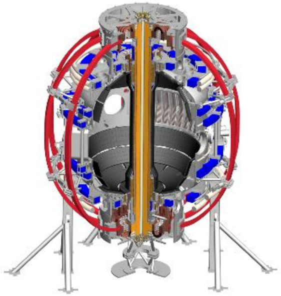
NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Liquid Metals: Near and Long-term Plans

M.A. Jaworski for the NSTX-U Team

NSTX-U Program Advisory Committee Meeting
Princeton Plasma Physics Laboratory, Princeton, NJ
January 9th, 2018



Outline

1. Why evaluate liquid metals as a plasma-facing component (PFC)?
    - Liquid PFCs resolve several problems plaguing solid PFCs
    - Liquid PFCs demonstrated to enhance confinement and can absorb more heat flux than do solid PFCs

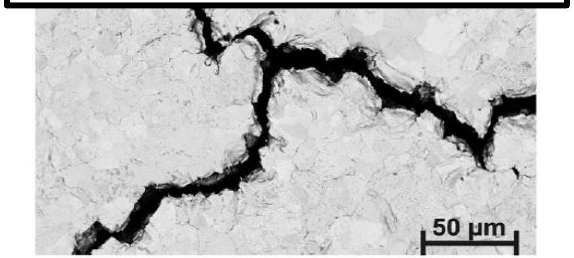
2. Why study liquid metals now and why in NSTX-U?
    - PMI Community workshop highlighted liquid PFCs in numerous priority research directions and high-impact cross-cutting activities
    - Integrated scenario assessment of ST requires movement away from C

Liquid metals present *intrinsic* advantages over solid PFCs in several areas

- Liquid metals provide a self-healing/renewable plasma-facing material
  - Immune to thermo-mechanical stresses
  - Returns to equilibrium after perturbations
  - Replenishment eliminates net-reshaping by plasma bombardment
- Separates neutron damage effects from plasma-material interactions
- Eliminates long-time constants associated with solid-wall material transport and evolution[a]
- **Demonstrated confinement effects and power handling capabilities**

[a] Stangeby, JNM 2011

Cracking after thermal shock loading



Wirtz, et al., JNM 2013

CMOD W-lamellae

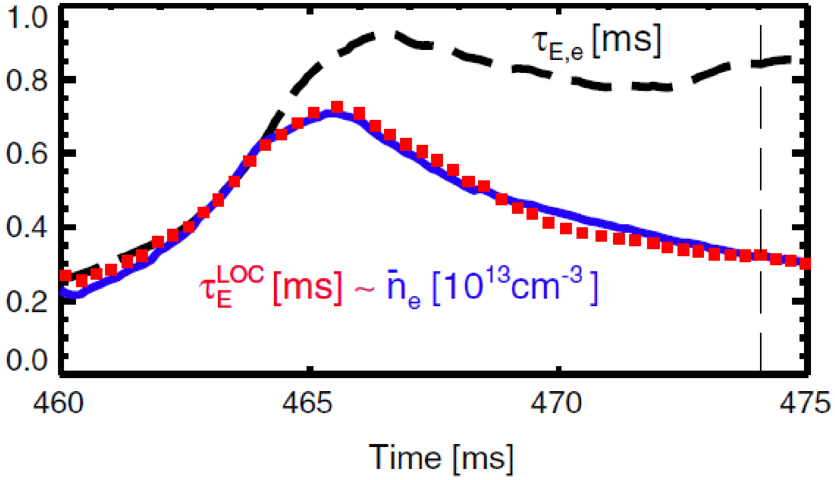
Coenen, et al., JNM 2013

Mo first-wall

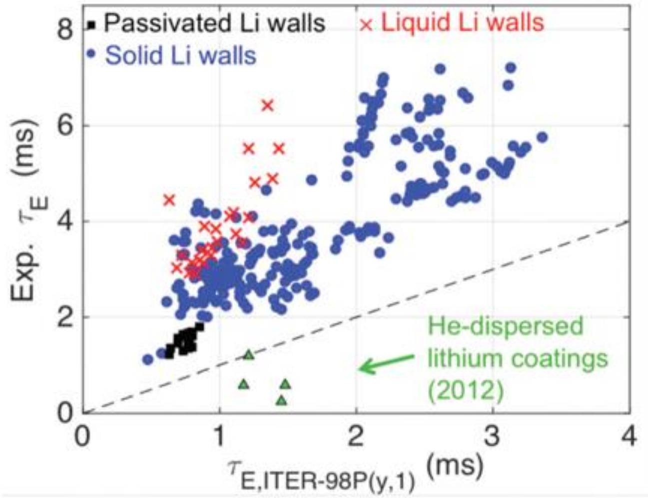
M. Reinke, private comm.

LTX demonstrated (again) confinement gains even with partial oxidation of Li coatings and Li pool

- Measured electron energy confinement exceeds neo-Alcator Linear Ohmic Confinement scaling ~3x (Boyle PRL 2017)
- Evaporated coatings monitored with MAPP diagnostic correlated with good performance to ~100 hrs (Lucia PhD 2015, Schmitt PoP 2015)
- **Key question: will flowing liquids perform like coatings (with impurities)?**



D. Boyle, et al., *Phys. Rev. Lett.* **119** (2017) 015001.



J. Schmitt, *et al.*, *Phys. Plasmas* **22** (2015) 056112.

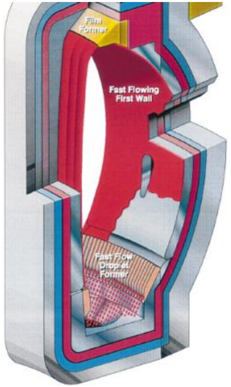
Liquid metal PFCs can absorb more heat flux than do leading tungsten technologies

- Actively cooled tungsten expected to survive **5-15 MW m^{-2}** steady-state

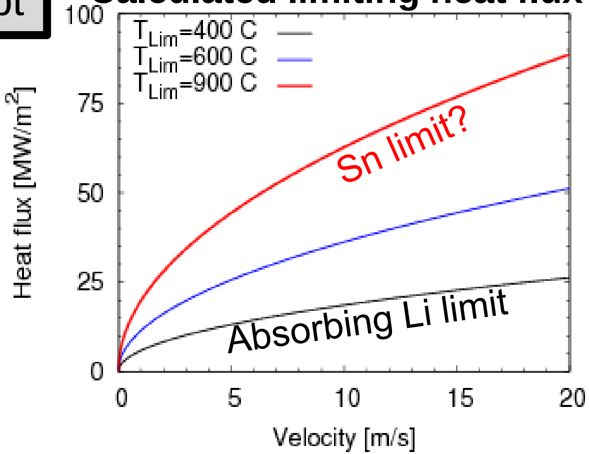
- Fast-flow systems advect power away from heating zones
  - Limiting temperature, heating size, and velocity determine limiting heat flux
  - Li, Ga, Sn all possible metals for use

- Slowly flowing liquid targets recently demonstrated in multiple configurations
  - Non-vaporizing, water-cooled tin demonstrated at **20 MW m^{-2}** in Magnum-PSI[a]
  - Vapor-shielded tin achieved self-regulated temperature up to **22 MW m^{-2}** in Magnum-PSI[b]

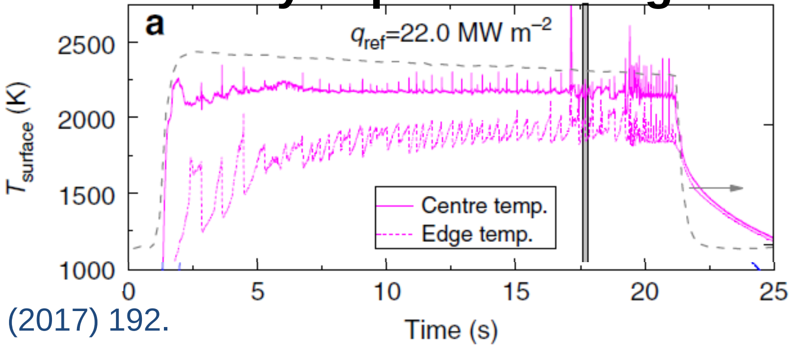
Fast Flow Concept



Calculated limiting heat flux

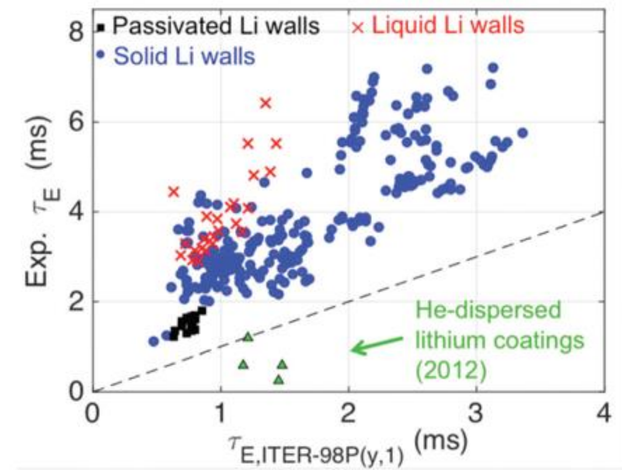


Steady vapor-shielding Sn



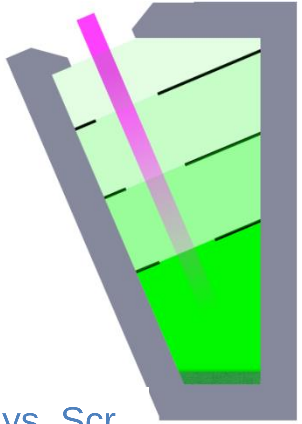
[a] Morgan, 2017 Nucl. Mater. Energy; [b] S. Van Eden, et al., Nature Comm. 8 (2017) 192.

L can absorb more heat flux than ungsten technologies



Enhanced confinement with vapor-box divertor[a]?

- Acti rvive 5-15
- Fast rom zone
  - Li ocity de
  - Li
- S on in
  - Non-vaporizin emonstrated **20 MW m^{-2}** in
  - Vapor-shieldec gulated temp up to **22 MW n**
  - Vapor-shieldin ved with NST inspired pre-fil um-PSI[c,d]



[a]Morgan, 2017 Nucl. M Eden, et al., N Comm. 8 (2017) 192. 2017; [d]R. Rindt, et al., Nucl. F

[a]Goldston, 2016 Phys. Scr.

Calculated limiting heat flux

Time (s)

Only in a confinement device can one assess the core-edge integrated scenarios

Outline

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2. Why study liquid metals now and why in NSTX-U?
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US PMI community workshop highlights the importance of developing tools that can extrapolate to a reactor

- Multiple priority research directions (PRDs) highlight need to advance concepts (including **liquids**):
  - PRD-A: limits on power and particle handling, including **liquids**
  - PRD-B: demonstrate dissipative divertor solutions, including **liquids**
  - PRD-C: develop solutions for main chamber components and tools for sustained operation
  - PRD-D: science of evolving materials, including **liquids**
  - PRD-E: understand impact of materials on core performance

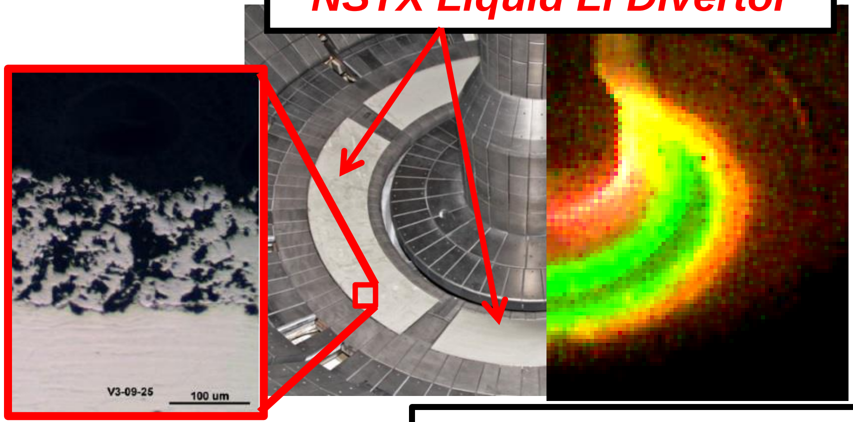
- Multiple high-impact, cross-cutting activities also identified:
  - CC-1: enhance exploitation of existing machines for PMI studies
  - **CC-3: understand the science of liquid surfaces and examine feasibility of liquid PFC solutions**

