NSTX-U

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

Experience and development of lithium and liquid metal experiments on the NSTX and NSTX-U devices*

MA Jaworski and the NSTX-U Team

Princeton Plasma Physics Laboratory

NUF-SULI Research Seminar
Princeton Plasma Physics Laboratory
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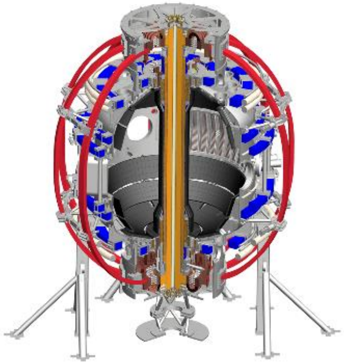
*Work supported by DOE contract DE-AC02-09CH11466

PPPL



Philosophy adopted for providing NSTX context for EURO*fusion* strategy

- Maybe liquid PFCs, but why *lithium*?
  - Key observations on PPPL experiments
  - TFTR, CDX-U, LTX
- Experience gained on NSTX
  - Evaporative coatings
  - The Liquid Lithium Divertor experiments
- Necessity of high-temperature lithium studies
- Proposed technical and scientific program for NSTX-U
- Open questions and possibilities for liquid metals

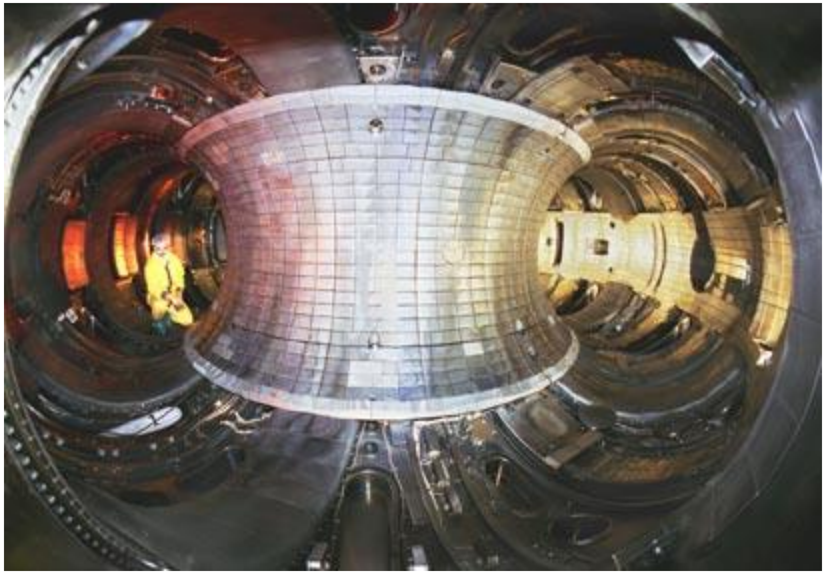
Liquid metal research in US spurred by lithium wall conditioning

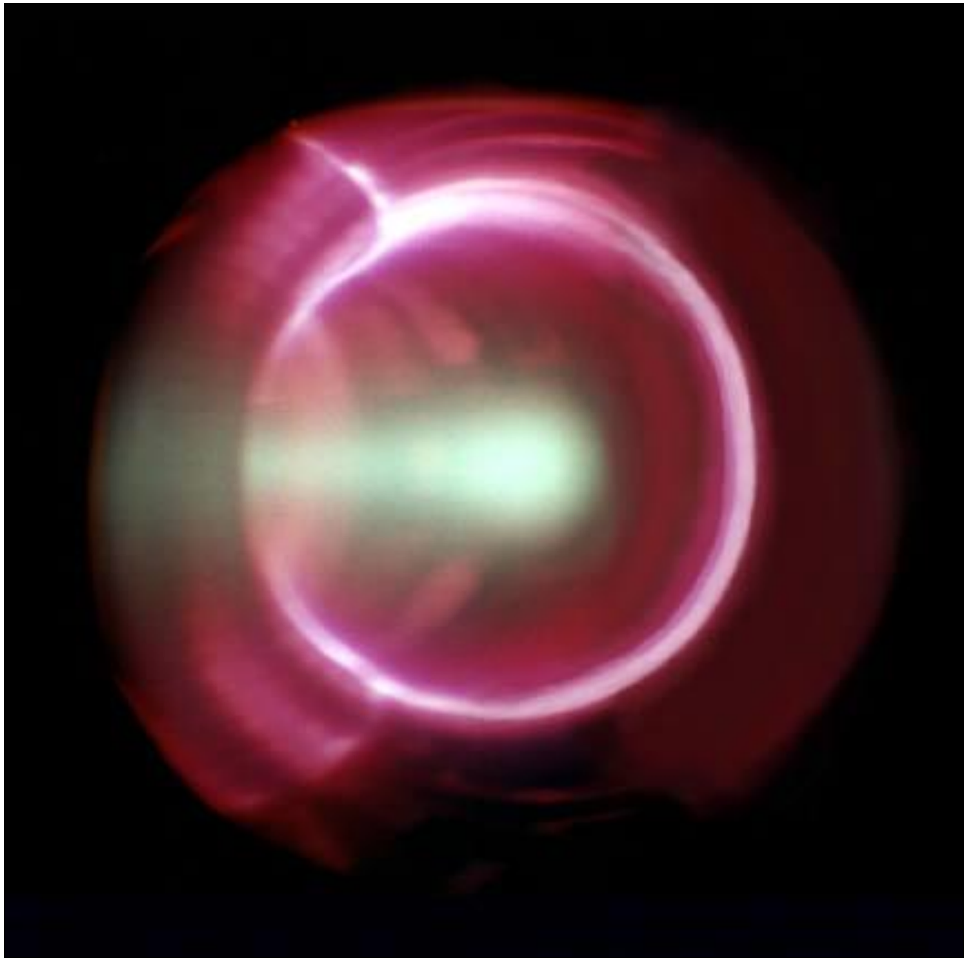
- Confinement improvements resulted in early interest in lithium
  - TFTR, CDX-U, LTX, NSTX all observed performance increases (US machine list)
  - T11-M, FTU, EAST, HT-7 have also seen benefits

