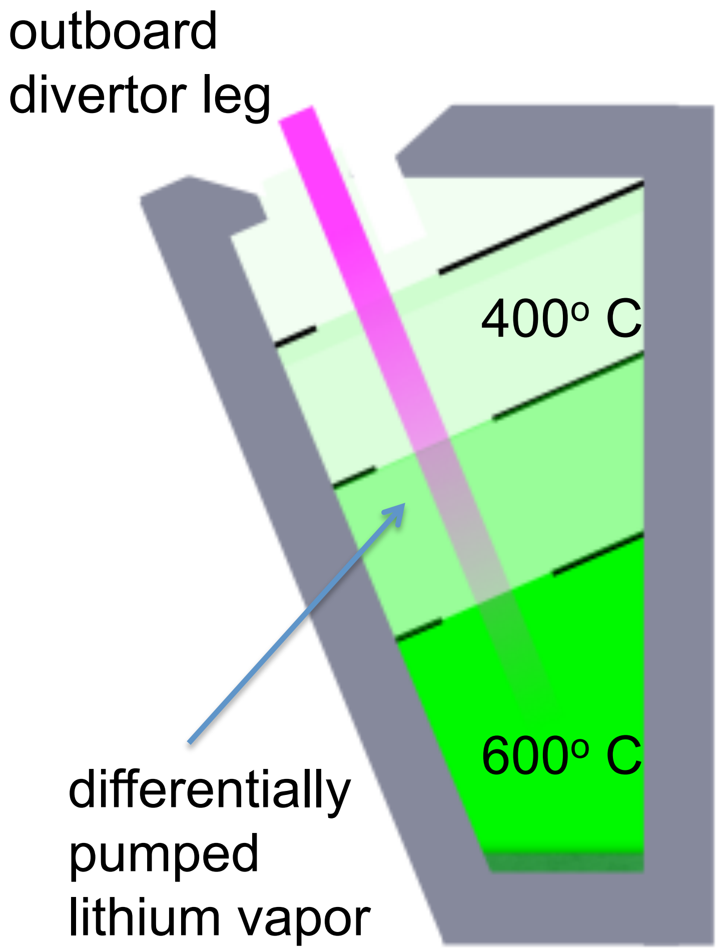


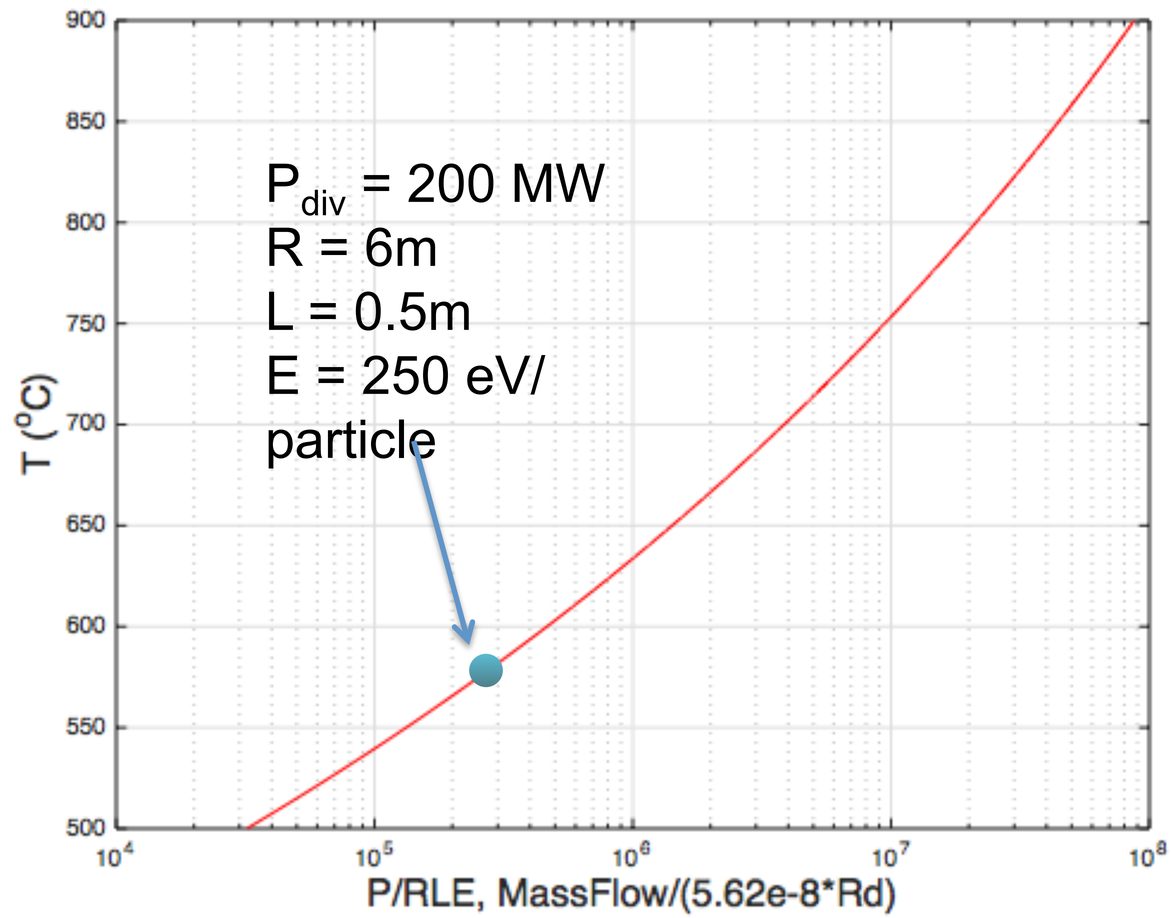
Pre-filled target concept



DEMO-relevant PFC concept

Steady-state Lithium Vapor Shielding concept





Lithium vapor in equilibrium with 600º C liquid in capilary porous system can detach DEMO divertor, with modest Li efflux. (Goldston)

Outline

- NSTX-U PFC upgrade plan
  - Long term plan for high-Z and flowing liquid metal PFCs
- LTX program and plans
  - Neutral beam heating and fueling upgrade
- Surface Science program
  - Sample results of lithium surface physics

LTX is testing the effects of lithium PFCs on tokamak performance

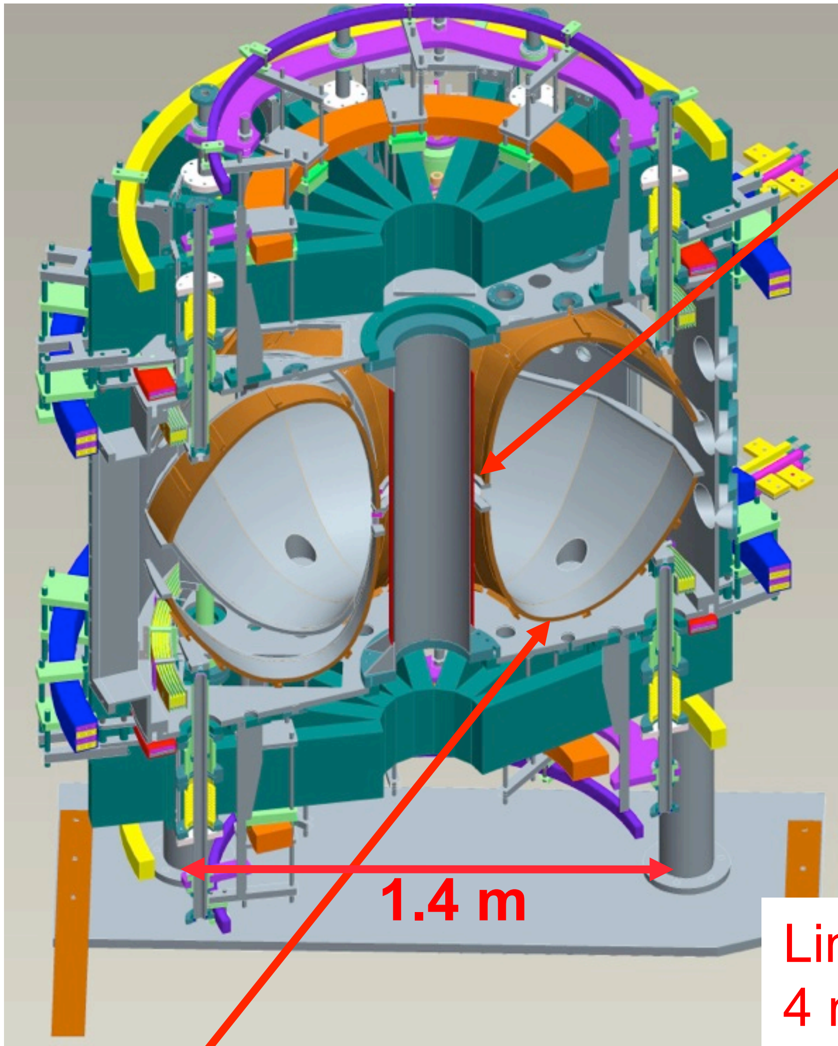
*Key research question: Can lithium produce isothermal confined plasmas,and suppress ∇T related turbulence**

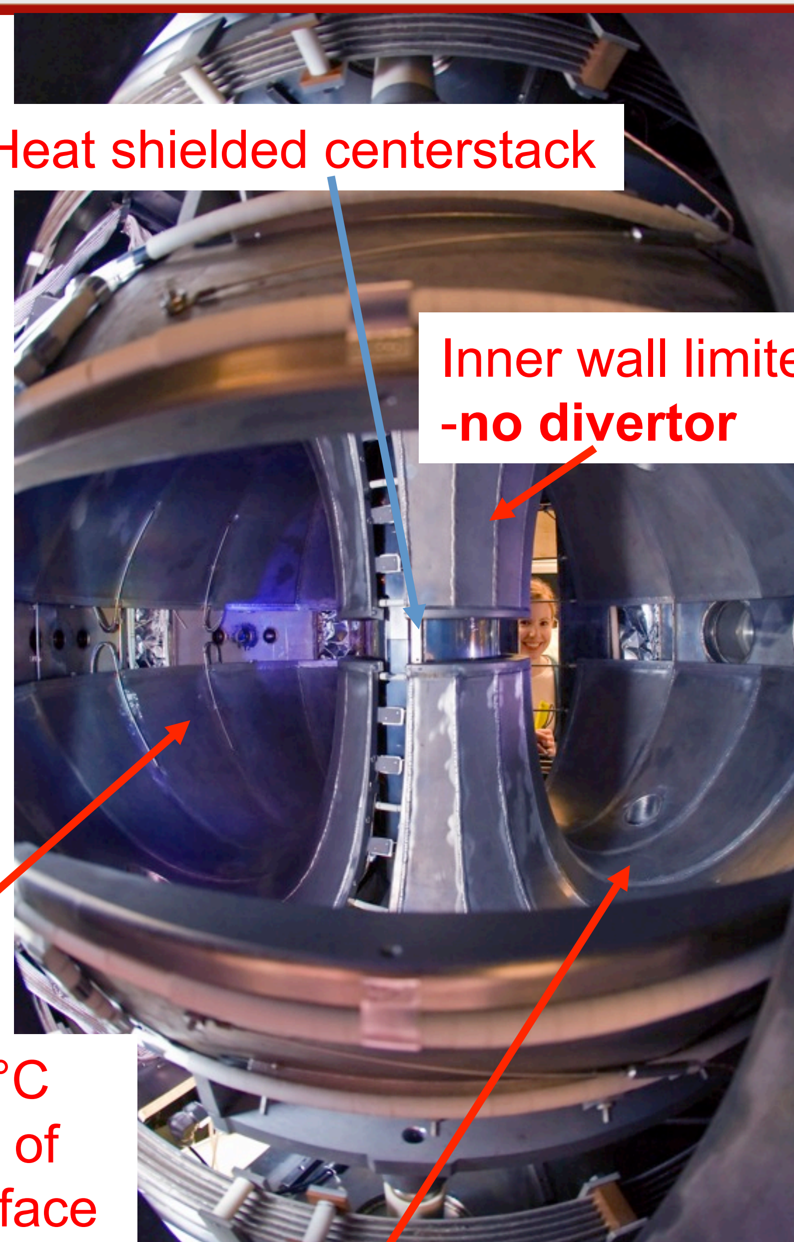
- LTX is a small, low aspect ratio tokamak
  - R_0 = 40 cm, a = 26 cm, κ = 1.55, δ = 0.2
  - B_{tor} < 1.7 kG
  - I_p < 100 kA
- Limited, not diverted
  - Conformal high Z (stainless steel) wall
  - Typically wall-limited on the high field side
- Ohmic only; no auxiliary heating at present
- Pulse length ≤ 50 msec
- Operated in hydrogen (gas puffing)
  - Fueled from the high field side midplane