See also Reinke's talk

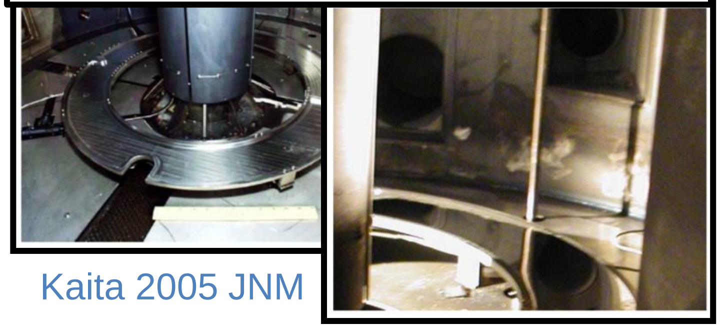
NSTX & PPPL expertise, and need for integrated solutions motivates for liquid metal mission in NSTX-U

- Years of developing Li science…
  - Diagnostics: dual-band IR (ORNL), divertor imaging/spect. (LLNL), MAPP (U-Illinois)
  - Theory: liquid stability, quantum molecular dynamics (SBU) and DFT (PU), whole-device material evolution modeling
  - Supporting surface science laboratories
- …and technologies
  - Lithium experimental methods: LITER, U-LITER, granule & aerosol injection, Liquid Lithium Divertor
  - Large area tray limiters, LTX shell system, etc.
- **NSTX-U can easily create $q_\perp > 20$ MW m^{-2}**
  - Full heating power: P/R~20

NSTX Liquid Li Divertor

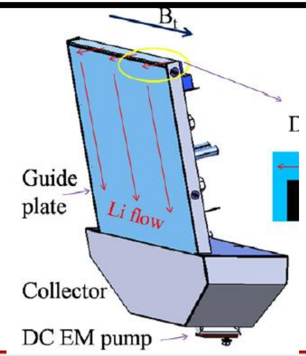


CDX-U large-area tray limiter



Kaita 2005 JNM

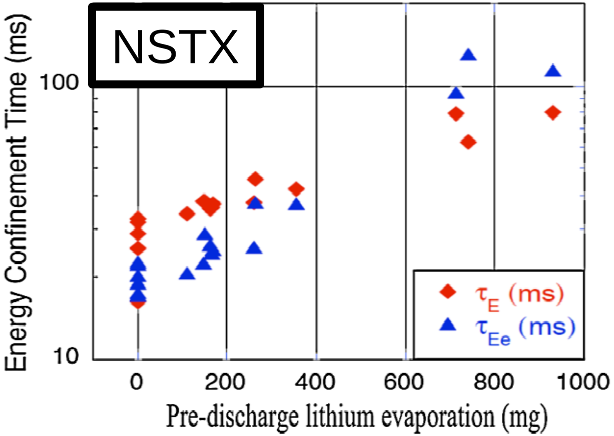
EAST FLiLi



Hu 2016 NF

Positive NSTX results motivate near-term plan with Upward LITER in NSTX-U

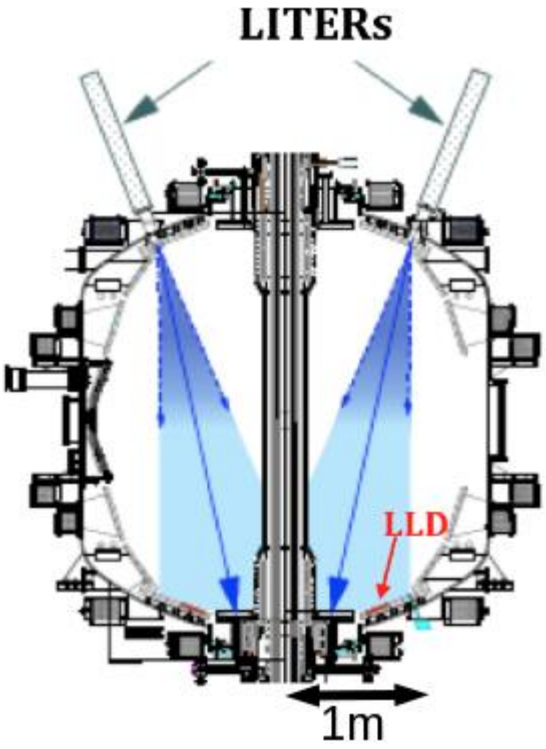
- Confinement improvement attributed to reduced recycling
- Machines at PPPL showing benefits of lithium conditioning over *increasing areas*
  - TFTR Li “super-shots”
  - CDX-U, LTX
  - **NSTX**[a]
- Others examining Li:
  - FTU, T11-M, HT-7,EAST, DIII-D
  - TJ-II, RFX



Upward LITER Development

Cai, 2017 IEEE TPS

NSTX Configuration



[a] R. Maingi, et al., *Phys. Rev. Lett.* **107** (2011) 145004.

High-Z + Li NSTX-U would advance multiple Priority Research Directions simultaneously in unique ST facility

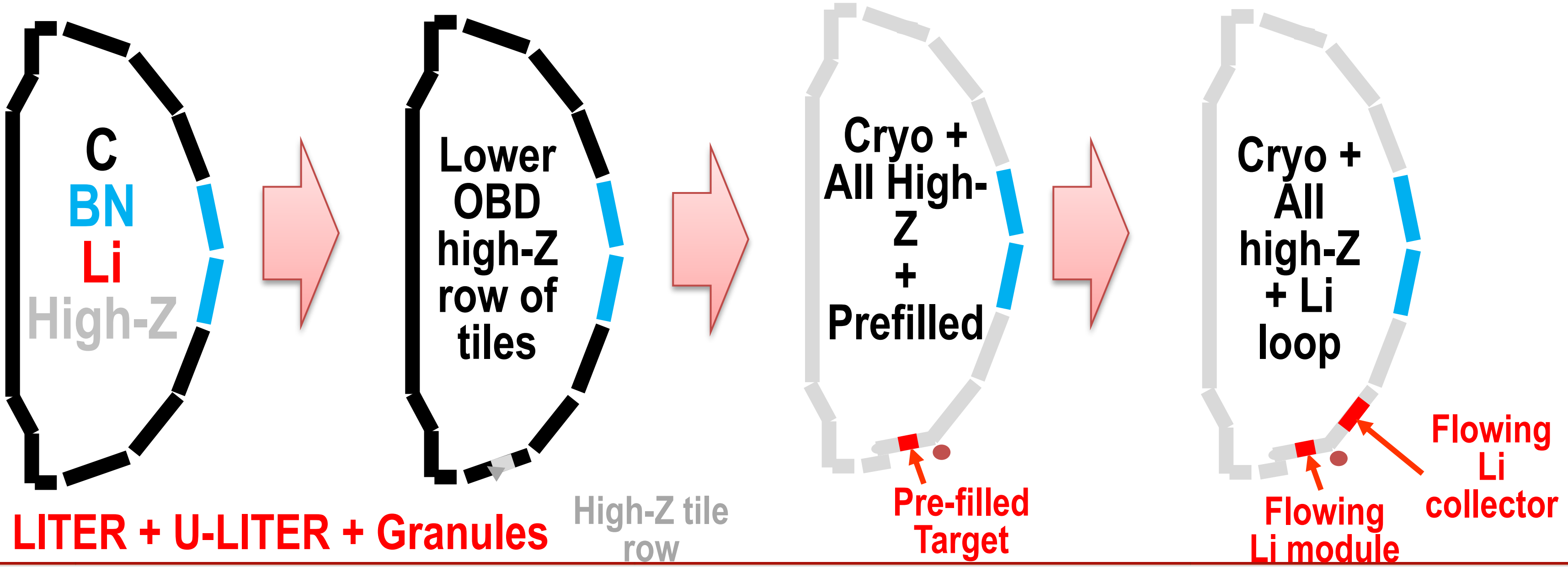
- NSTX and NSTX-U has emphasized surface science understanding of plasma-material interface (PRD-C,D)
  - MAPP deployed in 2016: year 1 capability
  - Studying impact of materials on plasma and vice-versa essential to whole-device modeling of material evolution

- A liquid metal-capable NSTX-U would enable high-Z vs. lithium comparison studies in a high-power device (PRD-A,B,C,E)
  - Extend LTX-beta studies
  - Builds on and complements continuing studies in higher A devices like EAST

- Heating power available to NSTX-U enables testing of liquid concepts to extreme power levels (PRD-A, B, C, E)
  - Potentially critical to ST line
  - Potentially critical to economical fusion energy concepts

One possible progression: staged conversion to mitigate risk while enabling integrated performance assessment of the ST

- Full high-Z conversion enables comparison with conventional high-Z
- Provides high-power analog to evaluate LTX confinement results
- Open divertor and flexible magnetic configuration mitigates risk

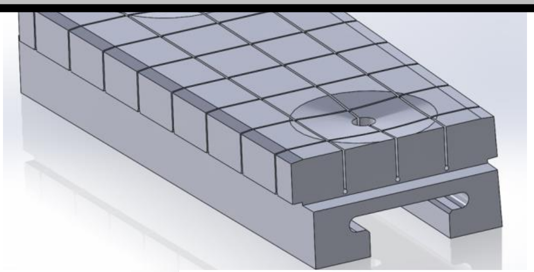


Most mature technologies proposed for current development path (emphasis on qualification testing)

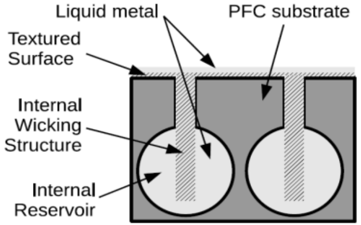
- Bulk high-Z for high heat flux regions, Mo/W coatings may be possible in low-heat flux regions

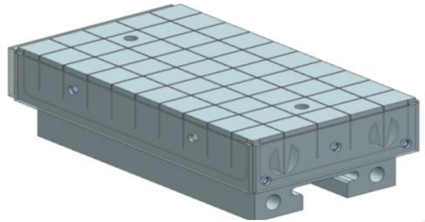
~2 yr deploy

2015-16 NSTX-U High-Z Design



- Pre-filled targets build on high-Z, high-heat flux designs

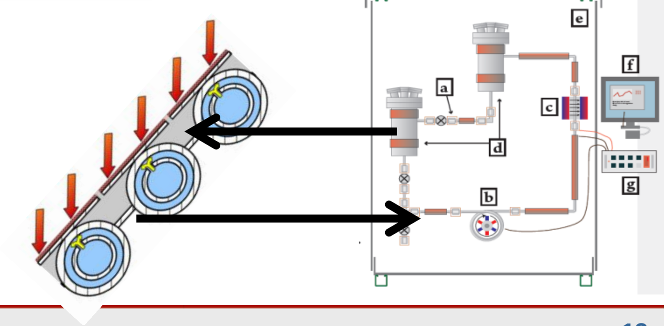




~2.5 yr deploy after high-Z

- External Li feed into reservoir region with inertial cooling provides near-term similarity to DEMO-relevant concepts

~10 yr deploy



The integrated assessment of the ST can be improved with near- and long-term PMI studies (Li + high-Z)

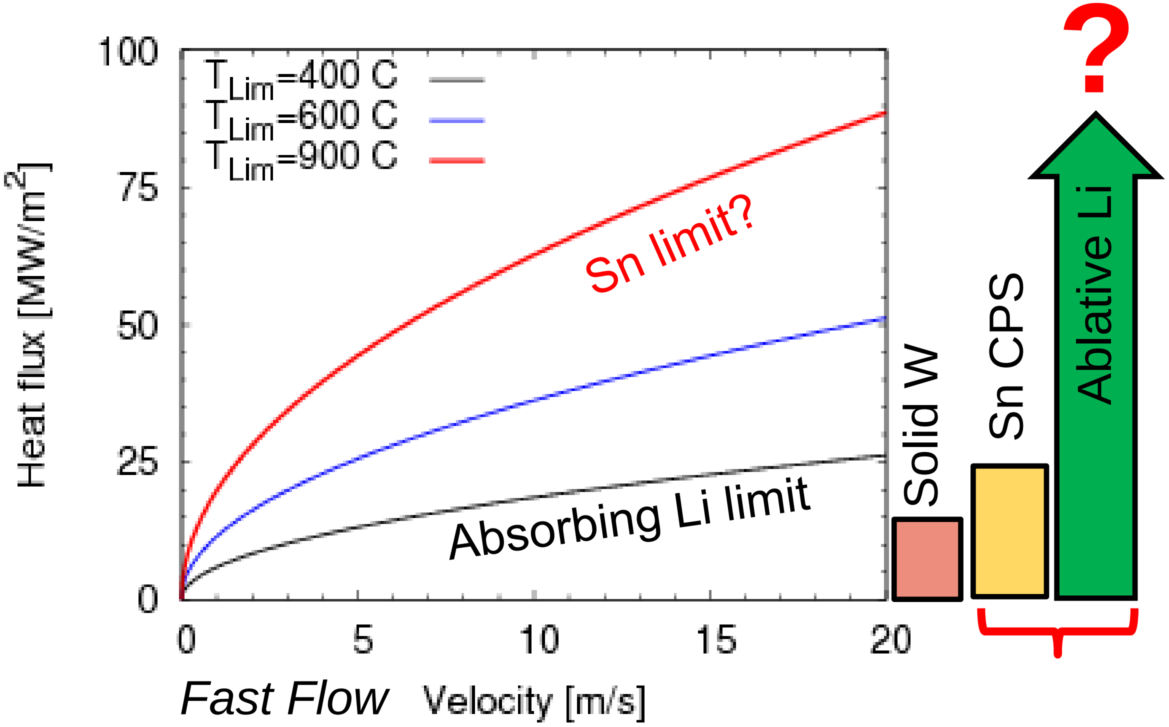
- Liquid metals have potential to solve several long-standing issues associated with solid PFCs
- Recent results continue to show confinement gains and potential for steady power exhaust
- US PMI Community identified the need to advance liquid metal science and technology, and evaluate feasibility
- A staged upgrade for NSTX-U can enable an integrated (plasma-material) assessment of the ST
  - New PFCs require sustained R&D starting now for second 5-year plan

Thank you!