- Lithium applied with multiple methods, only a few examples of liquid PFC in confinement device

- Reliance on evaporation related to technical readiness

Tokamak Fusion Test Reactor (did not utilize H-mode)





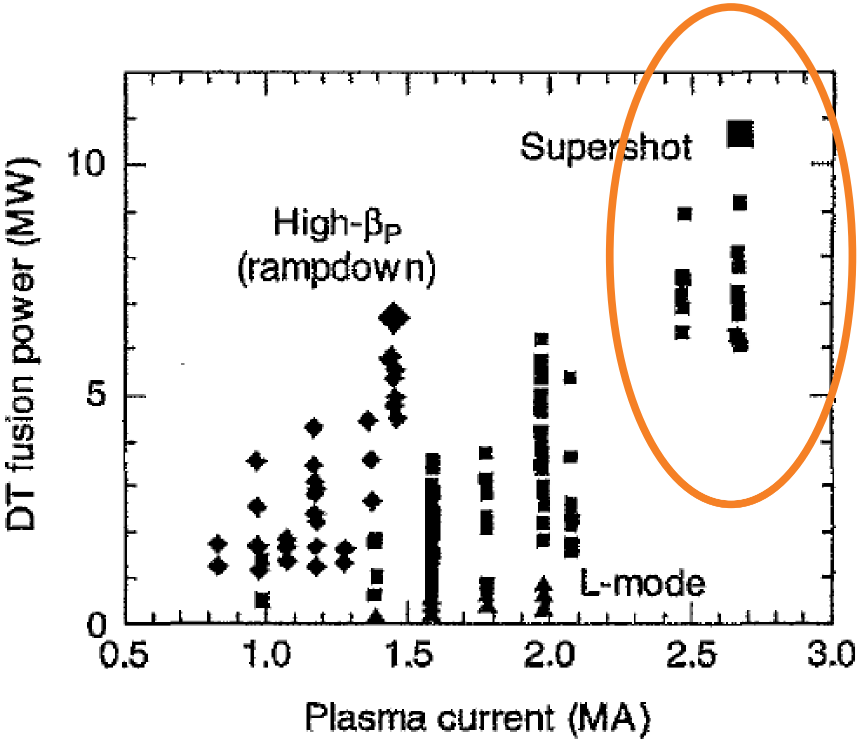
R_0 = 2.5m, a=0.87m,
I_p=2.7MA, B_t=5.6T
P_{NBI}=39.5MW, N_e=1e20m^{-3}
T_i=32keV, T_e=13.5keV, W_{tot}=6.9MJ
Tau_E=0.21s, $P_{D\text{-}T}$=10.7MW

$$Q_{D\text{-}T} = 0.27$$

Super-shot regime due to lithium wall conditioning

- Lithium injection with pellets and laser ablation conditioned walls
- Li extended super-shot regime from 2.0 to 2.7 MA
- Increased confinement from 160ms to 270ms