*S. Krasheninnikov, L. Zakharov, G. Pereverzev, Phys. Plasmas **10**, 1678 (2003), L. E. Zakharov et al., Fus. Eng. Des. 72, 149 (2004), J. Catto and R. D. Hazeltine, Phys. Plasmas **13**, 122508 (2006)

All plasma-facing surfaces are lithium coated

Typically a few 100 - 1,000 Å per evaporation





Heat shielded centerstack

Inner wall limited
-no divertor

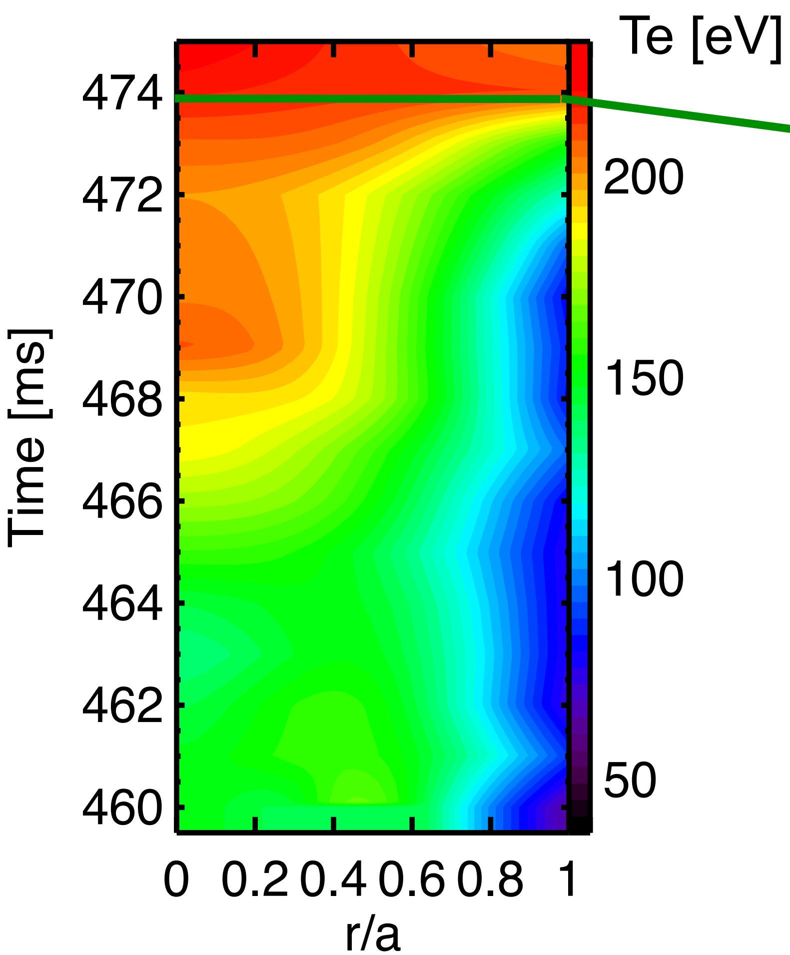
Liner >300°C
4 m^2 - 80% of
plasma surface

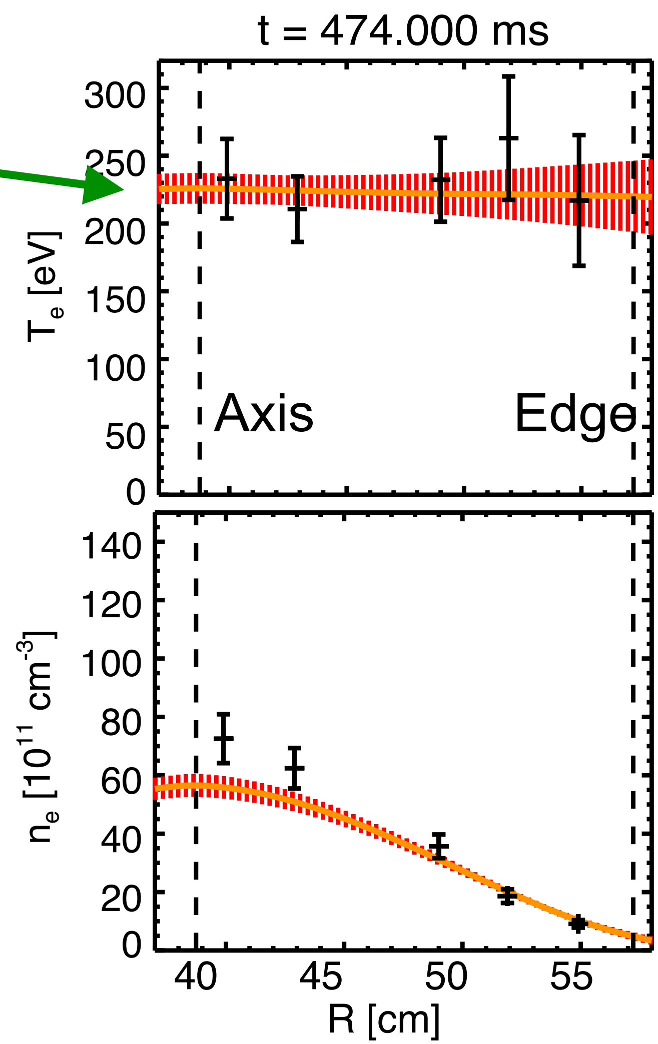
Inner heated shell (304L stainless steel on copper)

➡ Bottom of shells form **reservoirs for up to 300 cm^3** liquid lithium

Key result:
First observation of fully isothermal confined plasmas

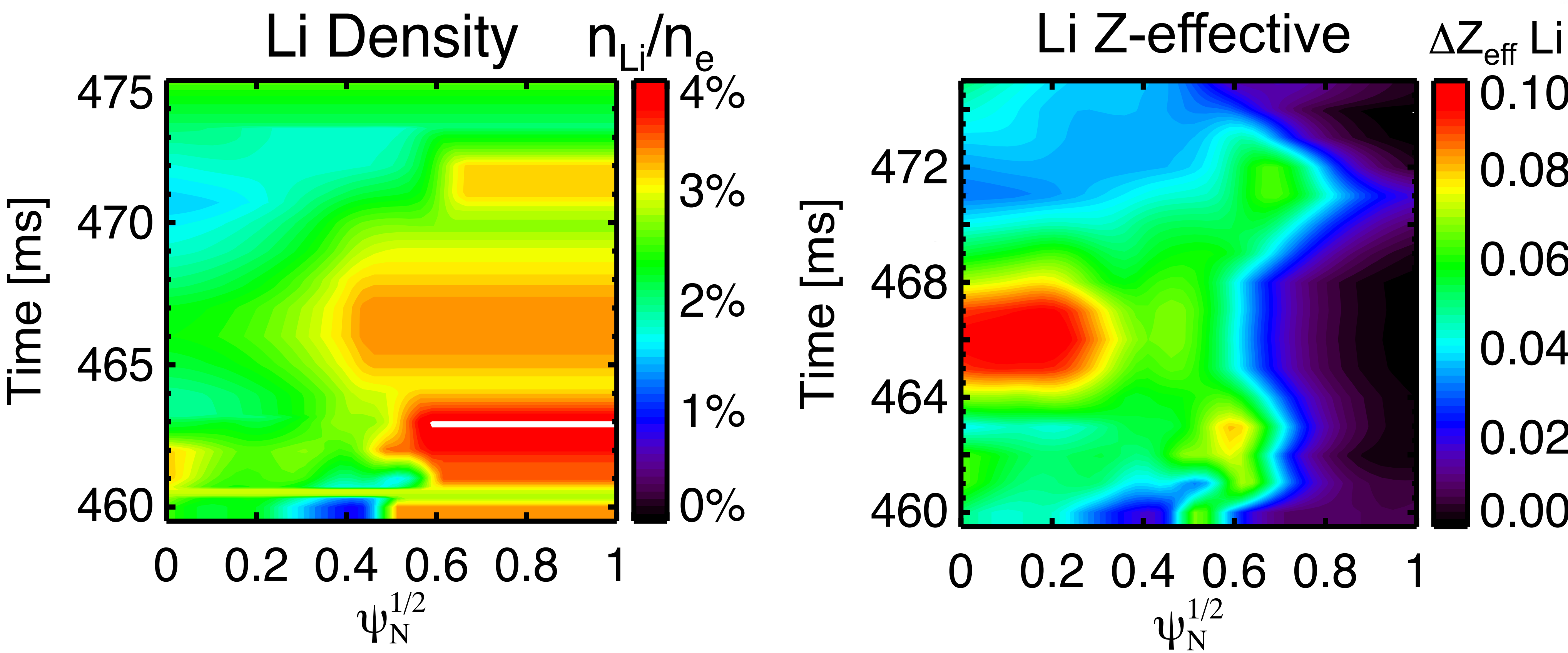
- Late in discharge:
  - Lithium suppresses recycling
  - No gas from puffing





- **No cooling: edge T_e = core T_e**

Lithium does not dilute core plasma or radiate power in LTX



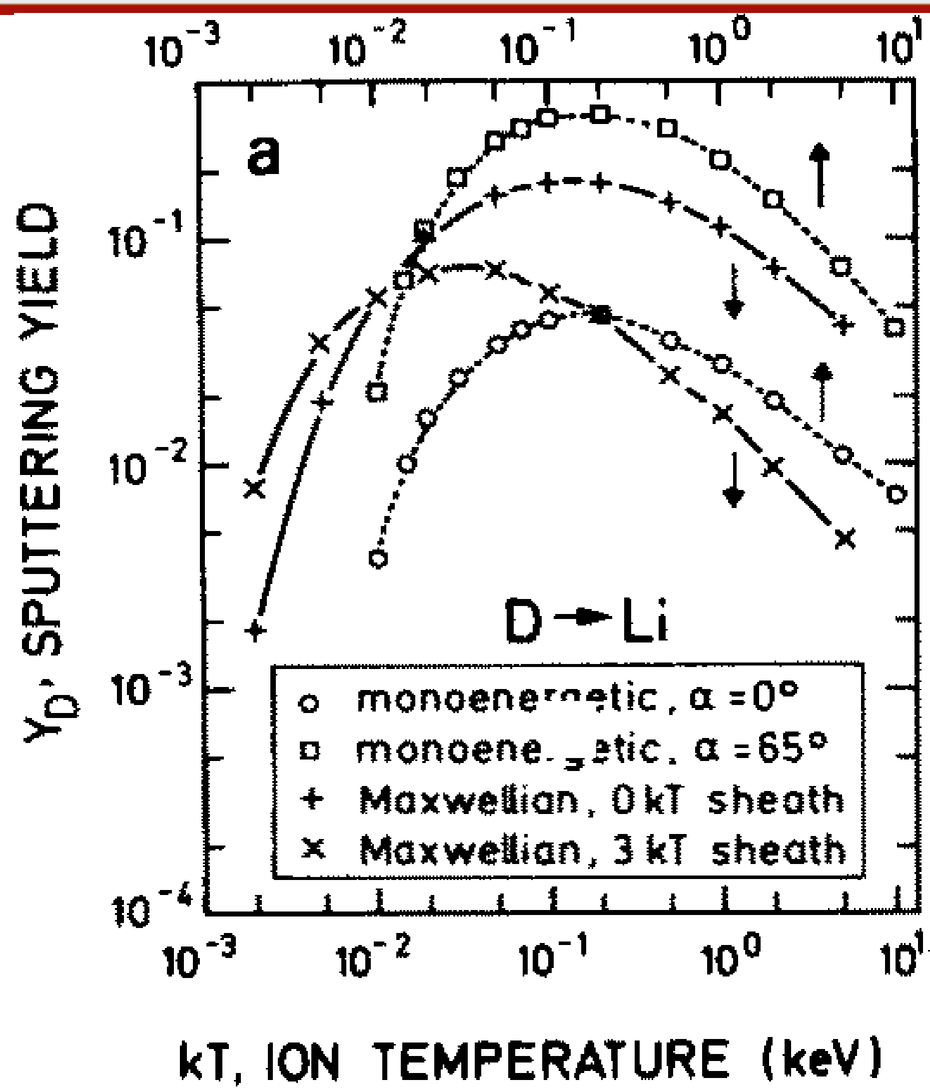
- Lithium impurity <2-3%
  - Modest radiation losses compared to tungsten walls
  - $Z_{effective}$ remains below 1.2
- Lithium influx will <u>decrease</u> with further energy increases

Sputtering characteristics of lithium PFCs compatible with a hot, low density edge

- At T_i ~ 10 keV ion sputtering yield for D on lithium is less than 1%
  - Comparable to yield for a ***1 eV*** plasma