Liquid metal PFCs can absorb more heat flux than leading tungsten technologies

- Actively cooled tungsten expected to survive 5-15 MW m^{-2} steady-state
  - Transients and neutrons lead to ~5 MW m^{-2}
  - Technological limitations lead to 9m major radius in EU DEMO1 (P/R=17)[a]
- Tin CPS water-cooled target demonstrated 20 MW m^{-2} in Magnum-PSI[b]
- *Unknown vapor-shielding limit*
  - Dependent on replenishment rate to surface (technology)
  - **Dependent on core plasma compatibility with divertor**

Perpendicular Heat Flux Limit

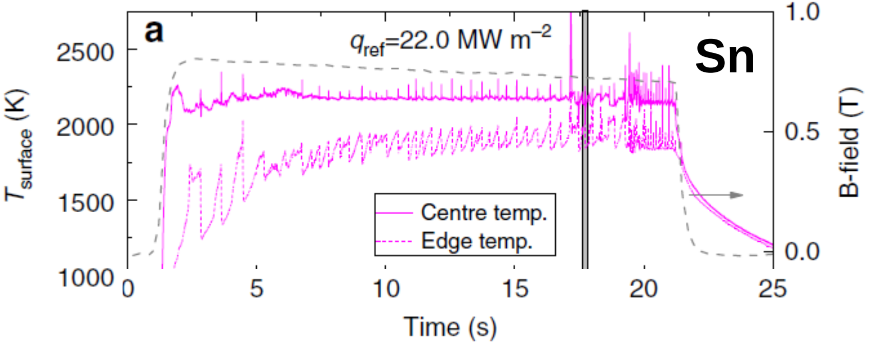


[a] Wenninger 2017 Nucl. Fusion;

[b] Morgan, 2017 Nucl. Mater. Energy

Vapor shielding experiments in linear plasma device; shows path forward for vapor-box concept

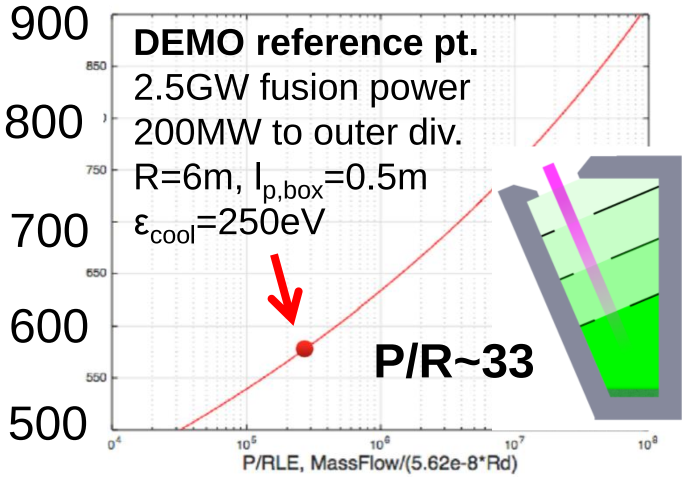
- Liquid Sn and Li targets tested
  - Magnum-PSI linear plasma
  - Both exhibit temperature clamping



- Li-target tested based on pre-filled concept

Rindt, PFMC 2017

- Vapor box 0D calculations indicate very high heat flux potential



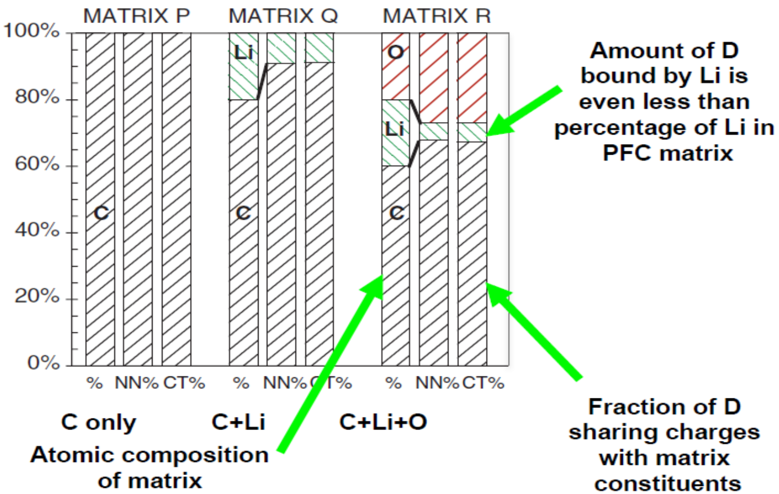
DEMO reference pt.
2.5GW fusion power
200MW to outer div.
R=6m, $l_{p,box}$=0.5m
ε_{cool}=250eV

P/R~33

S. Van Eden, et al., *Nature Comm.* **8** (2017) 192.
R. Goldston, et al., *Nucl. Mater. Energy* **12** (2017) 1118.

Multiple tools developed to study complex, substrate-dependent lithium chemistry

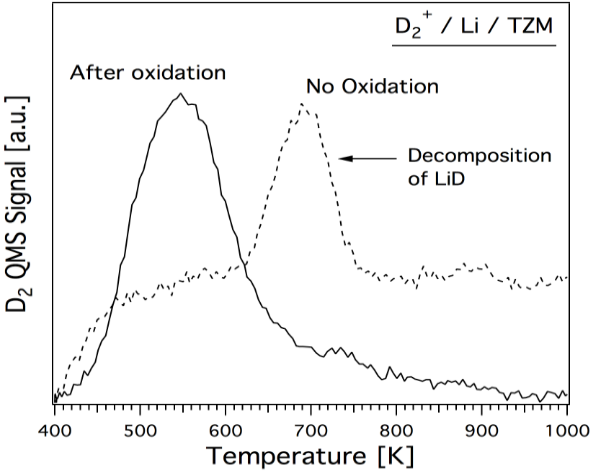
- Quantum modeling by Krstic indicates preferential bonding of deuterium to oxygen in carbon matrix (theory)
- Laboratory studies by Capece show increased absorption by oxidized Li, but lower thermal decomposition temperature (laboratory studies)
- MAPP diagnostic successfully deployed in NSTX-U 2016 run campaign



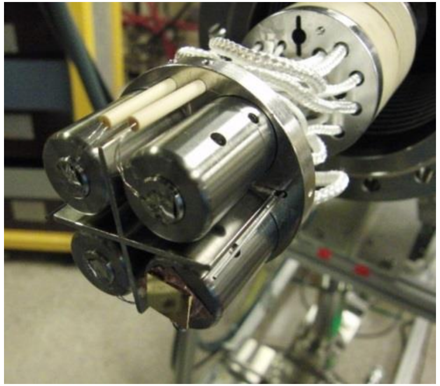
Amount of D bound by Li is even less than percentage of Li in PFC matrix

Fraction of D sharing charges with matrix constituents

Krstic, 2013 PRL



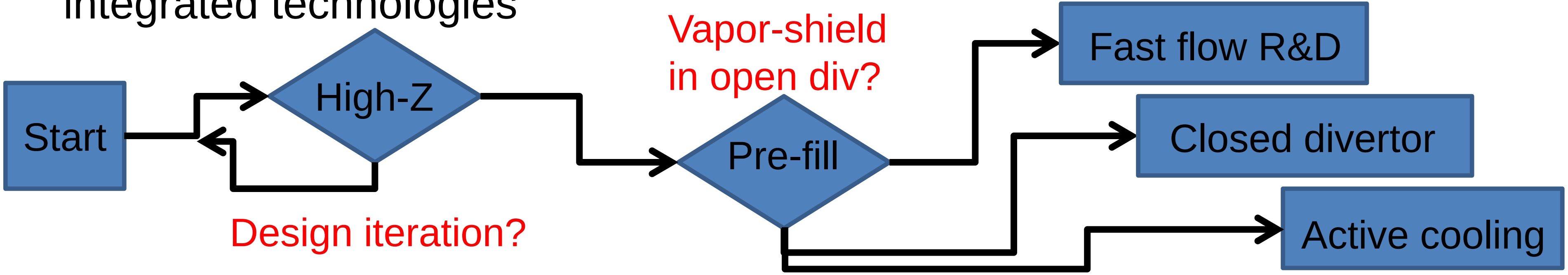
Capece, 2015 JNM



MAPP Diagnostic (U-Illinois)

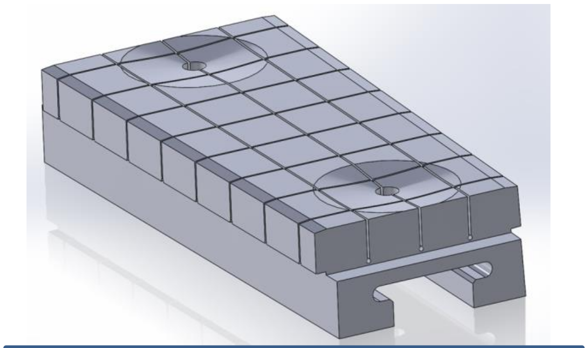
Multiple decision points in the research program leading to new science and technology opportunities

- NSTX-U PFC Recovery project emphasis on prototypes builds confidence
- High-Z introduction enables early evaluation of operational impact of new PFC materials
  - LITER and U-LITER allows near-term examination of increased areal coverage with lithium conditioning
- Pre-filled target performance presents decision points:
  - Is a closed divertor upgrade necessary for high-temperature (i.e. vapor box)?
  - Is active cooling or fast-flow required for long-pulse particle flux handling?
- Closed loop facility enables broadened facility scope for research on integrated technologies

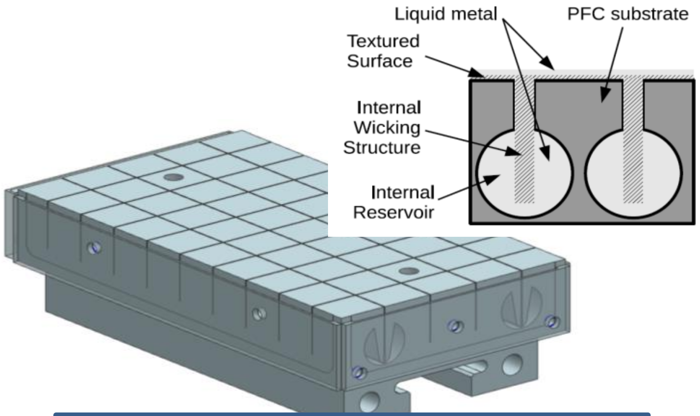


Most mature technologies emphasized for current development path

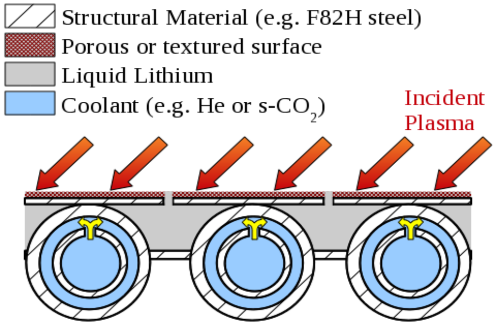
- Bulk high-Z for high heat flux regions, coatings may be possible in low-heat flux regions
- Pre-filled targets build on graphite and high-Z substrate designs
- External Li feed into reservoir region with inertial cooling provides nearest target technology for NSTX-U