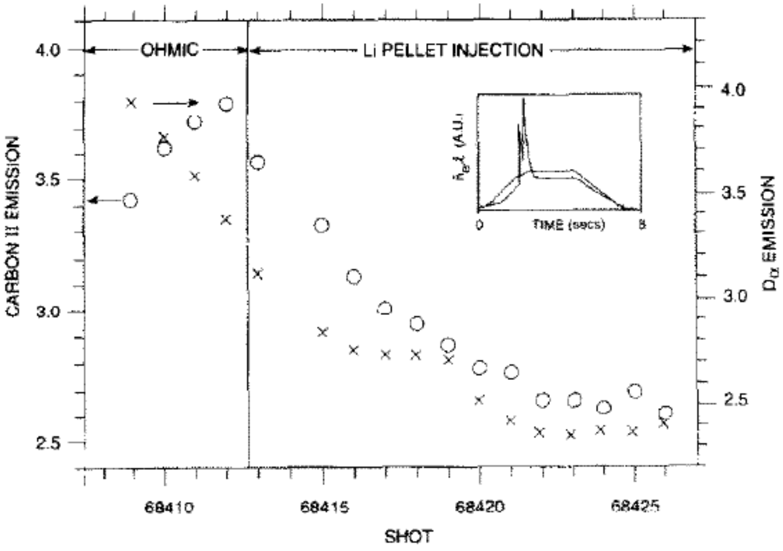
Only achieved with Li conditioning

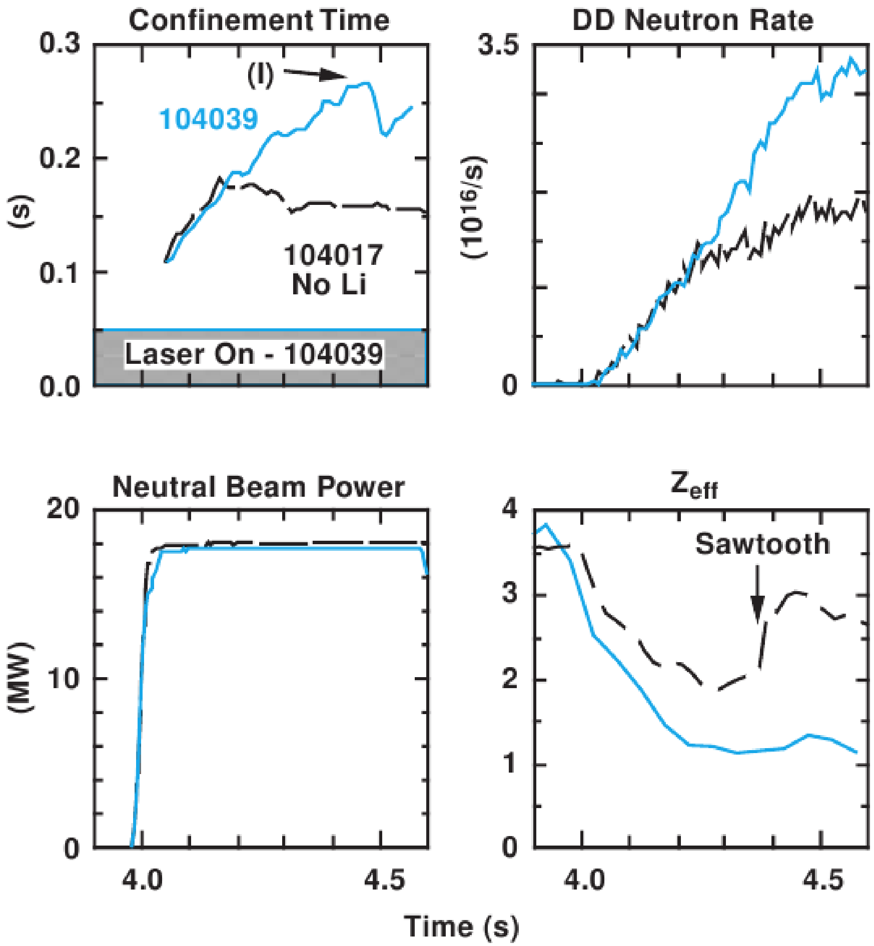


McGuire, et al., Phys. Plasmas 2 (1994) 2176.