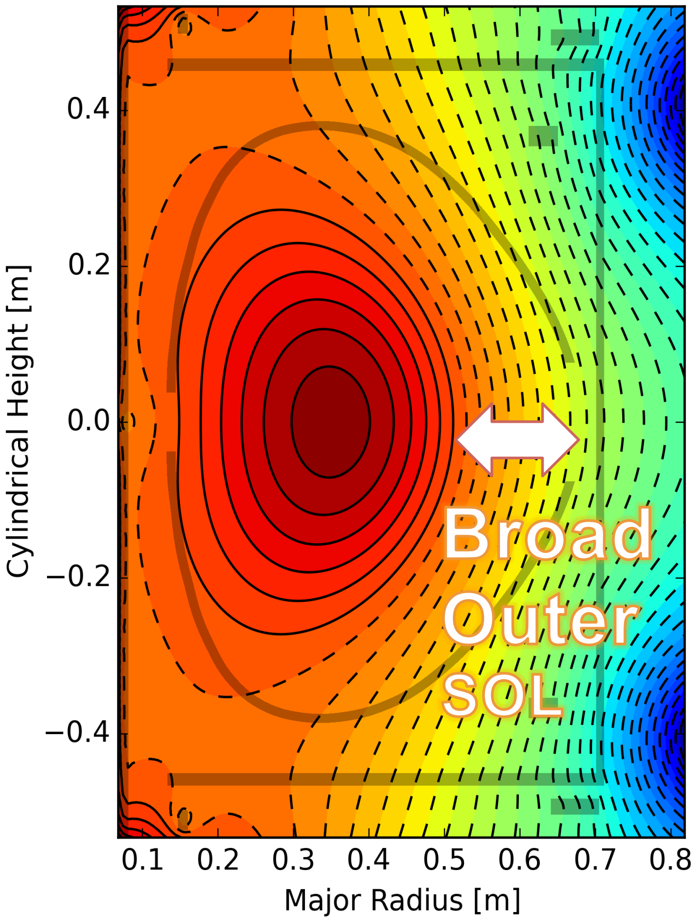
Exciting opportunity to address many fusion reactor issues:

- *Reduced turbulent energy losses*
- *Reduced erosion*
- *Reduced impurity influx*
- *Broader divertor heat flux.*



J. Laszlo and W. Eckstein, J. Nuc. Mater. 184(1991)22 – TRIMSP model. Also work by J.P Allain)

Scrape-off layer broadens with $\sqrt{T_{ion}}$ - reducing power loading at the wall



PSI-TRI reconstruction

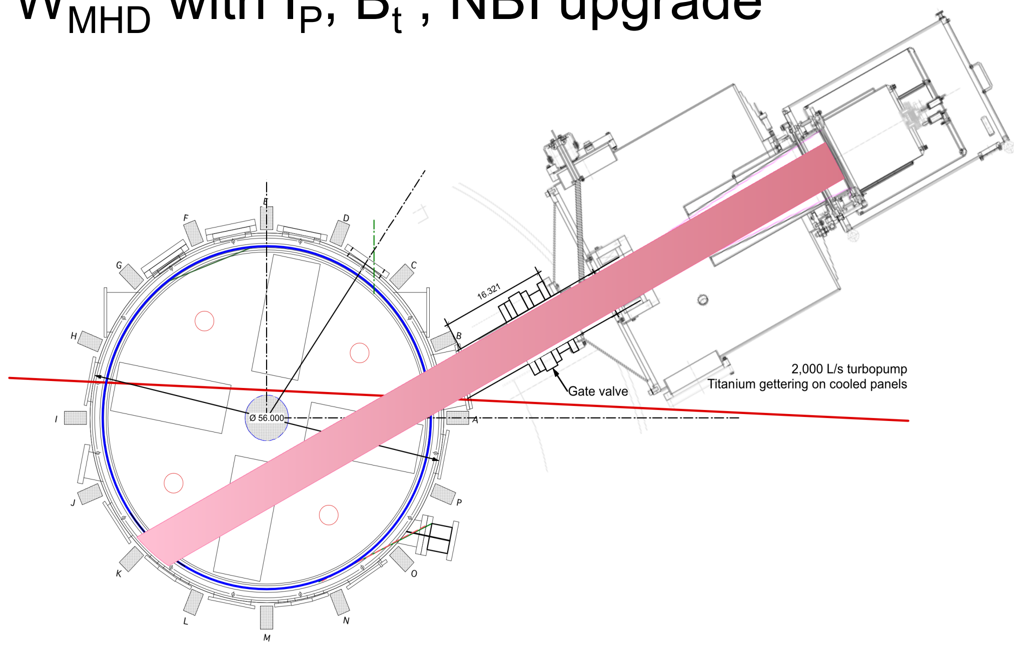
- Width of the scrape-off layer (through which the exhaust power flows) ~ $(T_{ion})^{1/2}$
- High edge ion temperature results in power spreading
- Diffuse, hot, low density plasma carries the exhaust power to the lithium wall
  - A liquid lithium wall would not be damaged by high energy particle flux

- Divertor power density broadened by an order of magnitude in reactor with hot, low density, low recycling edge
  - Compared to cold, dense, high recycling edge

Neutral beam will extend lithium wall studies in LTX-U
NBI systems on loan from Tri-Alpha Energy

- **Significant core fueling source replaces recycling**

- 17 – 23 kV, 35A, pulse length 30 – 50 msec
- P_{aux} >>P_{ohmic}; ~10x higher W_{MHD} with I_P, B_t , NBI upgrade
  - Large torque input



- New vacuum transfer station for surface analysis of wall samples
  - Collaboration with U. Tennessee (D. Donovan) and Princeton U. (B. Koel)

Outline

- NSTX-U PFC upgrade plan
  - Long term plan for high-Z and flowing liquid metal PFCs
- LTX program and plans
  - Neutral beam heating and fueling upgrade
- Surface Science program
  - Sample results of lithium surface physics

Why Emphasis on Surface Science ?

- NSTX-U will challenge the limits of existing materials.
- Novel solutions needed but knowledge base for LM PFCs incomplete.
- Tokamak trials essential but development cycle is multiple years per step and expensive.
- Surface science studies can help develop the knowledge base for optimal design of LM PFCs, lower the risk, allow high-risk/high payoff innovation, and accelerate the development cycle.
- Surface science enables model development and validation

Wide span of parameters and tools

Atomistic simplicity, clarity

Complexity, realism

Experiment:

- Single crystals, mono-energetic ion beams
- Amorphous materials, mixed materials, lab plasma sources.
- High flux, high fluence linear plasmas
- Tokamaks

Simulations:

- Atomistic simulations: 100s atoms, pS times e.g. DFT, MD
- Meso-scale models, adaptive time scales e.g. Xolotl.
- Tokamak scale models e.g. DEGAS, WALLDYN

Multi-institutional effort

Experiment ⟷ Simulations

Atomistic simplicity, clarity

↕

Complexity, realism

- PPPL Surf. Sci. Labs
- Princeton U. Surf. Sci. Labs
- U Illinois Nucl. Engin.,
- DIFFER Magnum PSI
- NSTX-U MAPP diagnostic
- EAST Li collab

– Princeton U.
  Density Functional Theory, Computational Fluid Dynamics

– Stony Brook U.
  Molecular Dynamics

– ORNL, UTK:
  Xolotl

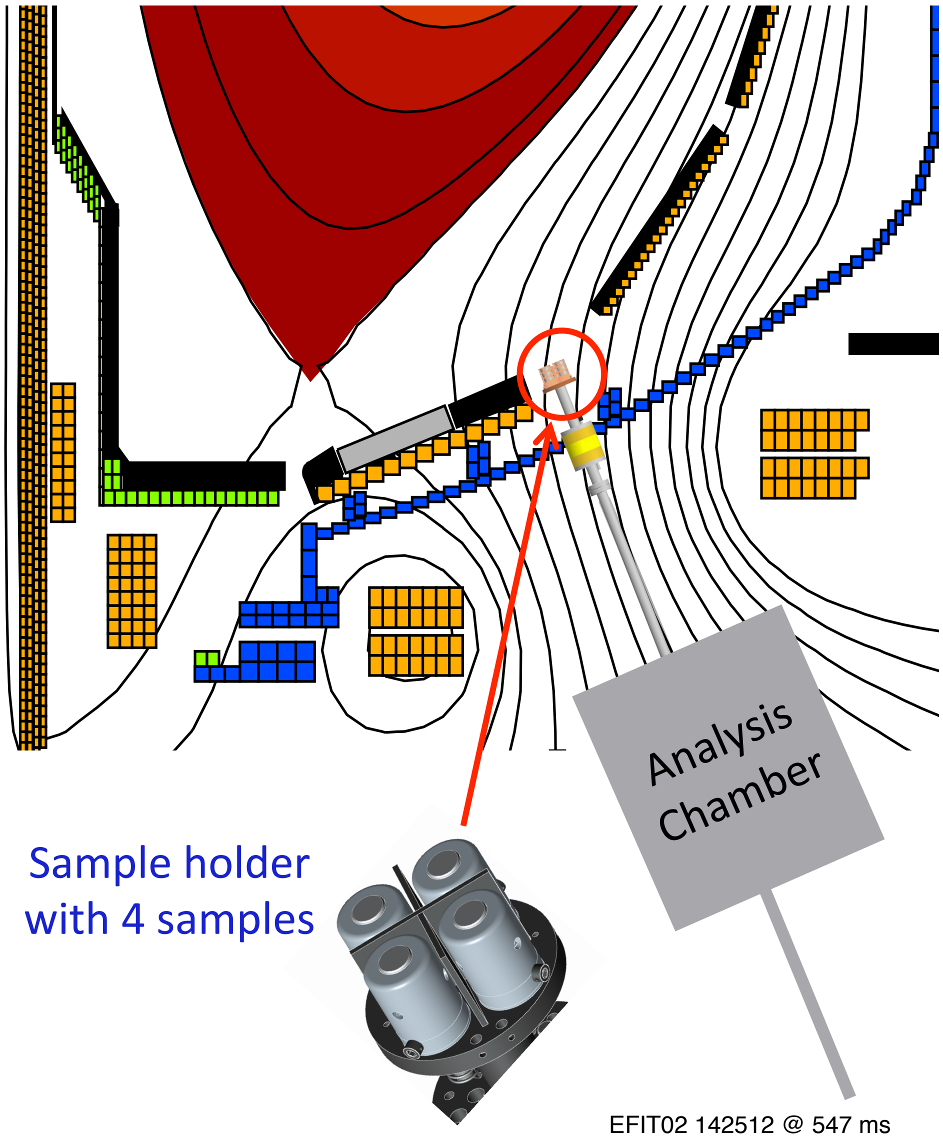
– PPPL:
  DEGAS, WALLDYN…

plus other non-PPPL US and International work

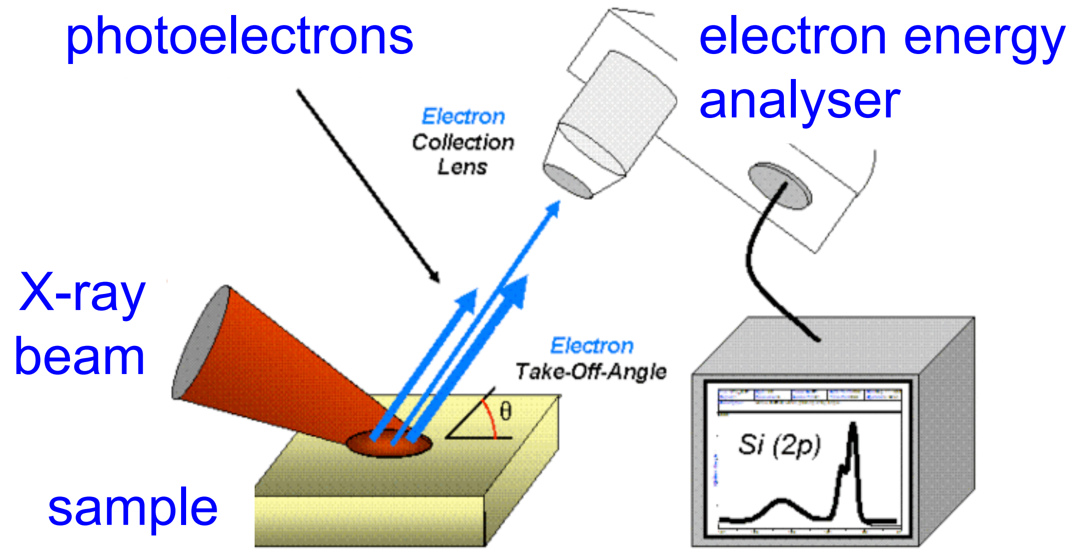
MAPP has opened window to surface chemistry

Materials Analysis Particle Probe (MAPP)

JP Allain, B Heim, F Bedoya, R Kaita et al…



Samples exposed to NSTX-U plasmas then withdrawn for analysis by X-ray Photoelectron Spectroscopy