High-Z PFC T-bar design



Pre-filled target concept



DEMO-relevant PFC concept

Sustained effort needs to start now if this is to be implemented in 2025-2030 timeframe

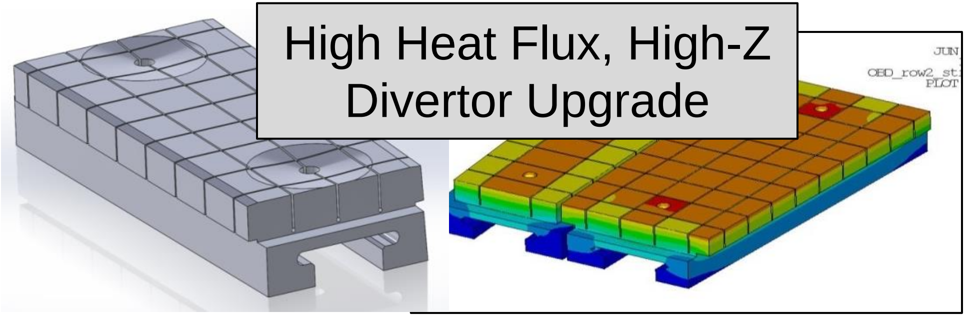
- Reverse schedule developed to identify dependencies in R&D
  - Pre-filled high-heat flux tiles build on High-Z HHF
  - High-Z high-heat flux and low-heat flux tiles build on PFC Recovery activity

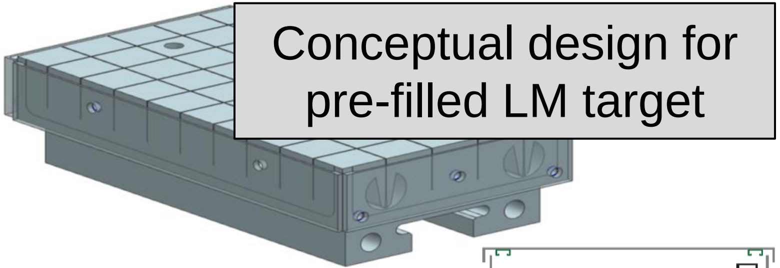
- Pre-filled tiles could be used in NSTX-U campaigns ~**6 years** from start (High-Z HHF in ~2 years)

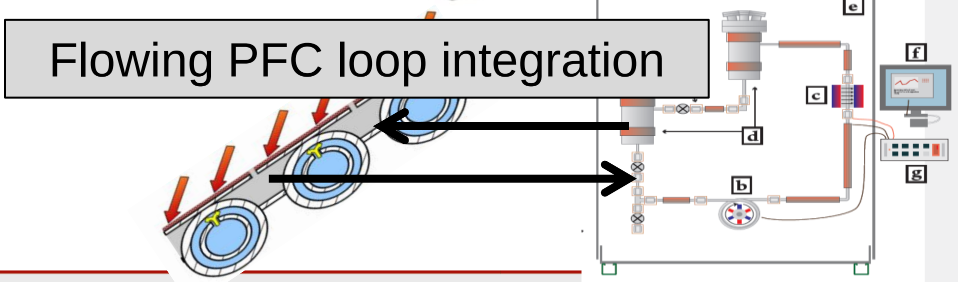
- Li R&D facility recommended to accelerate development
  - Serial R&D processes indicate ~10 years of development to integrated PFCs
  - Fully flowing modules require Li loop and handling R&D & ops experience
  - Fully flowing modules required for Li facility that **“runs as long as we want it to run”**
  - Building/facility recommended in PPPL Li Corrective Action Plan to consolidate Li activities as a best practice

A three-step progression can accelerate tests of flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER
2. Pre-filled liquid-metal target
3. Flowing LM PFC

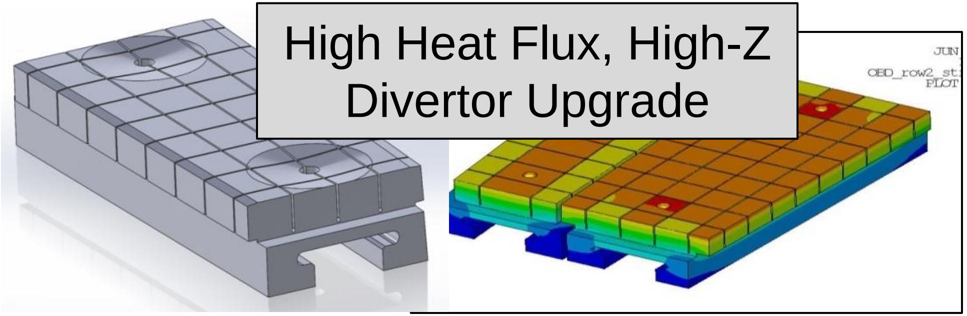

High Heat Flux, High-Z Divertor Upgrade


Conceptual design for pre-filled LM target


Flowing PFC loop integration

High-Z divertor tiles + Li evaporated coatings provide divertor analogue of Magnum-PSI experiments

1. High-Z divertor tiles + LITER + U-LITER
   - Scientific goals:
     - Short-period particle-flux handling through temperature ramp
     - 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 <u>high-temp. target</u> with limited inventory of Li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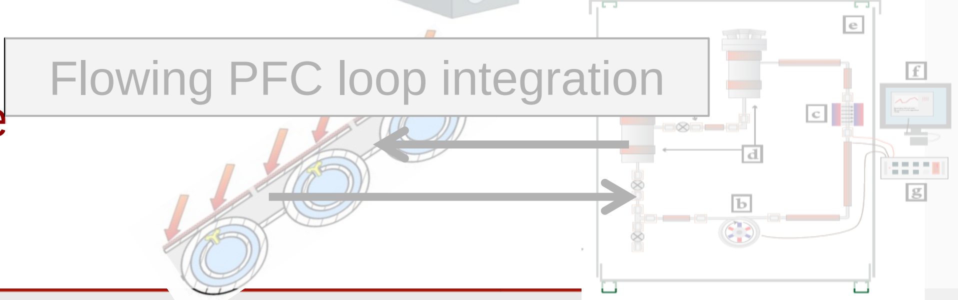
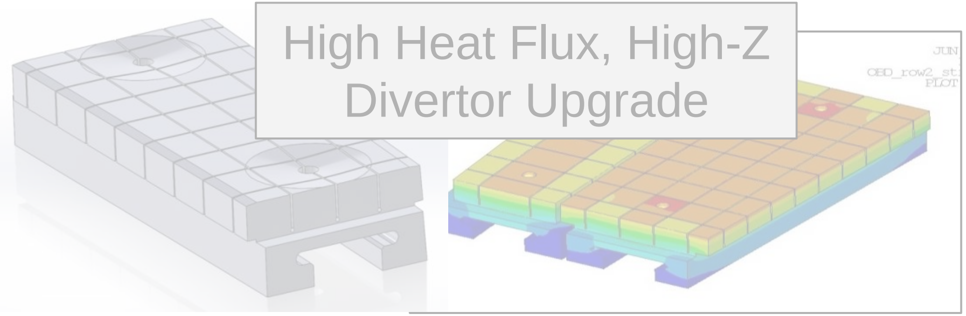
Conceptual design for pre-filled LM target


Flowing PFC loop integration

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

2. Pre-filled liquid-metal target
   - Scientific goals:
     - Short-pulse particle-flux handling with *localized* Li source
     - Test models of maintenance of LM wetting and coverage
     - Understand limits of LM passive resupply
     - Understand impact and core-edge compatibility of <u>high-temp. target</u> with **larger** inventory of Li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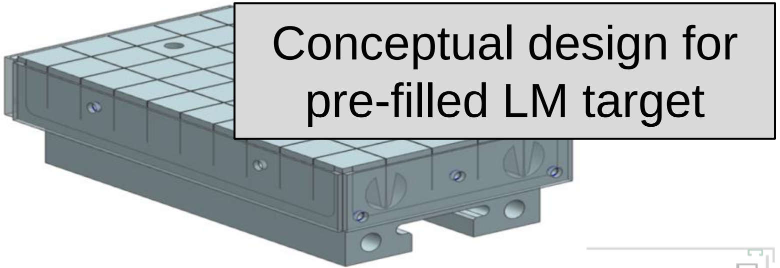
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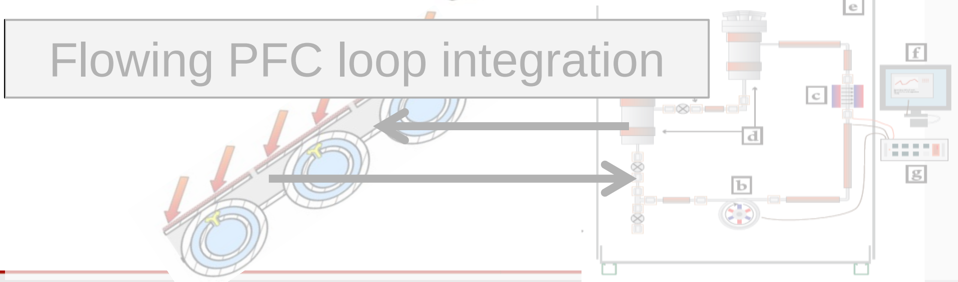
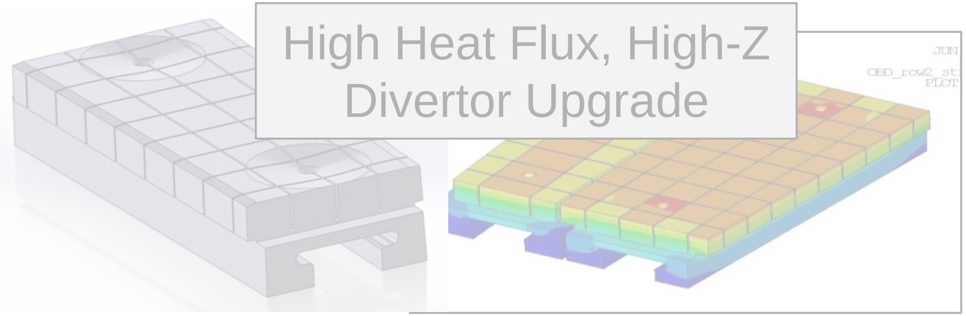

Flowing PFC loop integration

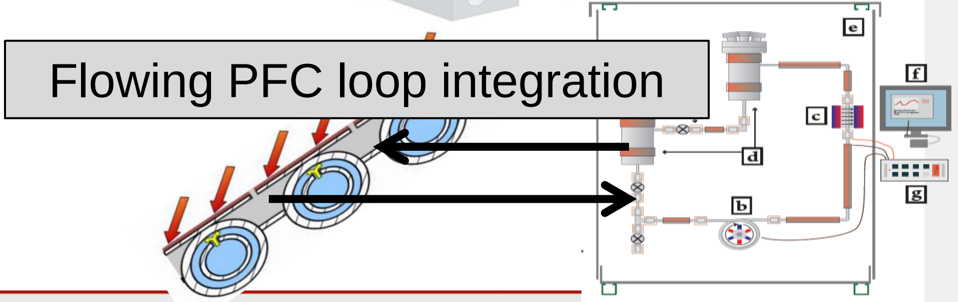
Final integration demonstrates LM introduction/extraction and inventory control

3. Flowing LM PFC

- Scientific goals:
  - Short pulse particle flux handling with localized, constant material
  - Assess material inventory control to/from LM target
  - Understand performance of passive + active replenishment techniques
  - Understand impact and core-edge compatibility of high-temp. target

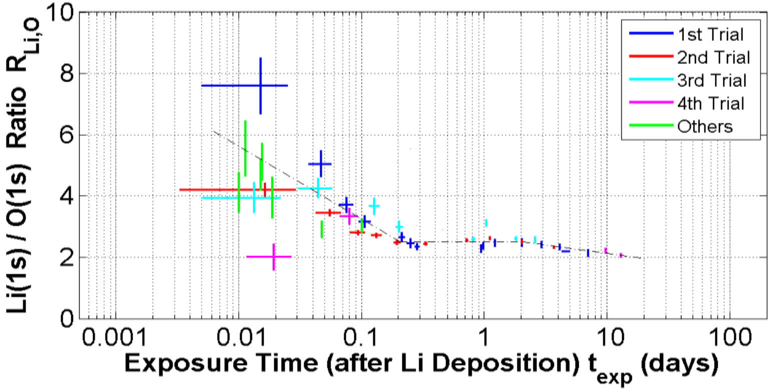

High Heat Flux, High-Z Divertor Upgrade


Conceptual design for pre-filled LM target

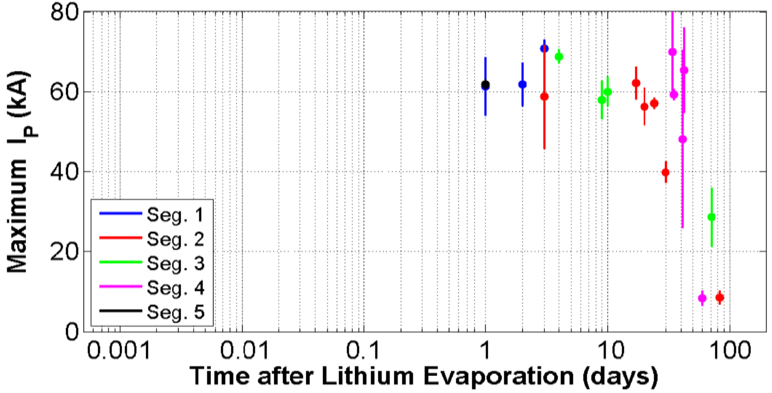

Flowing PFC loop integration

Measurements of surface composition after lithium application indicate formation of stable oxide layer