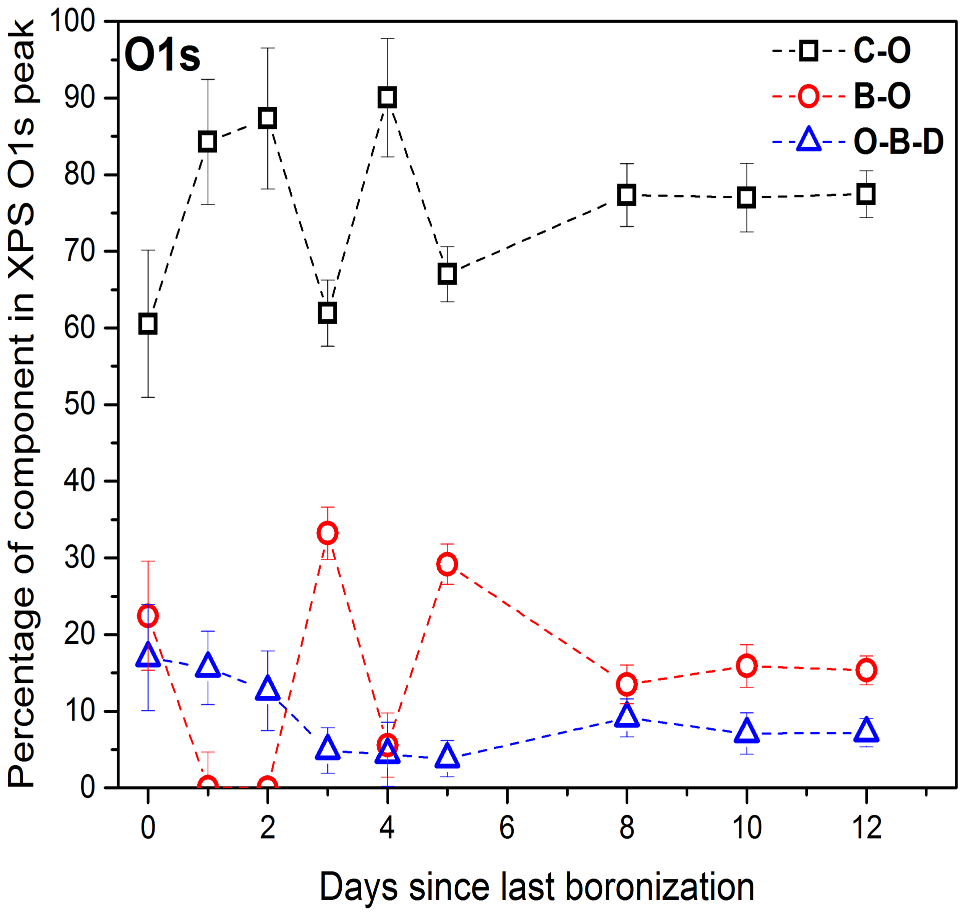


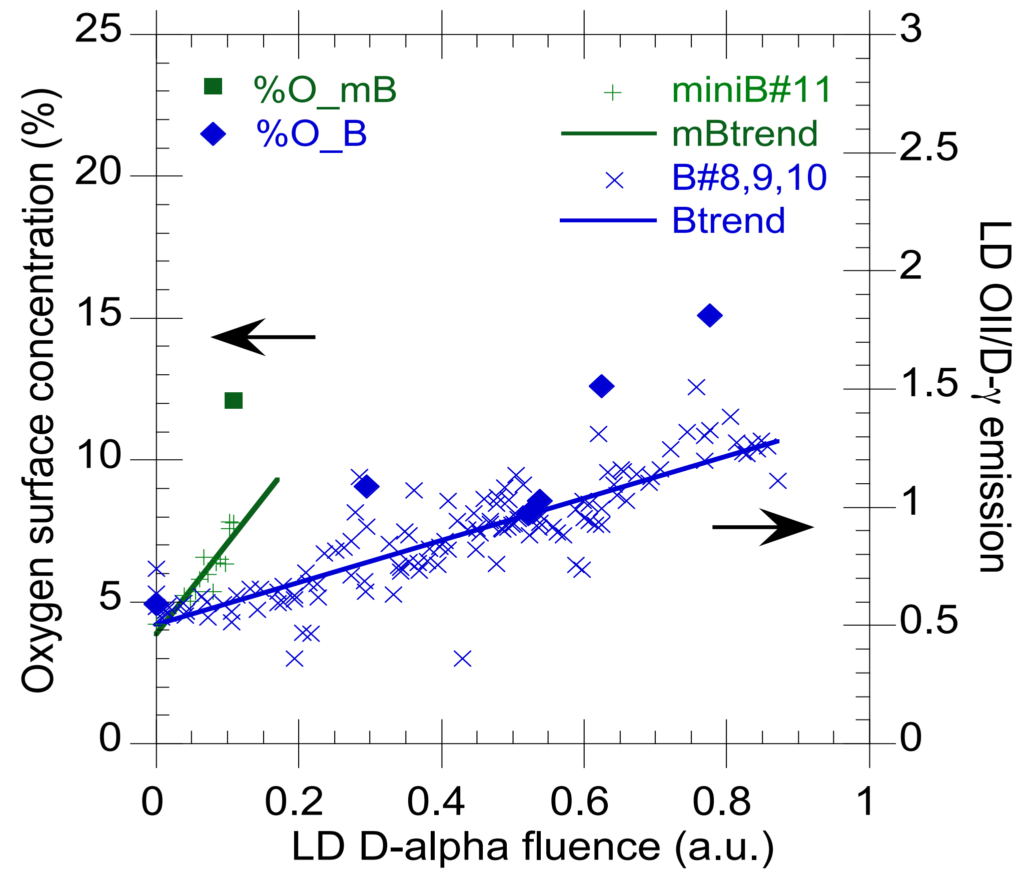
XPS spectrum shows elemental composition (and chemical shifts)

https://commons.wikimedia.org/wiki/File:System2.gif

Ion scattering and thermal desorption capability being implemented

MAPP data has revealed surface chemistry and correlation to plasma conditions





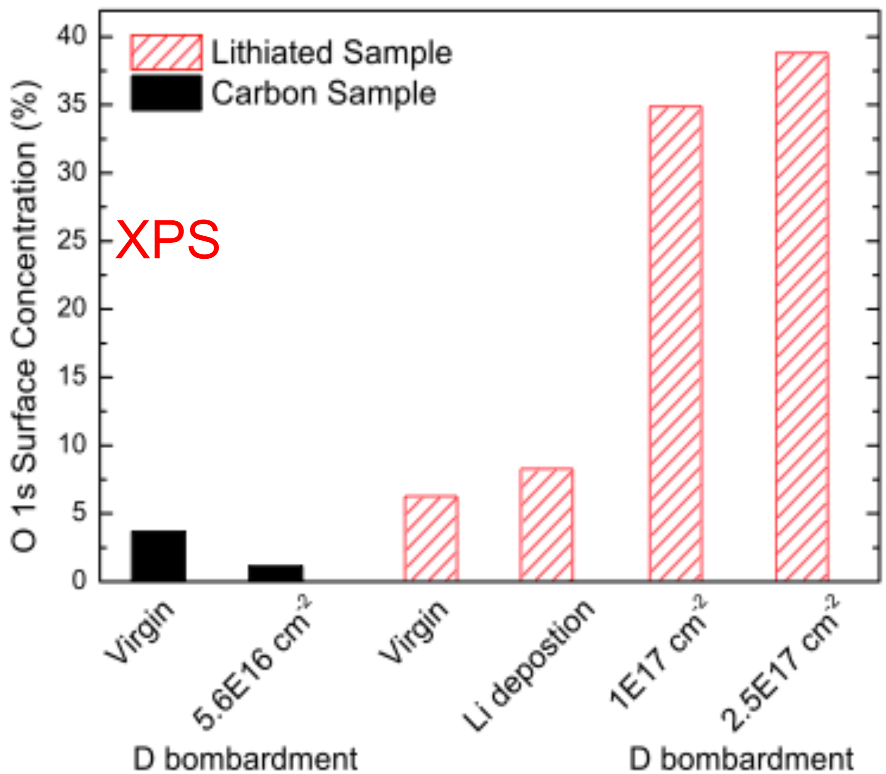
MAPP X-ray photoelectron spectroscopy reveals changes in PFC surface chemistry following boronization.

Bedoya NME 2016, Skinner NME 2016

The fast and slow O II plasma emission rise tracks the rise in surface atomic oxygen concentration as measured by MAPP XPS

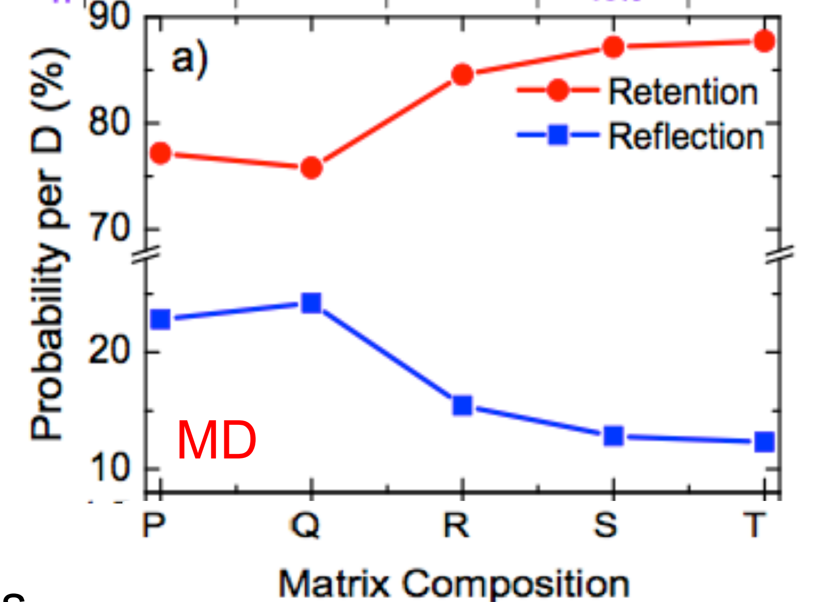
Example 2. Oxygen plays key role in D uptake by Li conditioned graphite

XPS data and MD simulations illuminate D retention



Matrix Composition

	P	Q	R	S	T
C	100%	80%	60%	52%	80%
Li		20%	20%	16%	
O			20%	16%	20%
H				16%	

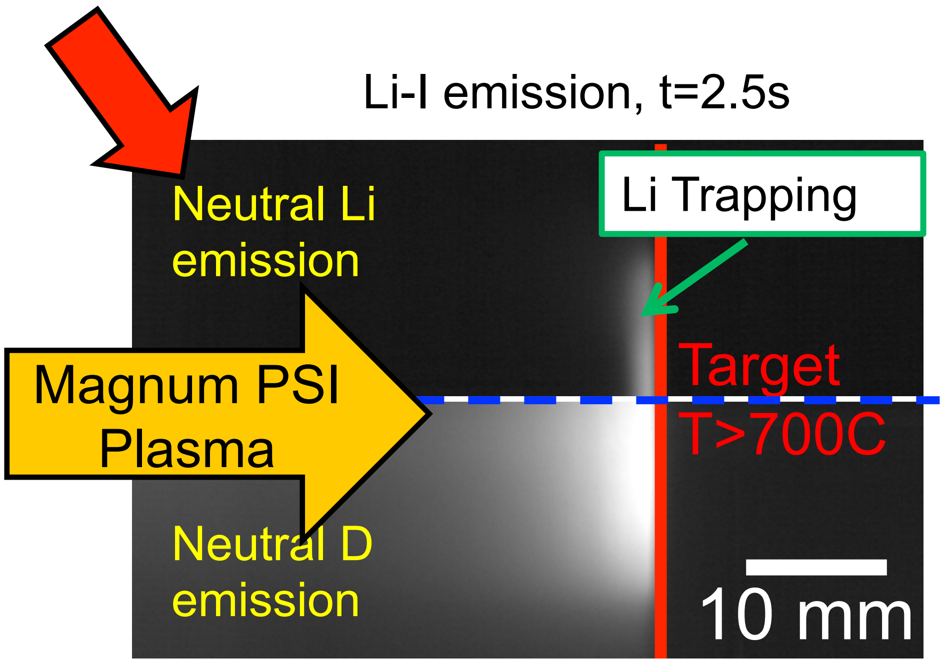


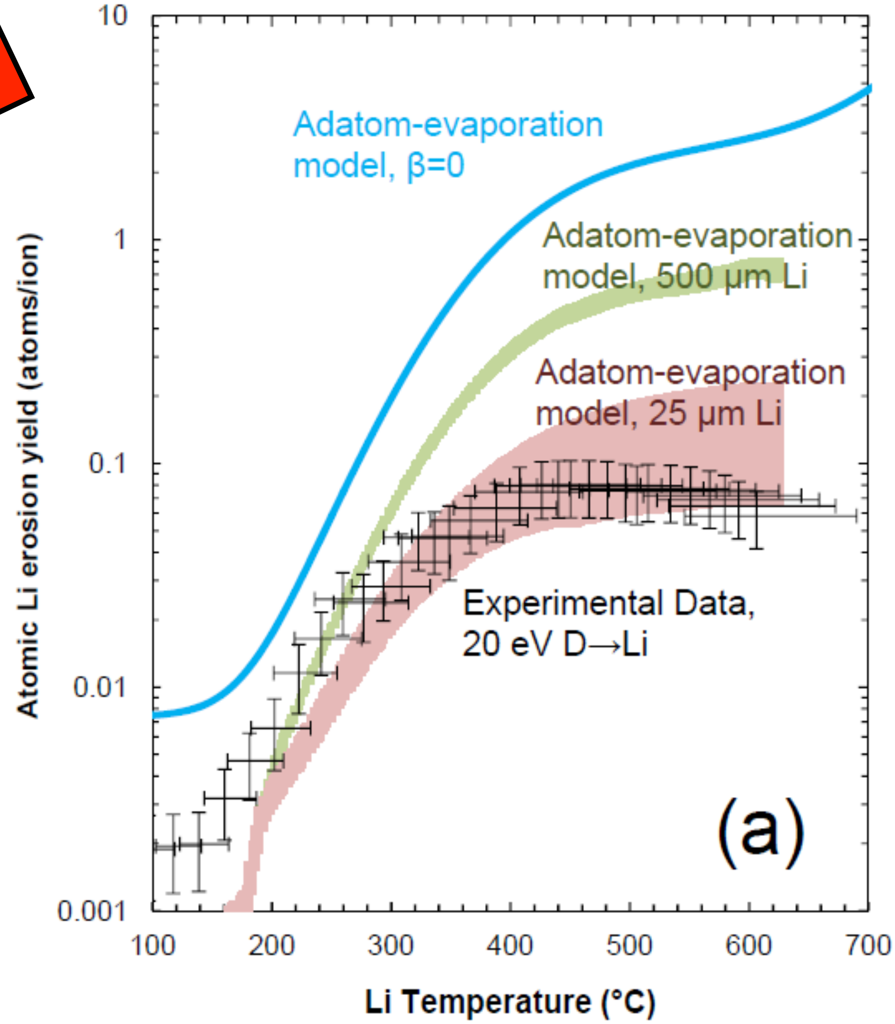
Lithium is a physical precursor that brings and retains oxygen to the surface thereby increasing the probability of D uptake by oxygen atoms. Krstic PRL, Taylor PoP 2013.

New insights into boronization from comparing MD simulations to NSTX-U MAPP XPS (Krstic, Bedoya, Allain…)

Example 3. Li PFC operation at higher temperatures than expected.

- Mixed-material effect reduces erosion due to LiD formation
- Plasma pre-sheath potential well large enough to retain eroded Li
- Significant implications for evaporative cooling concepts





β = D/Li

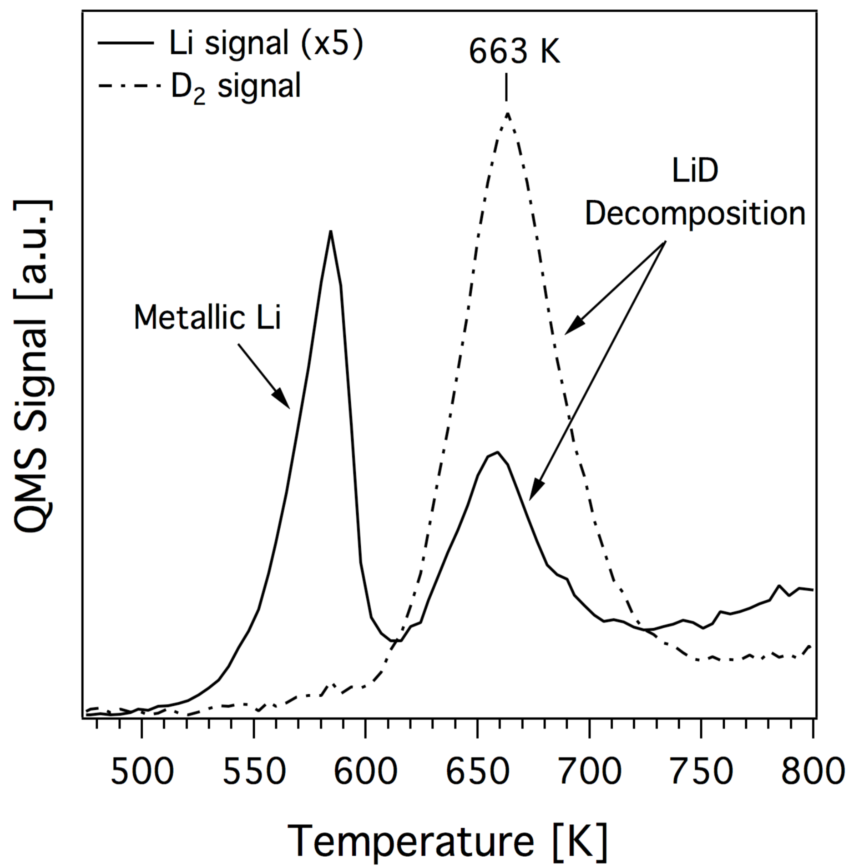
Abrams, Nucl. Fusion 2016

Example 4. Insights on operating temperatures from theory and surface science expts.

- First-principles density-function-theory applied to Li-D, predicts:
  - Reduced Li vapor pressure over LiD vs. pure Li
  - Preferential D-D sputtering
  - Reduced D diffusivity in LiD

Surface science experiments demonstrate reduced Li vapor pressure over LiD vs. pure Li

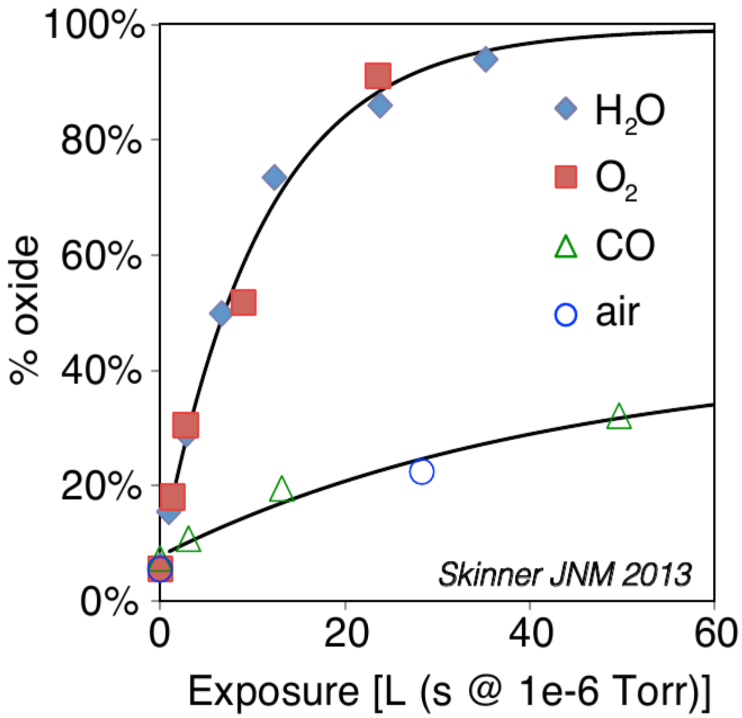
Temp. prog. desorption of LiD decomposition

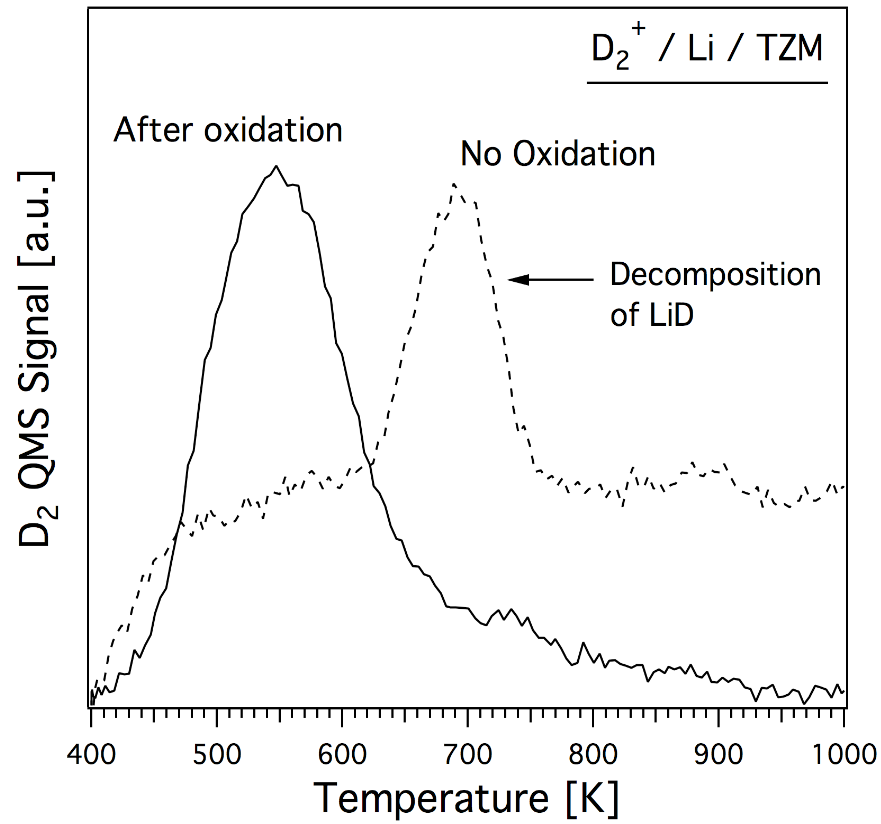


Chen, Nucl. Fusion, 2016 Capece JNM 2014

Example 5. Li PFC surface will be mixed material

Oxygen uptake by Li on Mo



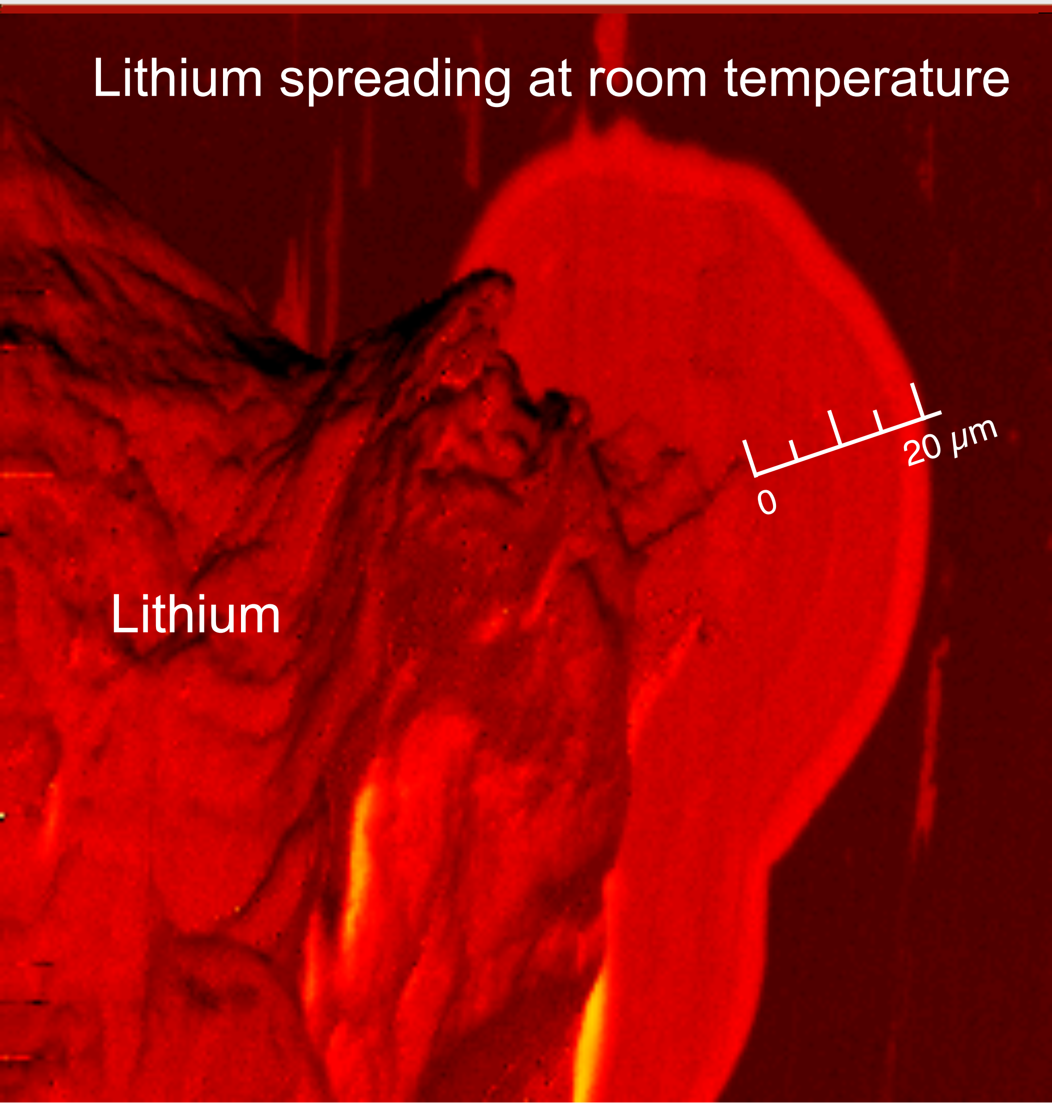


Oxygen uptake by lithium films quantified in laboratory experiments:
Oxide layer formation in ~200s in NSTX (~600s inter-shot time)