Lithium/Oxygen Ratio - Vacuum, T_S = 30 ± 10 °C



Temporal Evolution of Maximum I_P



- Results shown from several lithium evaporation experiments
- Surface exclusively Li_2O for ~100 hours at H_2O pressure of 2 x 10^{-9} T (upper figure)
- Persistence of maximum achievable plasma current – good plasma performance – suggests ability of Li_2O to retain hydrogen (lower figure)
- Low resolution of MAPP XPS system means more time time needed for scans
  - Li_2O formation from lithium unresolved for t < 1 hour

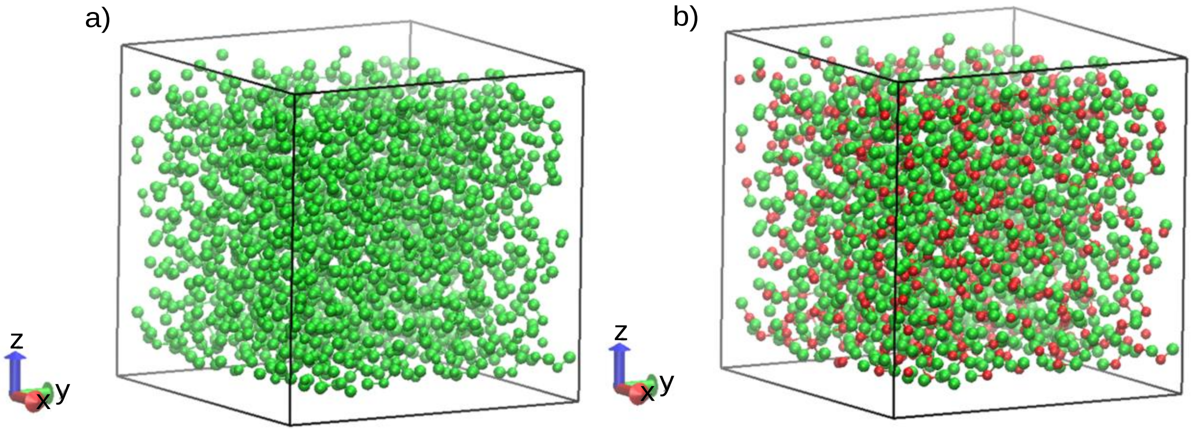
Hydrogen retention in lithium and lithium oxide measured under controlled laboratory conditions

- Used stainless steel ultrahigh vacuum chamber with 2×10^{-10} Torr base pressure
- Ni(110) single crystal high-Z substrate
- Lithium films created by thermal evaporation onto Ni substrate
  - Lithium oxide formed by O_2 exposure
- Lithium and lithium oxide films exposed to 500 eV H_2^+ ion beam for total total fluence of 4×10^{15} H^+cm^{-2}
  - Beam defocused over surface to provide total fluence of 4×10^{15} H^+cm^{-2}
- Hydrogen retention determined with temperature programmed desorption
  - Measurements made after irradiation with hydrogen at various lithium and lithium oxide film temperatures

Experiments simulated with molecular dynamics calculations

- **Classical molecular dynamics (MD) used**
  - **Each atom treated as point mass**
  - **Newton's equations integrated to compute motion**
  - **Individual force equation for each atom derived from potential energy functional for system**
- **Amorphous target surfaces of pure Li and Li_2O prepared for 90, 300, 400, 500, and 600K temperatures**
- **Computational cells of about 2000 atoms initially created at 300K for two cases**
  - **Random distribution of lithium atoms only**
  - **Predefined random distribution of 33% O and 67% of Li atoms**

Amorphous distribution of lithium and lithium oxide in unit cells

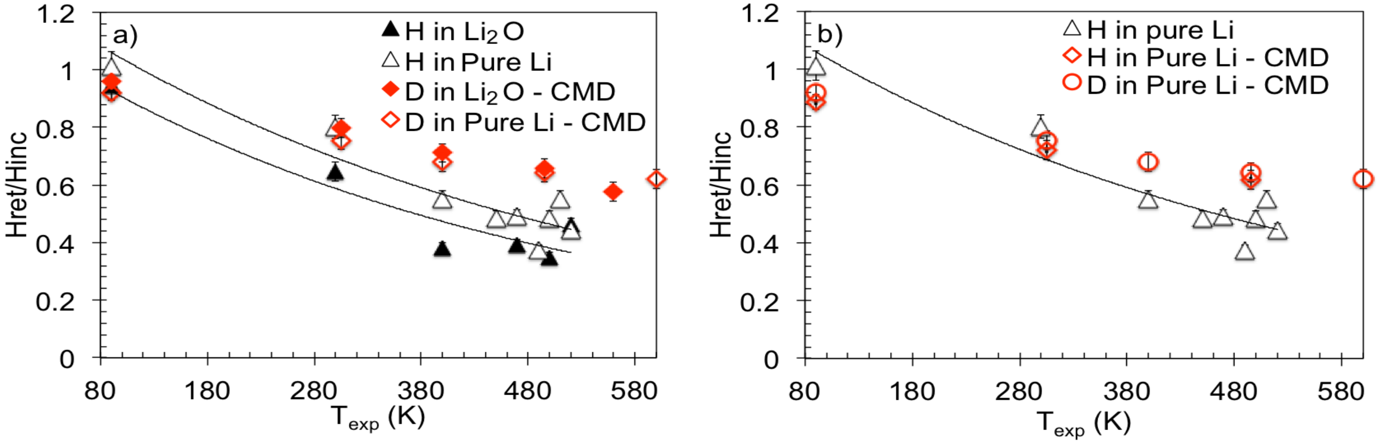


a) **Li system (2000 lithium atoms)**

b) **Li_2O system: 33% of O (660 atoms) and 67% of Li (1340 atoms)**

- **Green and red symbols represent Li and O, respectively**

Hydrogen retention in lithium and lithium oxide seen in laboratory experiments and MD simulations

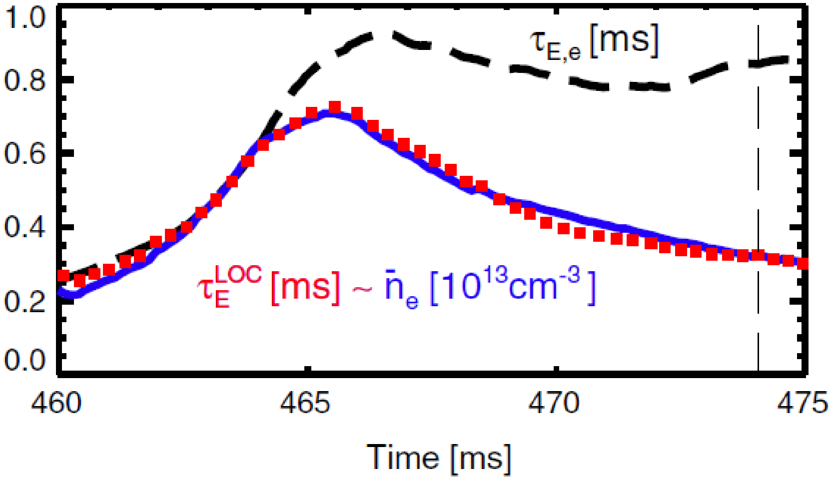


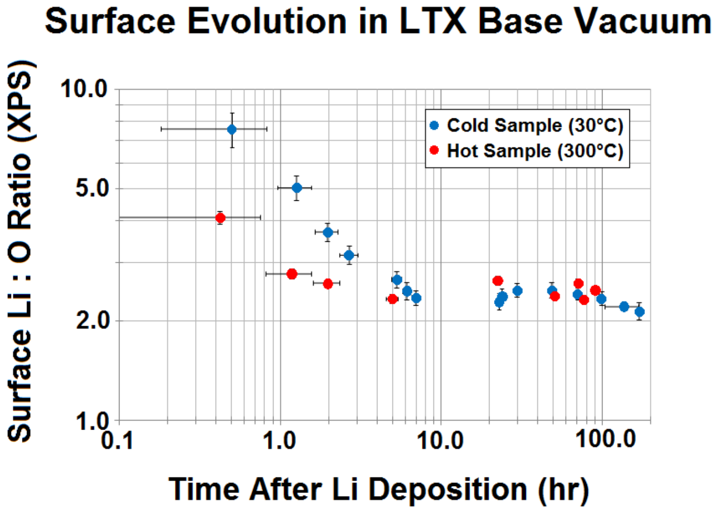
a) H retention fraction (H retention/H incident) in Li and Li_2O as function of exposure temperature and comparison with D retention from MD calculations

b) MD and experimental data on H retention fraction only in Li and Li_2O as function of exposure temperature.

LTX demonstrated (again) confinement gains even with partial oxidation of Li coatings and Li pool

- Measured electron energy confinement exceeds neo-Alcator Linear Ohmic Confinement scaling ~3x (Boyle PRL 2017)
- tored rman C
- **g liq s)?**

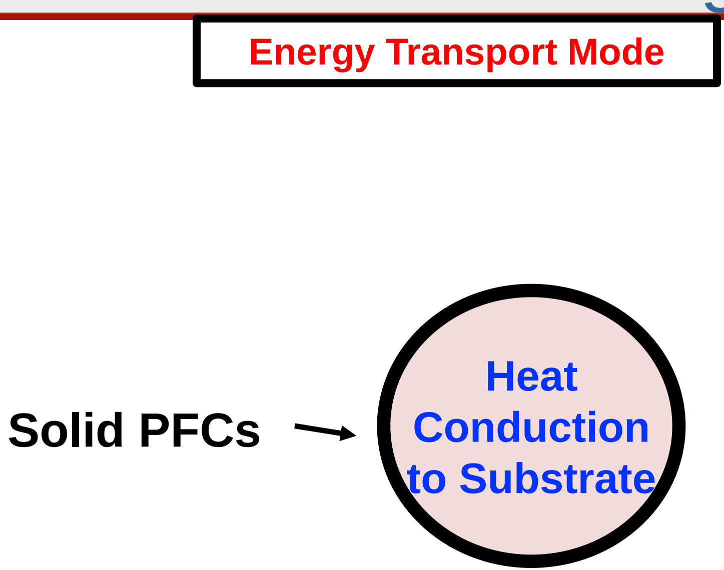




D. Boyle, et al., *Phys. Rev. Lett.* **119** (2017) 015001.

M. Lucia, PhD Thesis, Princeton University. 2015.

Liquid metal PFCs provide additional pathways for energy transport



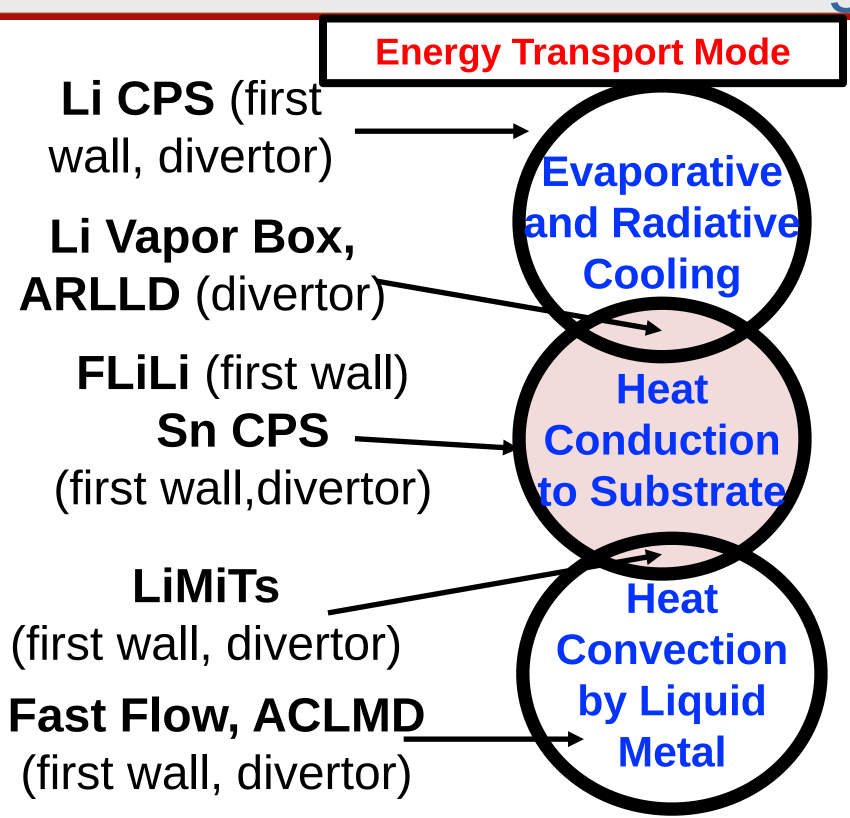
Energy Transport Mode

Solid PFCs

Heat Conduction to Substrate

- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation

Liquid metal PFCs provide additional pathways for energy transport



Energy Transport Mode

Li CPS (first wall, divertor)