TPD studies show increased D absorption by oxidized Li, but lower thermal decomposition temperature

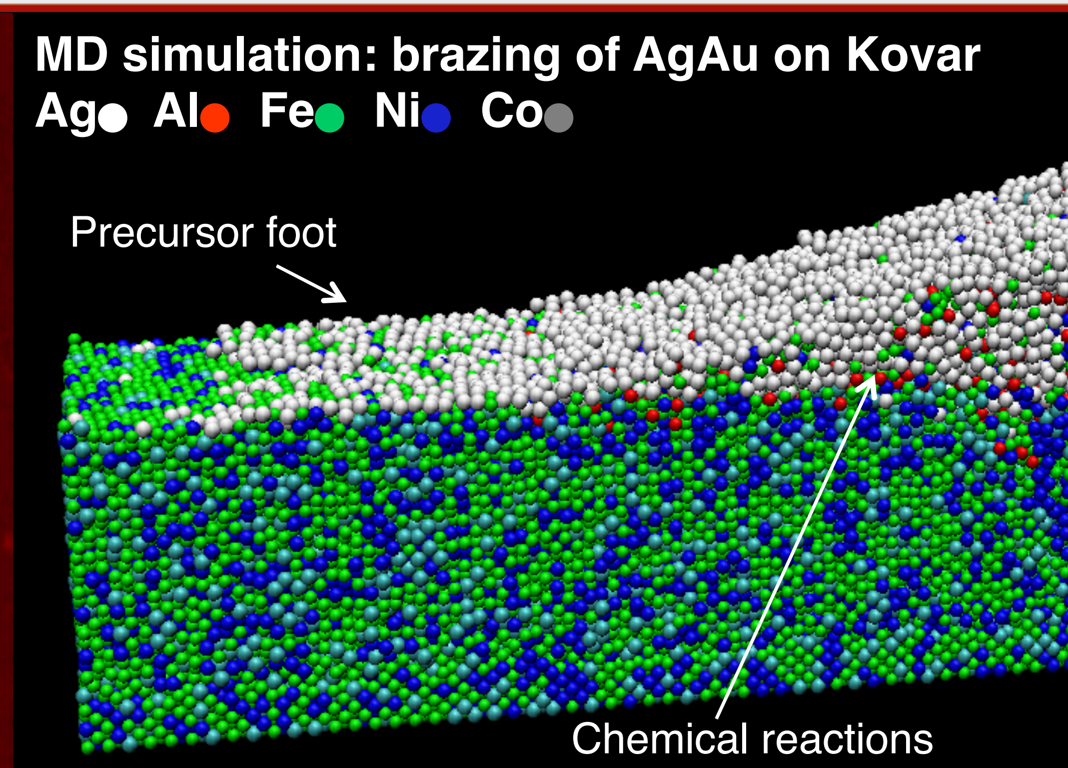
Skinner, 2013 JNM, Capece, 2015 JNM

Example 6. Lithium wetting of container at room temperature.



False color Auger image of lithium spreading over stainless steel at room temperature – relevant to wetting of liquid metal PFCs

C.H. Skinner J Nucl. Mater., 2016



M. Chandross, Welding Journal, 2015

Opportunity to advance science and technology with atomistic understanding of reactive wetting

Potential areas for new collaborations

- MPEX testing of NSTX-U PFC prototypes
- Proposed removeable divertor test module (Zweben).
- Li – D separation and processing
- Li vapor box
- Corrosion, slag
- Other topics…

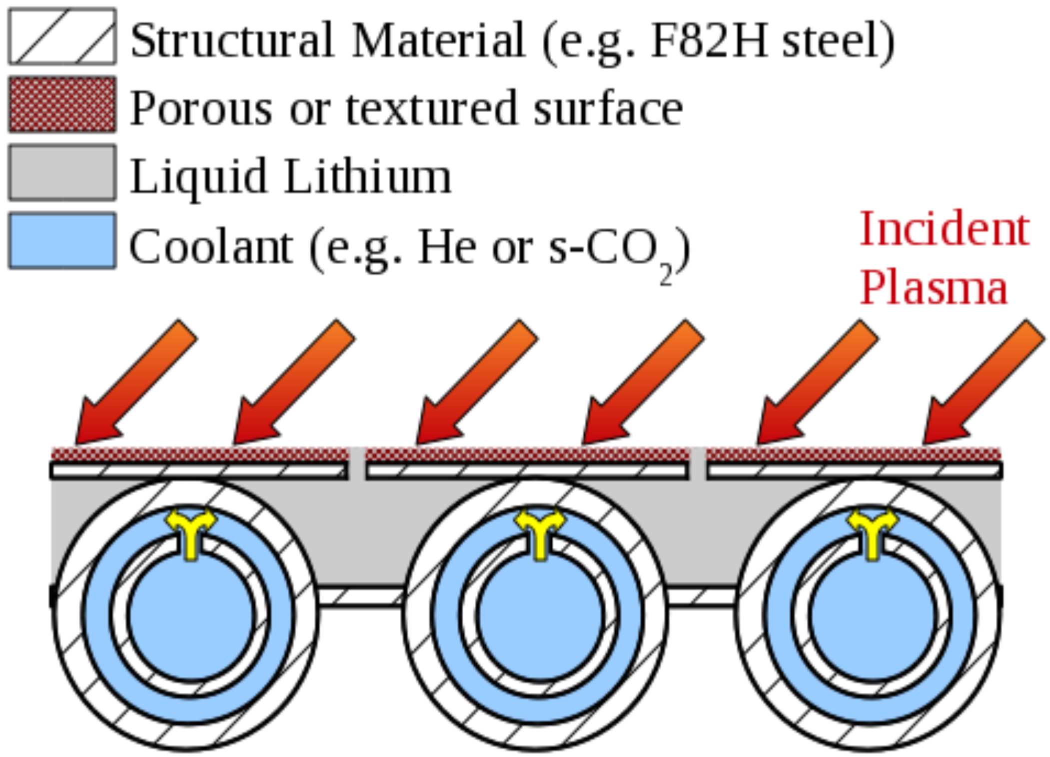
Summary

- **NSTX-U** will make staged progression to metal PFCs.
- **LTX**: first observation of fully isothermal confined plasma.
- **Surface science** is advancing knowledge base for faster, better LM PFCs

- BACKUP

An approach to a liquid-metal PFC: Actively-supplied, capillary-restrained systems

- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Inertially cooled PFC would be modest step from pre-filled targets



e.g. inter-pore spacing calculation: 1cm spacing provides replenishment of 16-40Hz emptying events at optimum pore size

Jaworski, PPCF 2013

Pre-filled target research and development plan snap-shot

- Multi-institution collaboration to address practical and scientific questions
  - US partners: JP Allain, DN Ruzic (UIUC)
  - International: P Rindt, N Lopes-Cardozo (TU/Eindhoven), TW Morgan (FOM-DIFFER)
- Wetting and handling tests to be conducted on candidate surface materials in the Netherlands, Illinois and PPPL
- Heat flux testing of pre-filled targets proposed as part of thesis work at Magnum-PSI (P. Rindt, Fall 2016 restart of device)

Bake-out survival and recovery is a key question for pre-filled and flowing PFCs

- Two strategies in development
  - removable macro films (demonstrated on Magnum-PSI, CPS-method)
  - Eroding nano-scale protective films
  - Summer experiments conducted by Jaworski at UIUC with collaborators will establish viability of methods

- Surface cleaning (oxide removal) demonstrated previously
  - Elevated temperature + plasma bombardment (He, Ar)
  - PISCES-B, Magnum-PSI demonstrations

Overview of proposed experimental studies at UIUC

- Development and testing viability of nanoscale, removable films (leverage low-temperature, controlled plasma processing equipment)

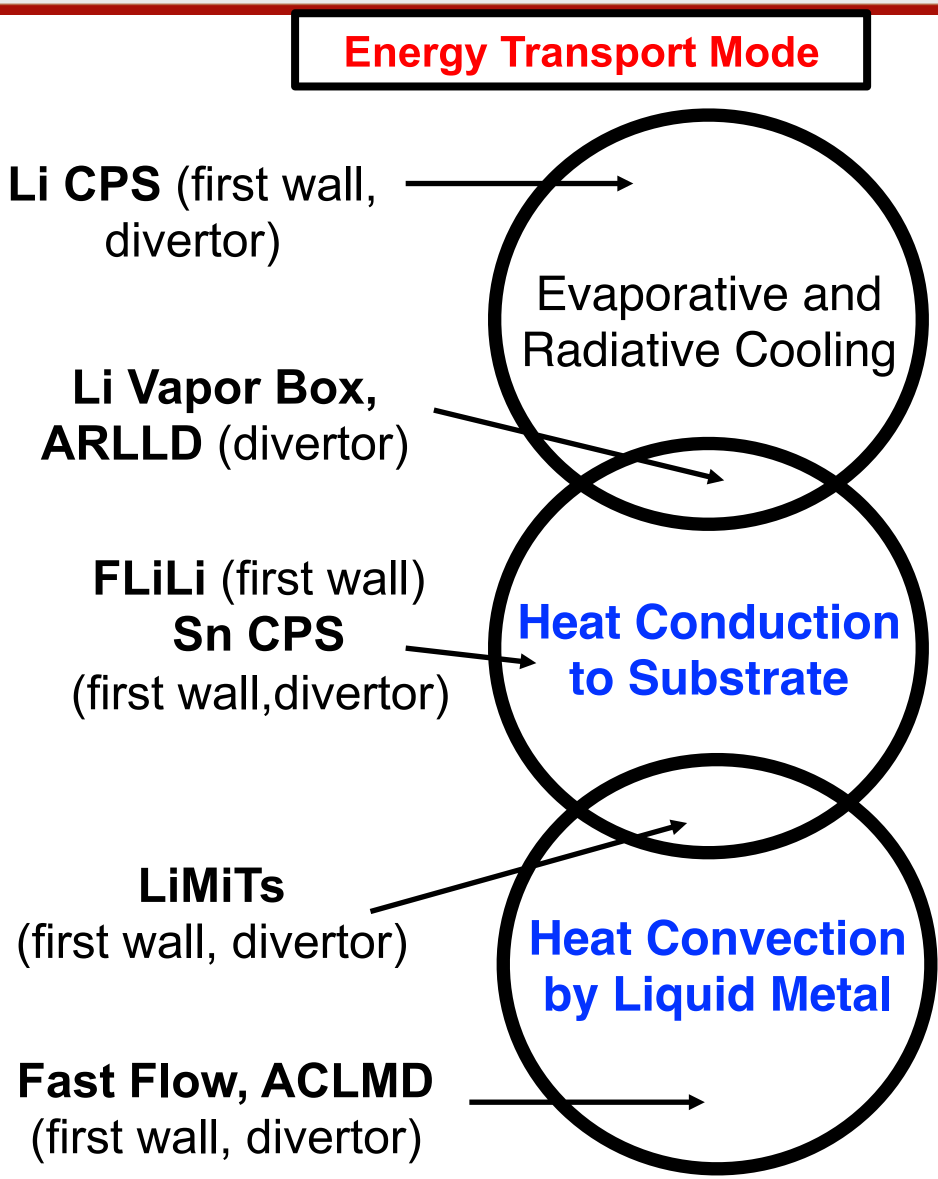
- ELM-like heat pulse survival and recovery (leverage DEVEX device)

- Characterization of Kelvin effect in porous liquid metal system, multiple substrates

- Evaluation of liquid layer thickness and coverage from passively replenished systems