Li Vapor Box, ARLLD (divertor)

FLiLi (first wall)

Sn CPS (first wall,divertor)

LiMiTs (first wall, divertor)

Fast Flow, ACLMD (first wall, divertor)

Evaporative and Radiative Cooling

Heat Conduction to Substrate

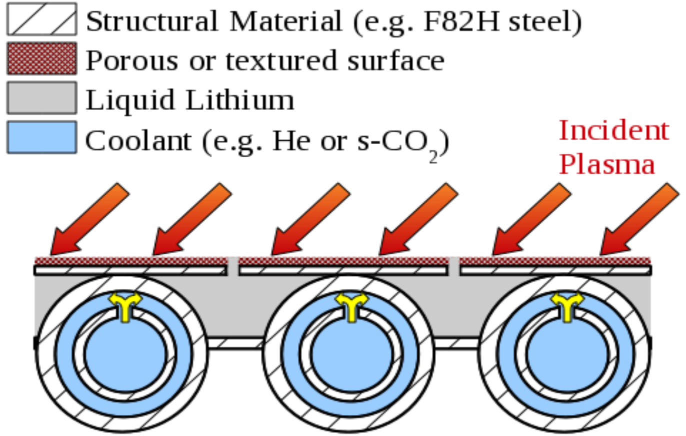
Heat Convection by Liquid Metal

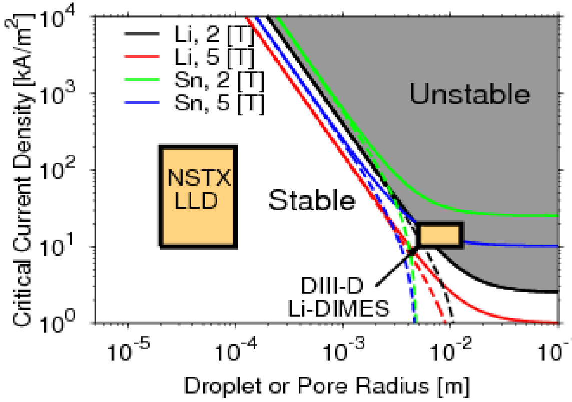
- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- Liquid metals access *mobility* as additional tool for energy transport
- Particle retention in Li a strong function of temperature links PMI physics to the technology

An DEMO-relevant concept provides guidance for relevant technologies in NSTX-U

- Stability achieved by porous substrate
- Closely connected primary coolant and liquid lithium reservoir/supply structure
  - Temperature controls evaporation and condensation
  - Temperature controls hydrogen retention
- Continuous flow to/from the surface to flush gettered material and maintain wetted surfaces (substrate protection)

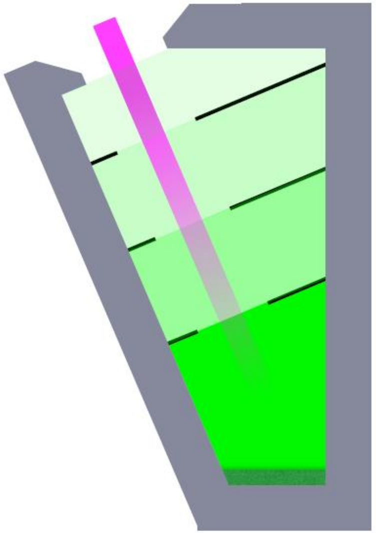
Jaworski, et al., *Plasma Phys. Control. Fusion* **55** (2013) 124040.

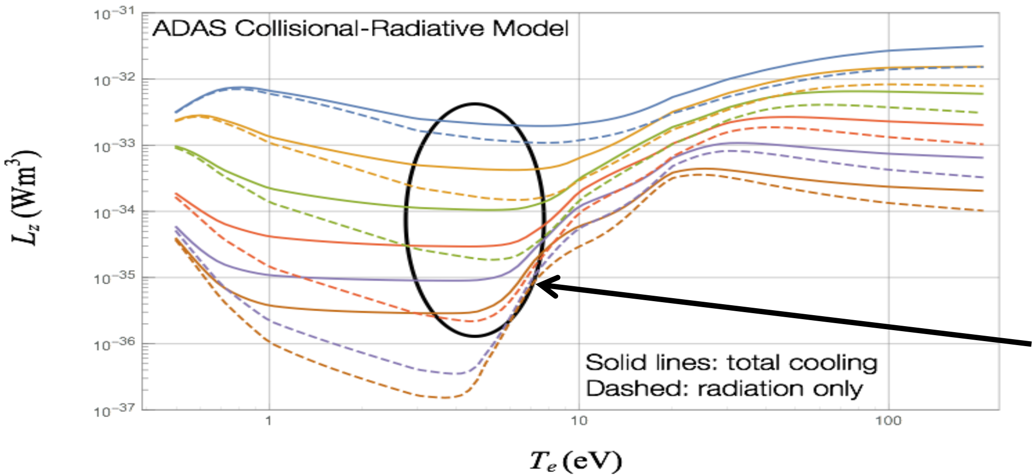




Li Vapor Box (LVB) Divertor

- Li vapor divertor target is constrained in space by differential pumping
  - Bottom chamber reaches equilibrium density of ~ $10^{22}/m^3$ @ 750 C
  - Upper chambers pump by condensation, at much lower temperature
- Plasma energy is dissipated in bottom box





$n_e = 10^{19}\mathrm{m}^{-3}$

$n_e = 10^{19.5}\mathrm{m}^{-3}$

$n_e = 10^{20}\mathrm{m}^{-3}$

$n_e = 10^{20.5}\mathrm{m}^{-3}$

$n_e = 10^{21}\mathrm{m}^{-3}$

$n_e = 10^{21.5}\mathrm{m}^{-3}$

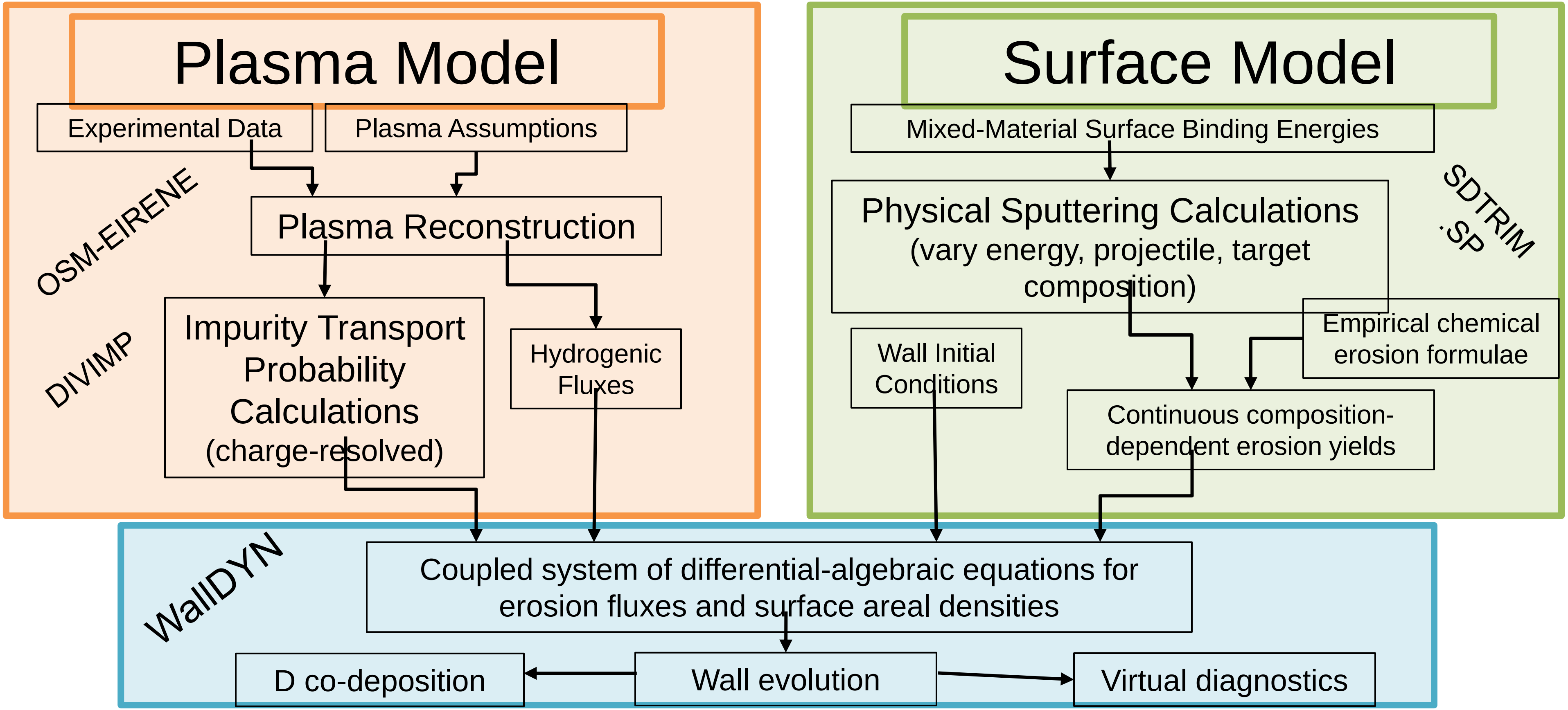
$\tau_z = 100\mu\,\mathrm{sec}$

$n_z = \tau_z S/V$

$$\left.\frac{\Delta E}{ptcl.}\right|_{cool} = \frac{\Delta t V p_{cool}}{\Delta t V dn_z/dt|_S} = \frac{n_e n_z L_Z}{n_z/\tau_z} = n_e \tau_z L_Z \sim 6.2eV/ptcl.$$

Goldston, ISLA 2015

WallDYN: An integrated global model for mixed material migration



Plasma Model

Experimental Data

Plasma Assumptions

OSM-EIRENE

Plasma Reconstruction

DIVIMP

Impurity Transport Probability Calculations (charge-resolved)

Hydrogenic Fluxes

Surface Model

Mixed-Material Surface Binding Energies

SDTRIM.SP

Physical Sputtering Calculations (vary energy, projectile, target composition)

Empirical chemical erosion formulae

Wall Initial Conditions

Continuous composition-dependent erosion yields

WallDYN

Coupled system of differential-algebraic equations for erosion fluxes and surface areal densities

D co-deposition

Wall evolution

Virtual diagnostics

WallDYN parameterizes plasma impurity transport with DIVIMP 2D Monte Carlo code

- 20k neutrals launched from each wall bin
  - Energy and angular distribution typical of sputtered particles
  - Deposition location, charge state recorded
- R ≡ Fraction of eroded flux from “source” that ends up in a certain charge state at “destination”
- 1 Algebraic equation for influx of each element & charge state:

$$\Gamma^{IN}_{wall,elem}(t) = \sum_{source} R^{wall}_{source} * \Gamma^{OUT}_{source,elem}(t)$$

- Assumptions:
  - Impurity concentrations are low enough not to disturb plasma (“trace impurity limit”)
  - Plasma transport timescale << wall evolution timescale
  - Plasma does not change in time