- Calibration of UIUC calorimeter probes

Liquid metal PFCs provide additional pathways for energy transport

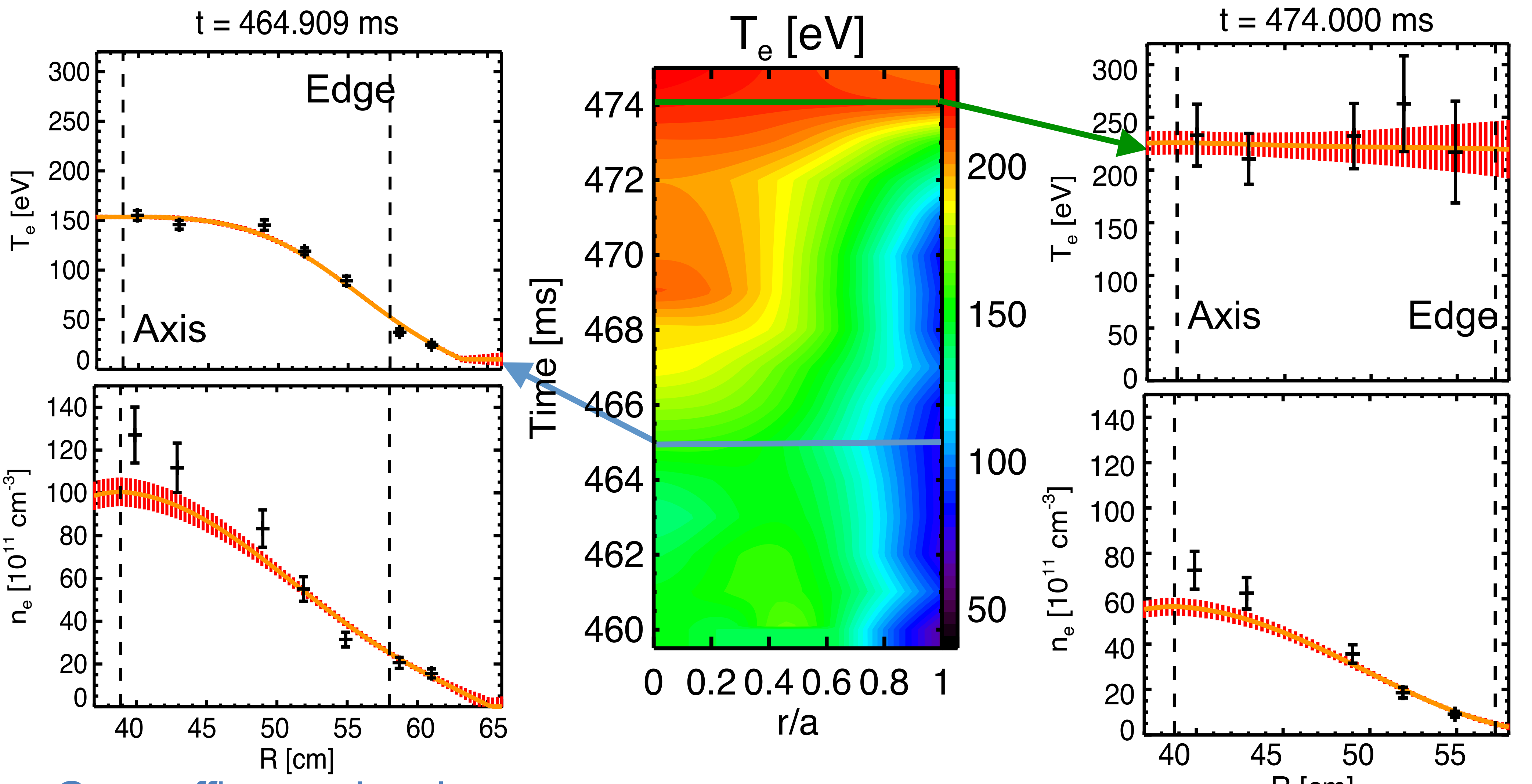


- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- High-power density on slow-flow lithium leads to vapor-shielded targets for extreme heat flux mitigation
- Fast-flow concepts can exhaust extreme amounts of power via convection but are less mature

Key result:
First observation of fully isothermal confined plasmas

- Early in discharge:
  - Lithium suppresses recycling
  - But: gas puffing to raise density

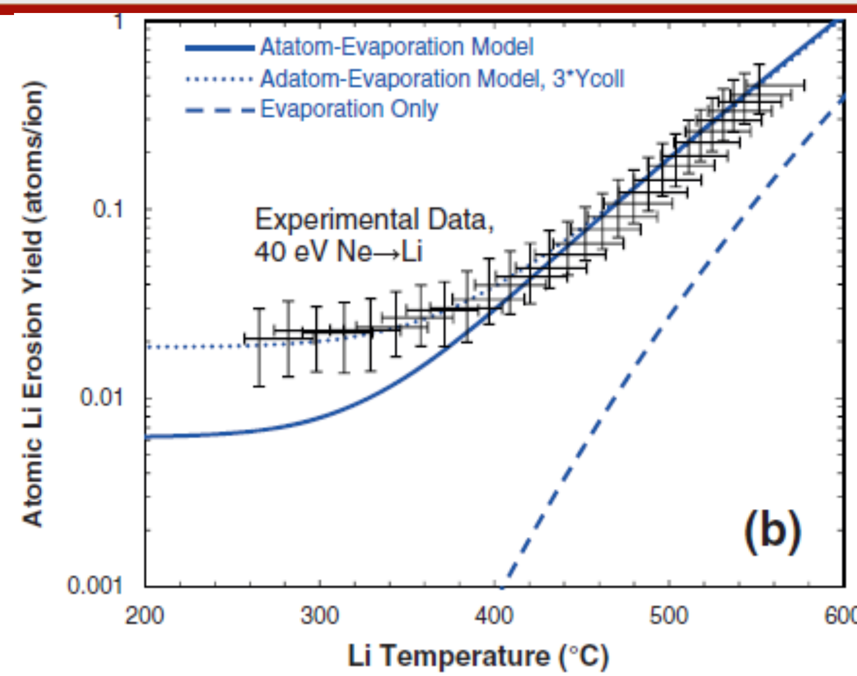
- Late in discharge:
  - Lithium suppresses recycling
  - No gas from puffing

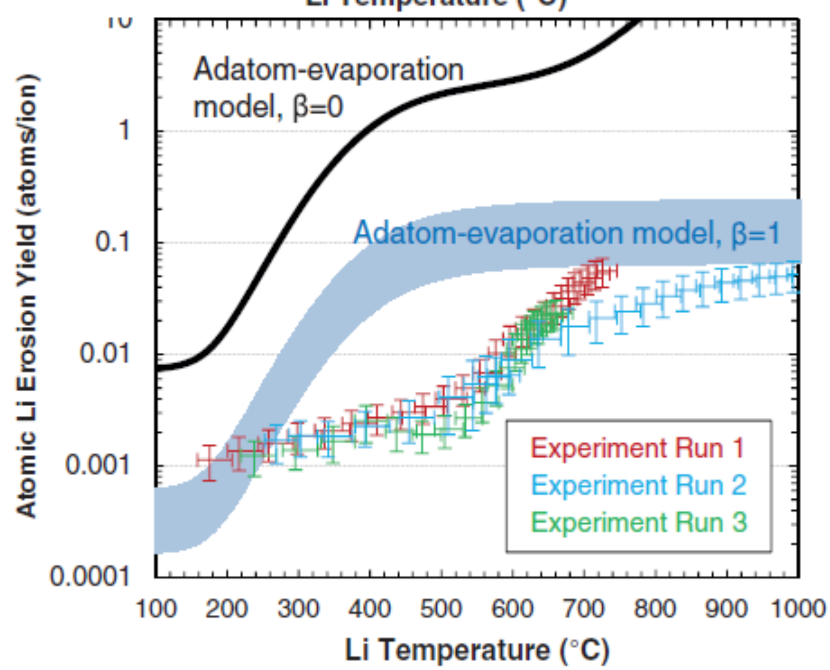


- Gas puffing cools edge
- No cooling: edge T_e = core T_e

Suppressed Li erosion observed under high flux deuterium bombardment

- Experiments conducted on Magnum-PSI
  - Evaporated coatings (loaned LITER unit)
  - Pre-filled liquid targets
  - Temperature ramp from incident plasma bombardment
- Found clear mixed-material effect due to deuterium bombardment



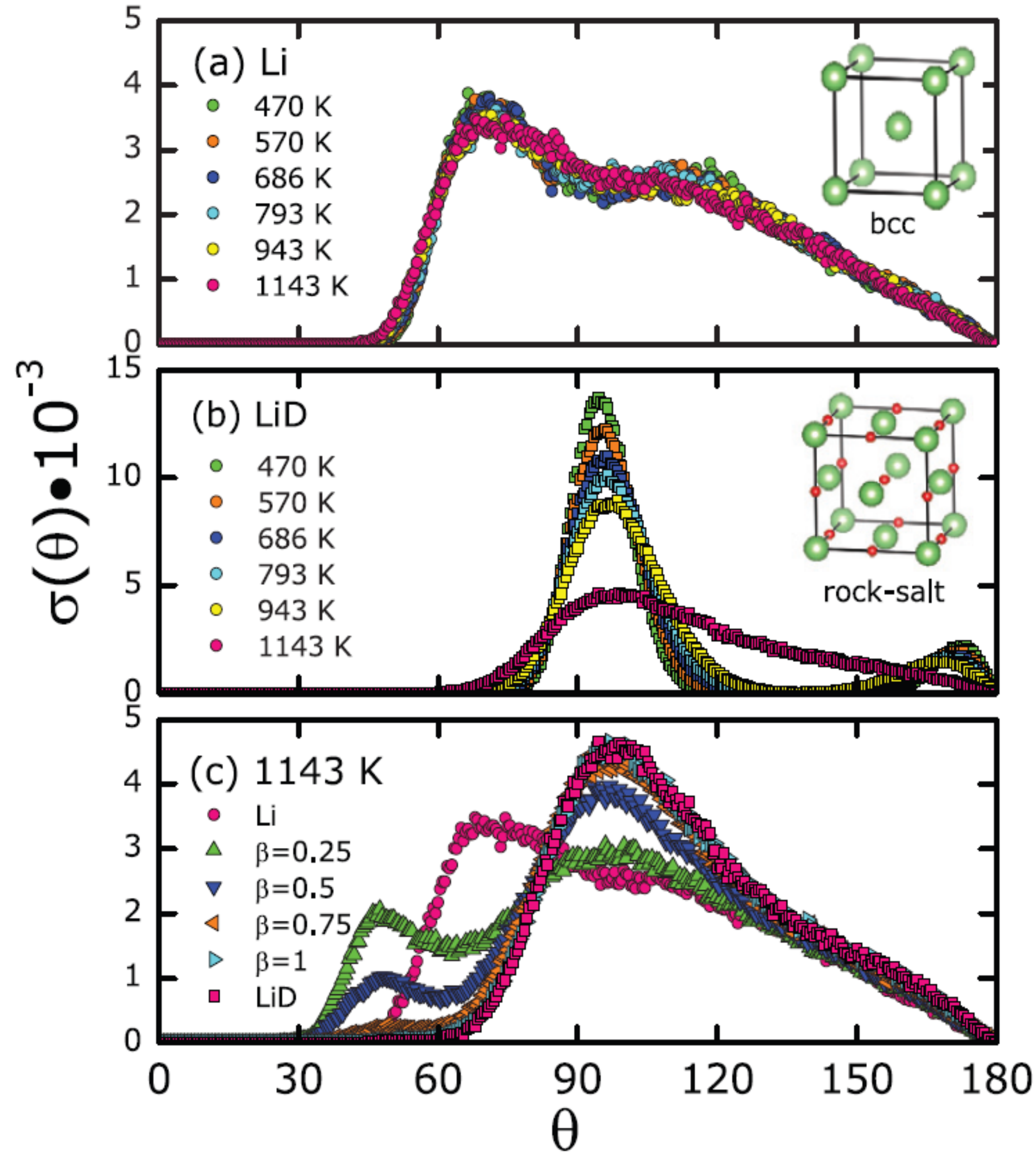


Abrams, 2016 Nucl. Fusion

Quantum modeling of Li-D system indicates formation of LiD likely and impacts transport

- First-principles density-function-theory applied to Li-D mixed problem
  - DFT simulations calculate interatomic potentials as opposed to classical MD
  - Limited to 100s of atoms and 10-20ps simulation times