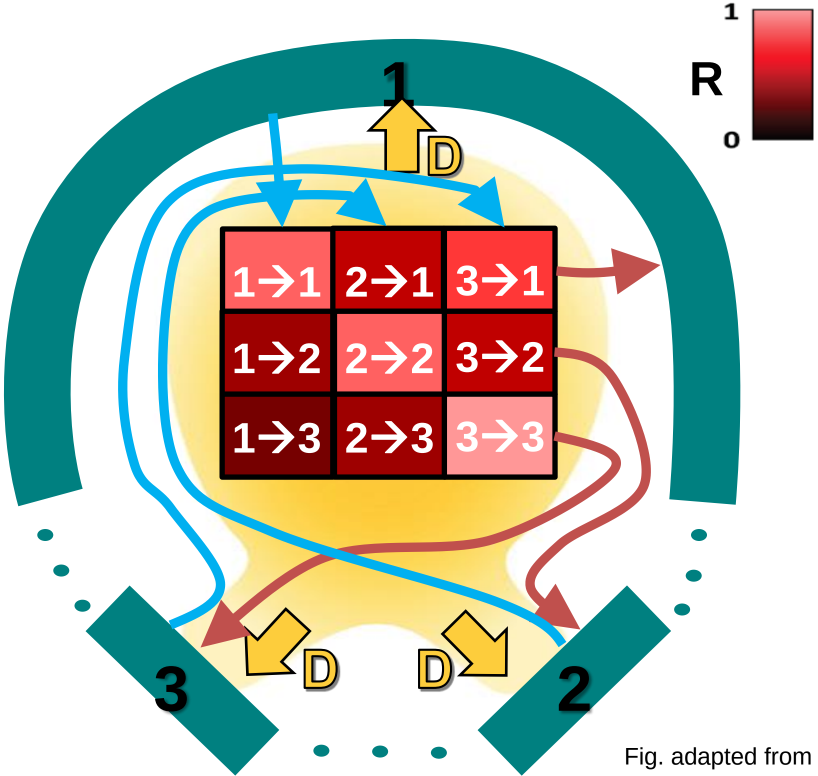
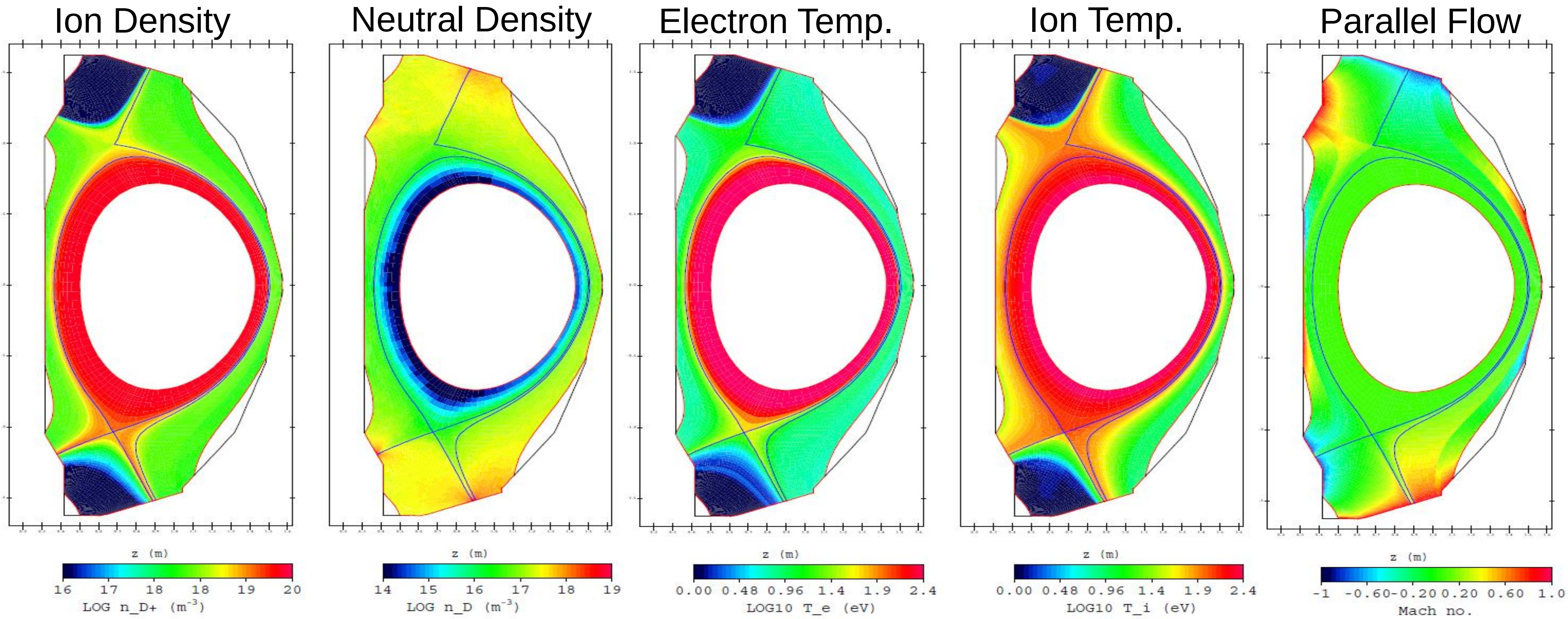


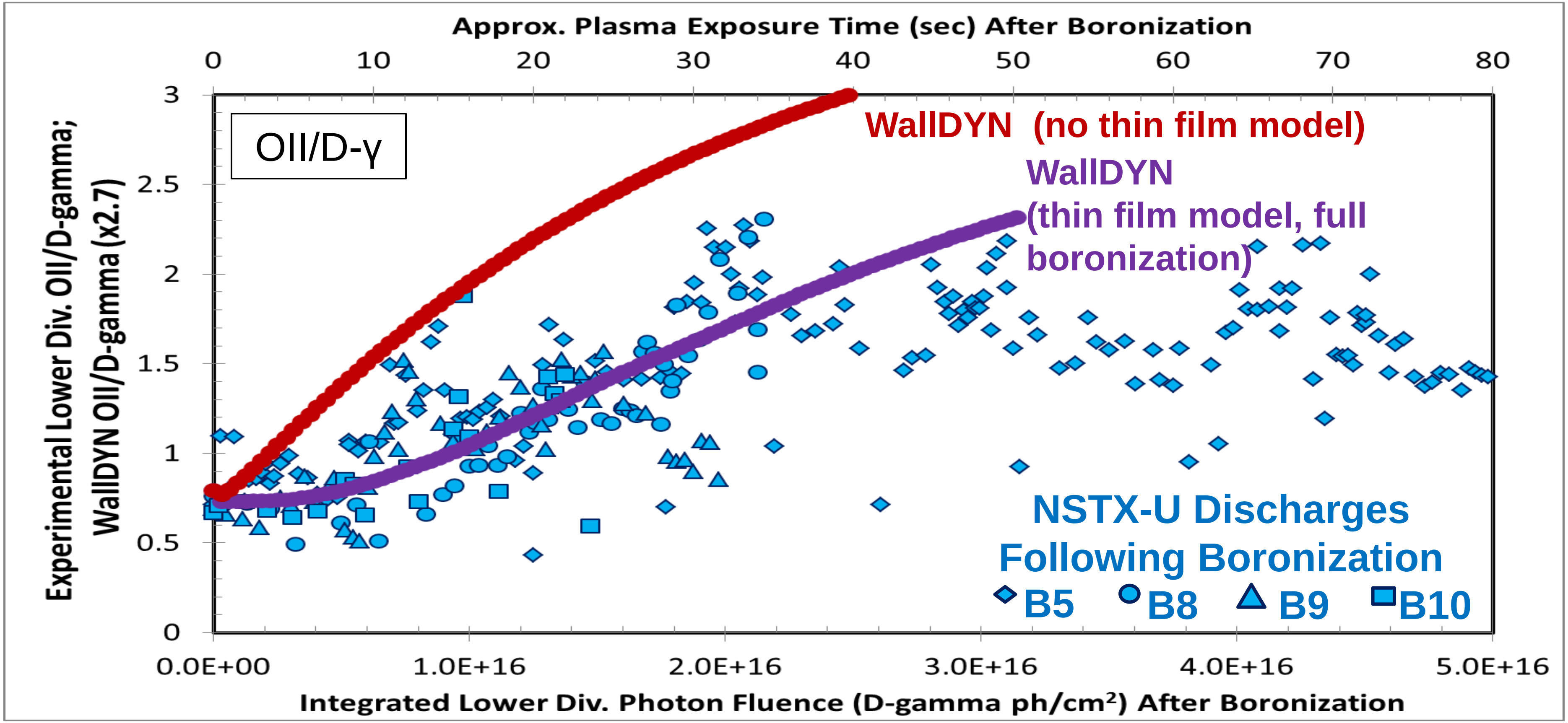
Fig. adapted from Meisl NF 2016

OSM/EIRENE edge plasma background generated for NSTX-U

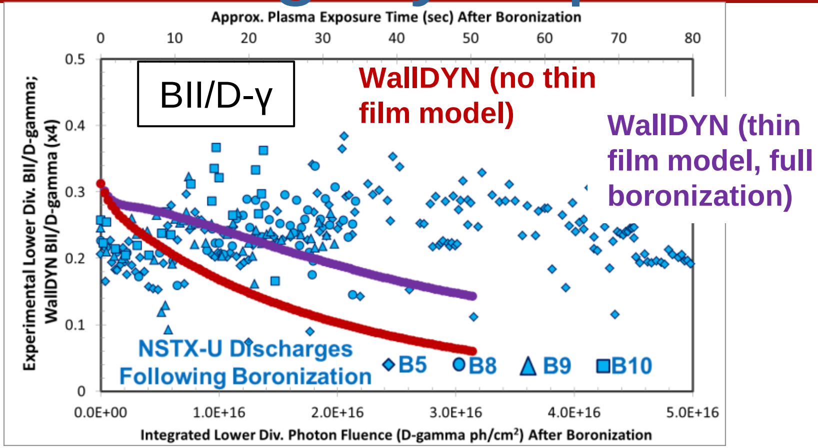


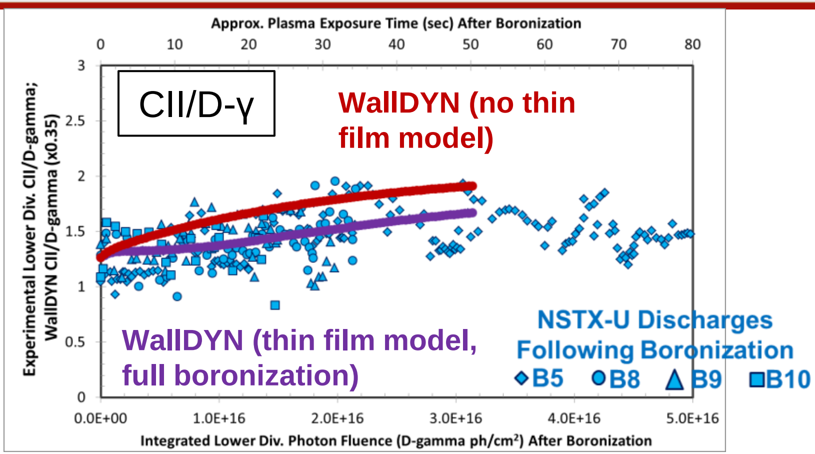
- High strike point density/temperature, large radial gradients (H-Mode like)
- No external flow/pinch applied

Results: agreement with OII emission trends greatly improved with thin film model



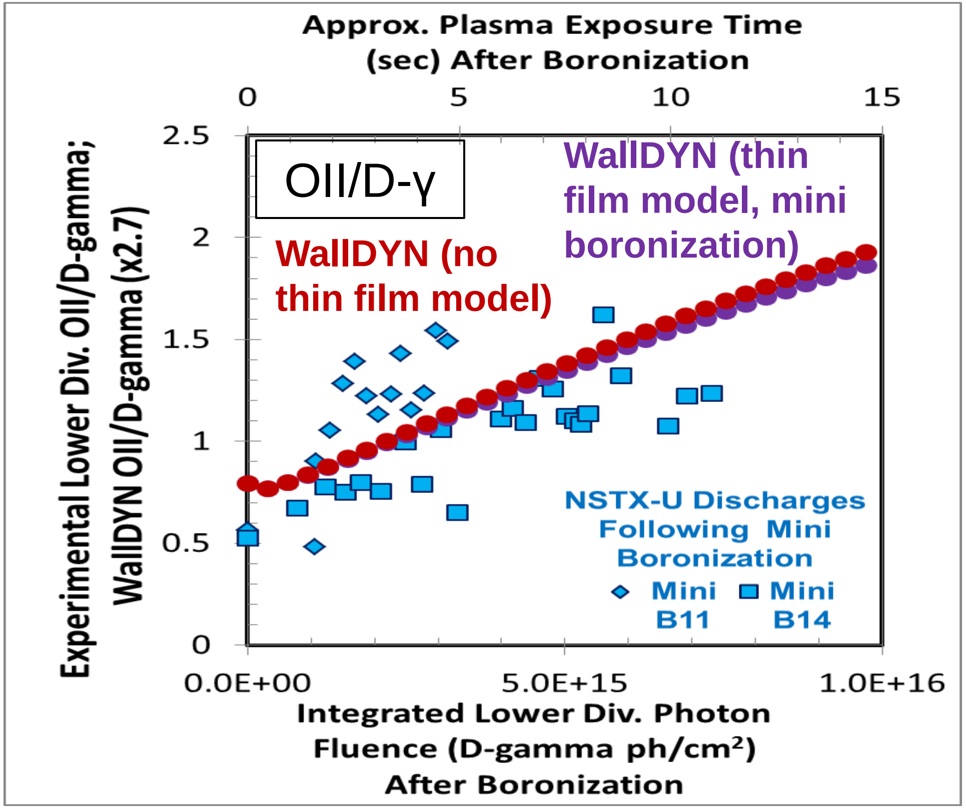
Results: agreement with BII, CII emission trends slightly improved with thin film model