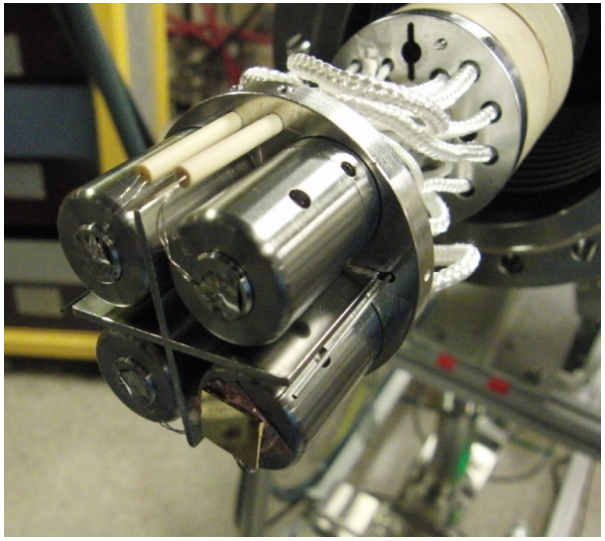
- Bond angle distribution provides “finger-print” compounds in simulation
  - Shows rapid formation of LiD compounds

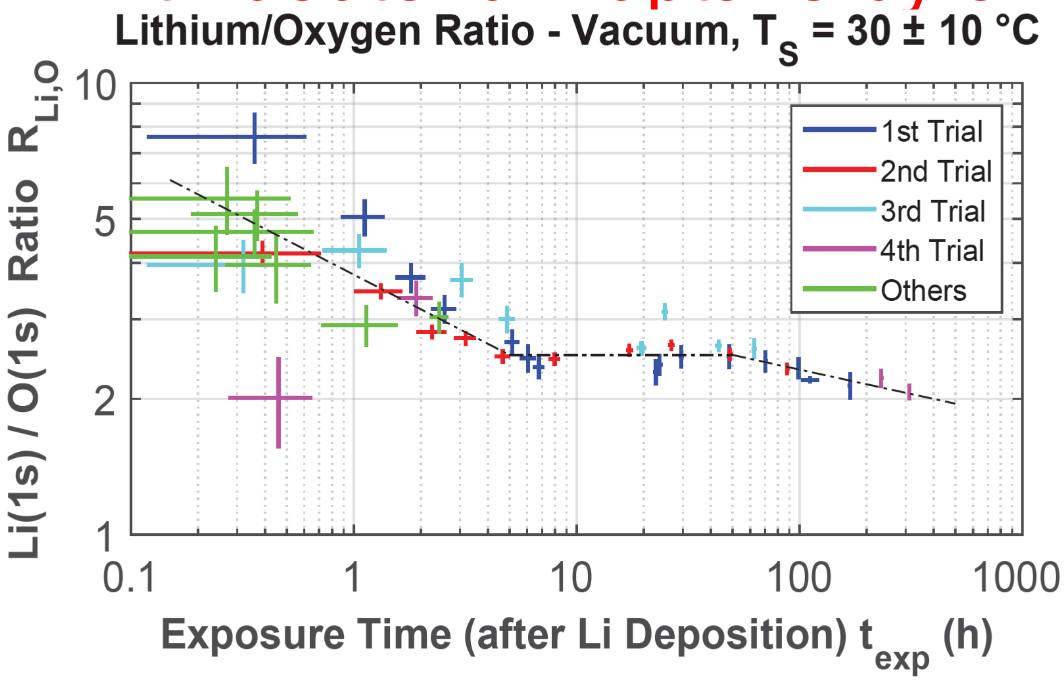


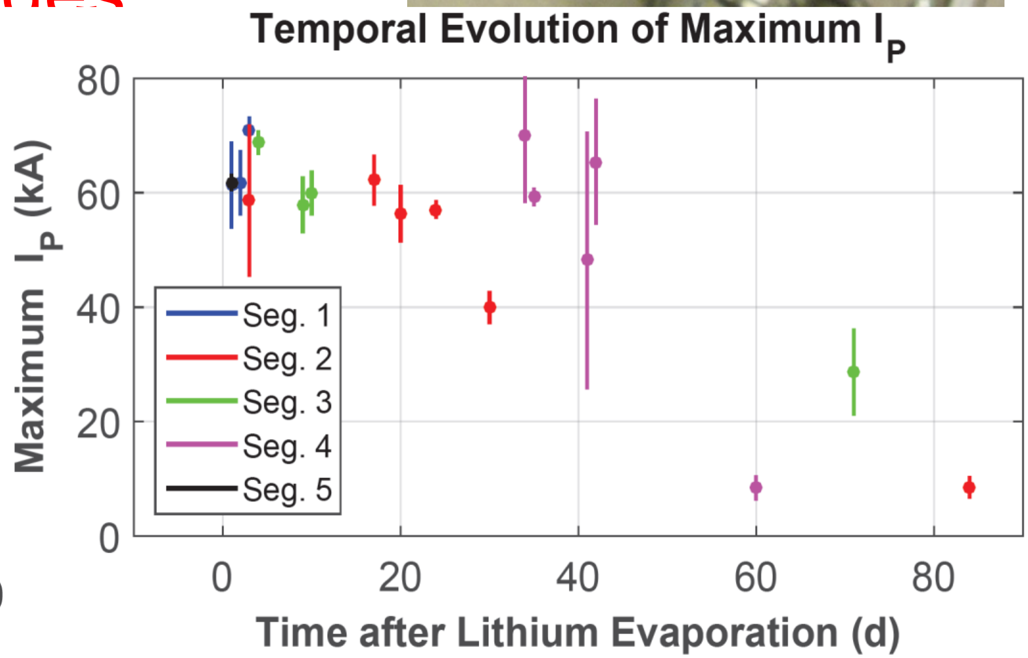
Chen, 2016 Nucl. Fusion

Material Analysis and Particle Probe (MAPP) measurements suggest deuterium retention by oxides

- Multiple surface analysis tools available (XPS, TPD, LEISS)
- Show rapid oxide formation in LTX despite very low H_2O partial press
- Good performance in LTX persists on order of 1000 hr (~40d), consistent with deuterium uptake by oxides







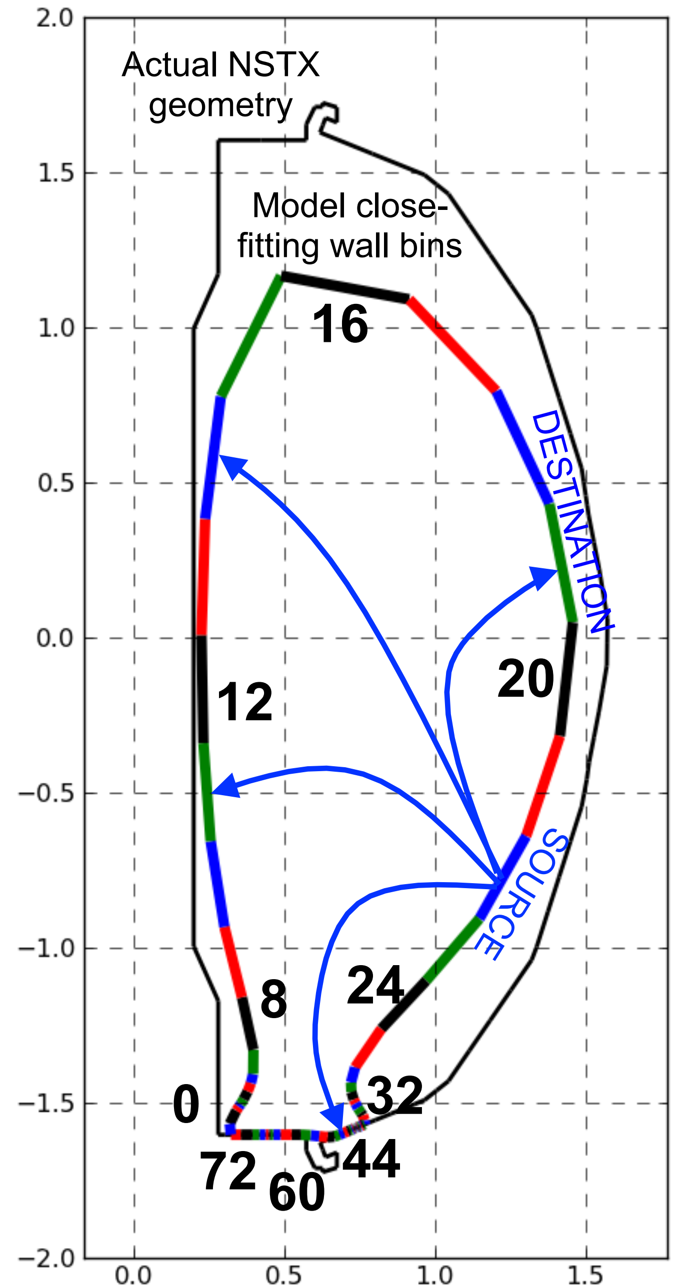
Lucia, PhD thesis, Princeton Univ. (2015), Kaita, ISLA 2015

Understanding material mixing and migration major thrust in NSTX-U

- Material migration modeling with WallDYN code implemented on NSTX plasma data
  - WallDYN developed to describe material evolution (Schmid, 2011 JNM)
  - Utilizes large set of DIVIMP runs to generate transport matrix
  - Mixed-material model determines impurity production from each surface

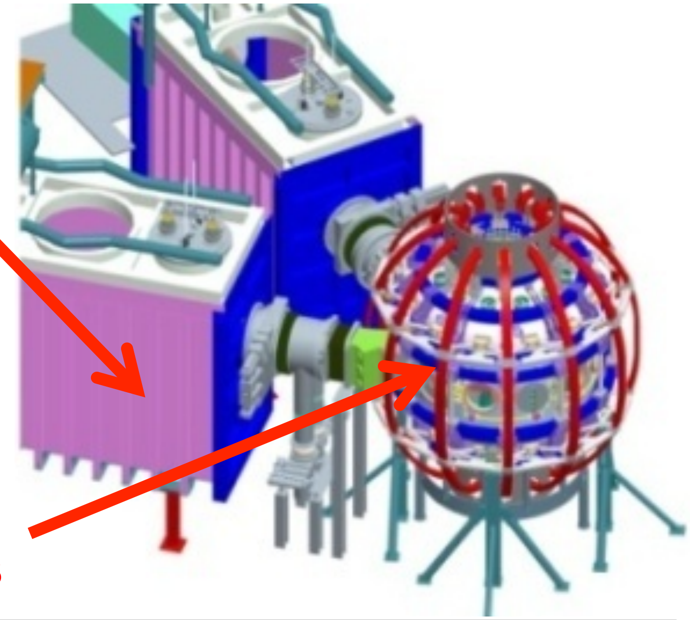
- Initial parametric modeling undertaken to identify key variables and sensitivites
  - e.g. relative impacts of divertor conditions (Nichols, 2015 JNM)
  - Impact of mixed-material erosion model

Nichols, 2015 APS



NSTX-U plasma-facing components (PFCs) will be subjected to significant heat and particle fluxes

- NSTX-U is the newest US machine
  - 2x NBI heating power (<13MW)
  - 2x current (<2MA) and field (<1T)
  - 5x pulse length (<5s)
- Experimental capabilities push toward DEMO-relevance
- Open divertor provides unique opportunities for experiments



Machine	R_0 [m]	P_{AUX} [MW]	P/R [MW/m]	P/S [MW/m^2]	τ_{pulse} [s]
NSTX*	0.86	6.8	8	0.2	1
NSTX-U*	**0.93**	**19**	**21**	**0.6**	**5**
JET†	2.95	35	12	0.2	20
DIII-D†	1.74	20	11	0.4	6
AUG†	1.65	27	16	0.6	10
CMOD†	0.7	6	9	0.7	2
MAST†	0.87	7.5	9	0.25	1
ITER†	6.2	100	16	0.15	400
ST-Pilot‡	**2.2**	**190**	**86**	**0.7**	6×10^6
ST-DEMO‡	**3.2**	**520**	**161**	**0.9**	∞

Fundamental Surface Science studies

- PFCs in NSTX-U will have to withstand higher particle and heat loads:
- ***How will Li perform under the plasma conditions of future fusion devices (heat and particle flux, ion energy, surface temperature, etc.) in terms of:***
    - ***H isotope intake ?***
    - ***Impurity segregation ?***
    - ***Evaporation (operational temperature range) ?***

- Fusion experiments occur in challenging conditions for understanding PMI processes:
- Complex environment in terms of characterization of the plasma parameters, particle species, energies, fluxes, sample temperature, *etc.*
- Technical difficulties for performing *in-situ* analysis
- **Laboratory experiments have many advantages**

- – Lab experiments allow simulating materials and coatings in a controlled way and understanding the fundamental physics and chemistry occurring at surfaces
- – It is possible to utilize surface sensitive analysis techniques and directly follow the surface chemistry
- – Well-characterized ion beams in terms of energy and ion species
- – Thin film layers can be deposited in a controlled way on various substrates