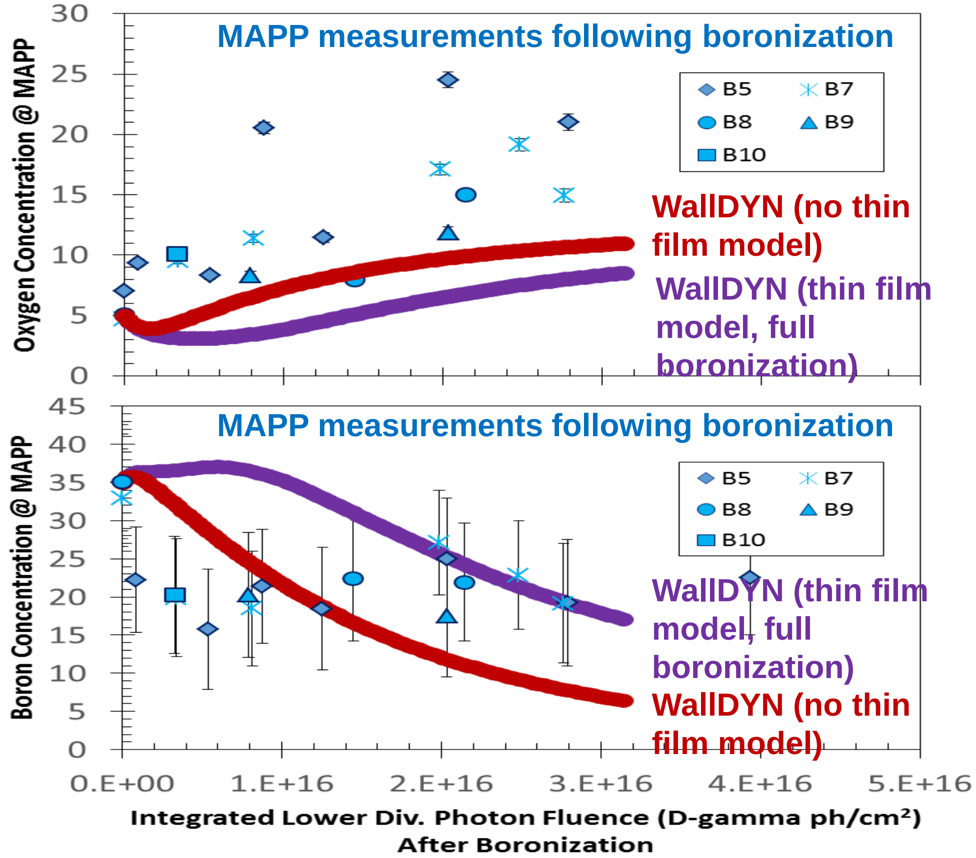
- Thin film model brings WallDYN into good agreement with experimental oxygen emission trends following full boronizations
- No experimental trend in carbon emission following boronization
  - Good agreement with both WallDYN models
- No experimental trend in boron emission following boronization
  - Poor agreement with both WallDYN models
  - Reason for continued disagreement is under investigation

Results: agreement with mini boronization emission trends similar with either model



- Thin film WallDYN model capable of differentiating between full and mini boronizations
  - Captures faster rise in impurity influx following mini boronization
- Both model and experiment show degradation of mini boronization coating on time scale of ~ 1 run day (15 sec plasma exposure)
- For mini boronization, thin film WallDYN model is nearly identical to old WallDYN model
  - Makes sense, because boron film applied to divertor (~30 A) is thinner than reaction layer (ion penetration depth ≈ 40 A)

Results: surface concentration evolution during simulations



- Both WallDYN models underestimate the rise in oxygen surface composition observed in MAPP
- Surface boron agreement inconclusive

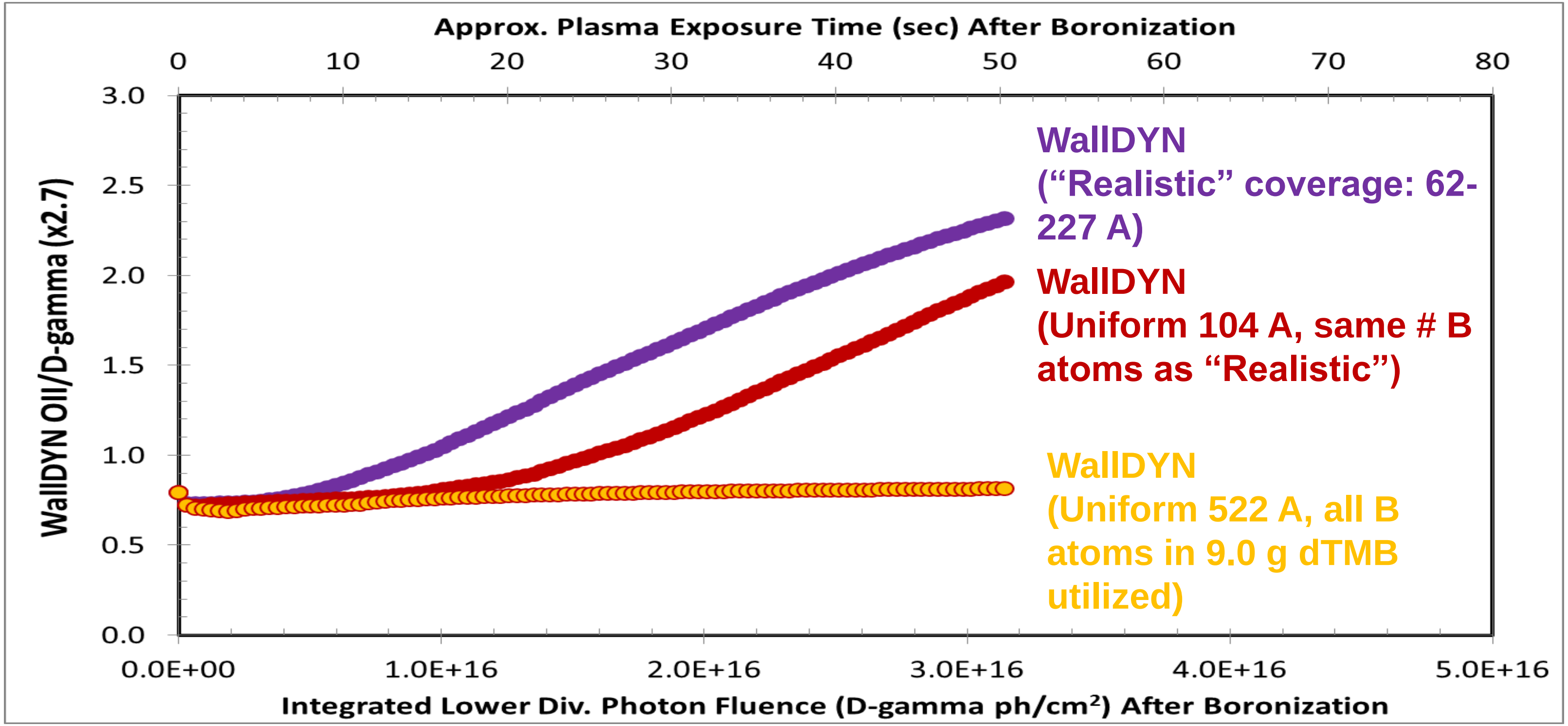
- Models do not take into account chemical state of surface
  - e.g. B-O vs. B-B vs. B-C bonds
  - May be important!

For more B/C/O surface discussion see:

F. Bedoya JO4.10 Tue PM

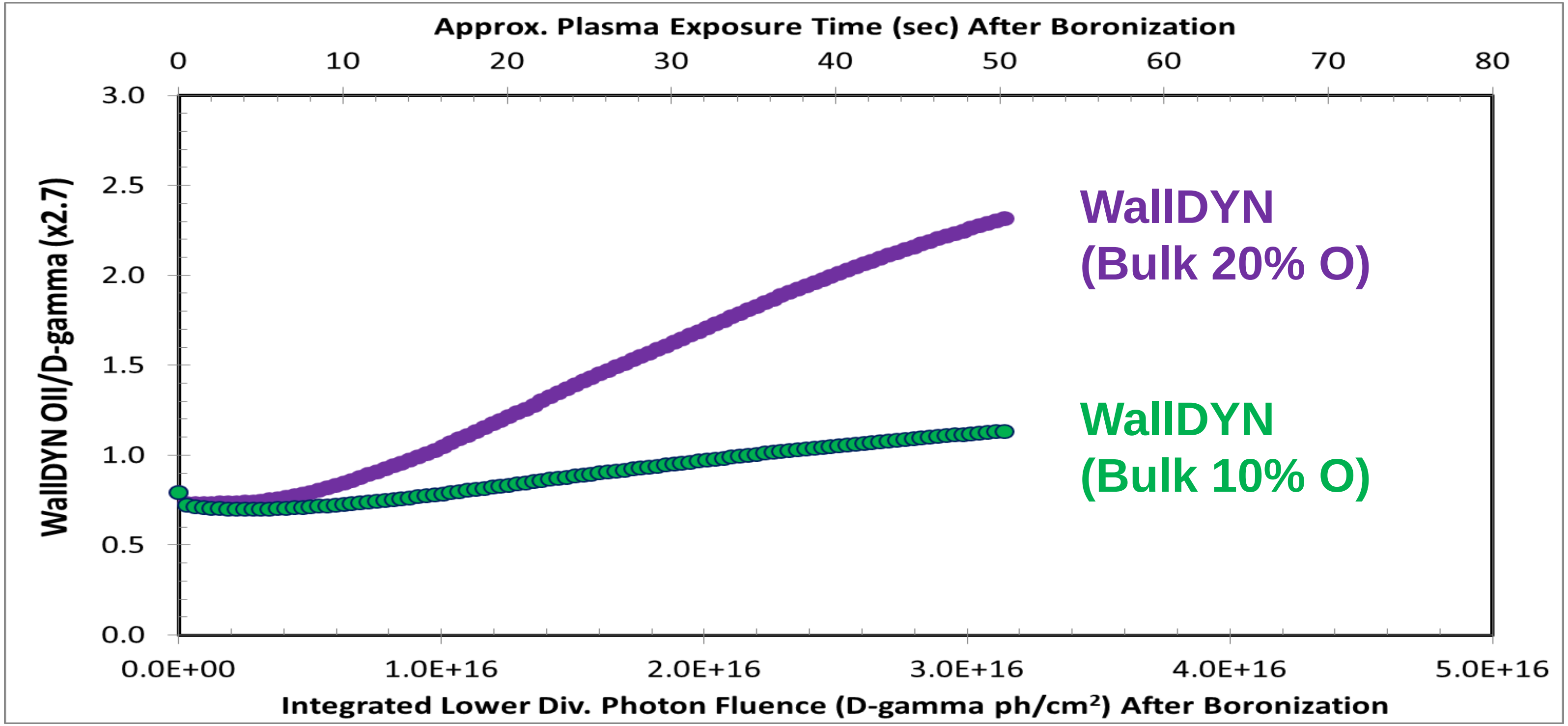
H. Schamis PP11.57 Wed PM

Effect of more uniform boron coverage on oxygen evolution (*aka more GDC electrodes*)



- Uniformity of boron coatings is controlled by properties of He glow discharge and the number of anodes

Effect of lower bulk oxygen concentration on oxygen evolution (*aka better bakeout*)



- Bulk oxygen content is typically controlled by pre-campaign conditioning (bakeout, etc.)