Lithium super-shots the culmination of significant efforts to condition carbon

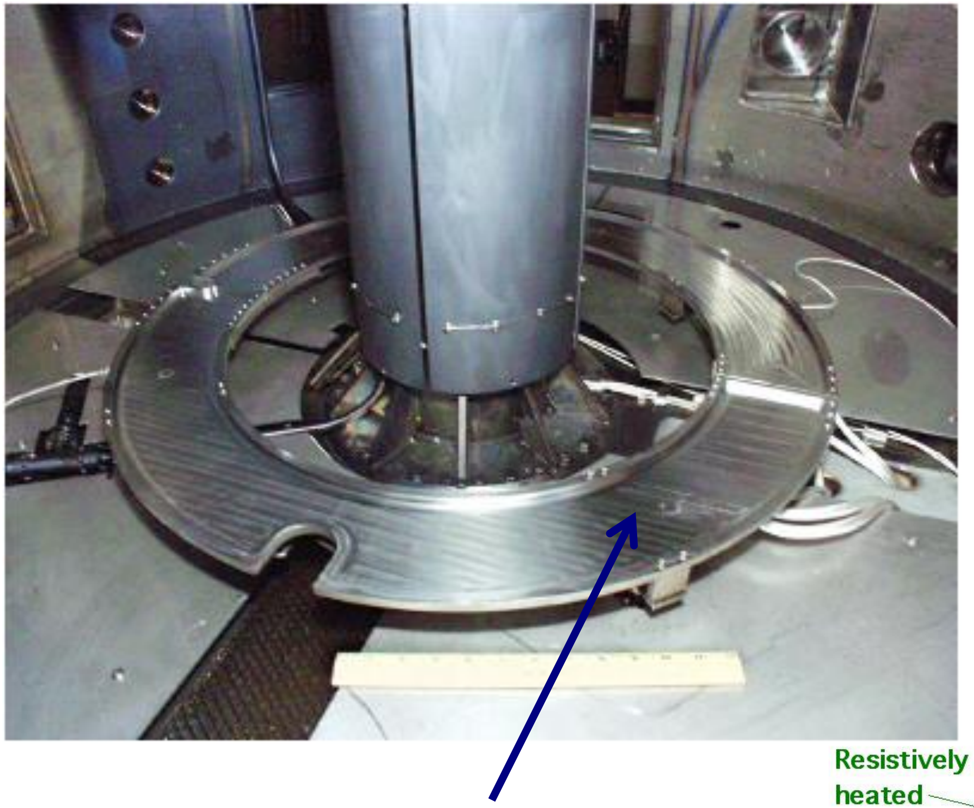
- Super-shots required extensive conditioning campaigns
- More than just H-alpha decrease during Li conditioning…





Strachan, et al., JNM **217** (1994) 145.
Mansfield, et al., NF **41** (2002) 1823.

CDX-U utilized large-area, free-surface liquid metal limiter tray



R_0= 34 cm, width = 10 cm, 6 mm deep

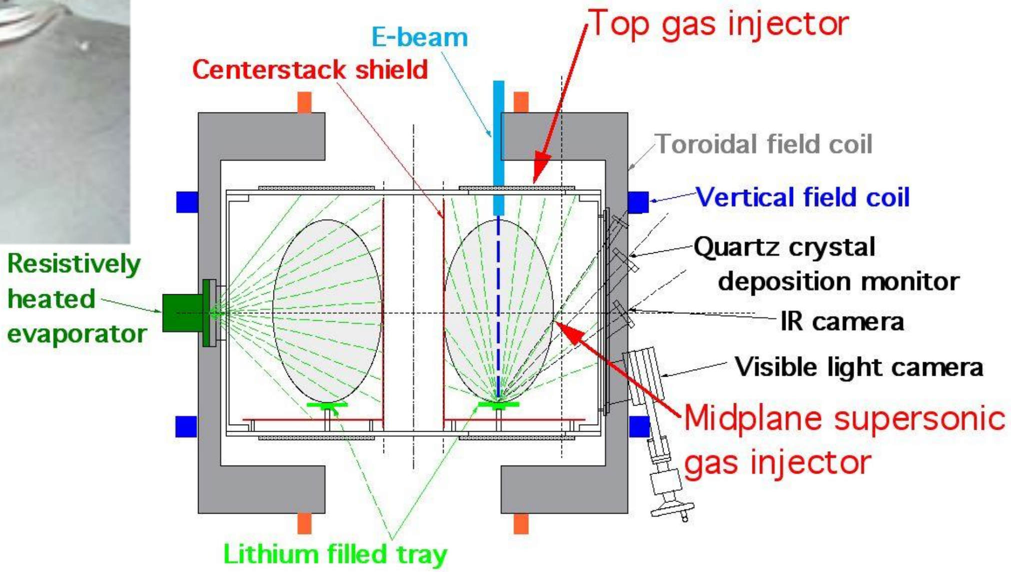
~0.5kg Li inventory

R_0=34 cm
a = 22 cm

$\kappa \leq 1.6$
$B_T(0) \leq 2.1$ kG

$I_P \leq 80$ kA
$\tau_{disch} < 25$ msec

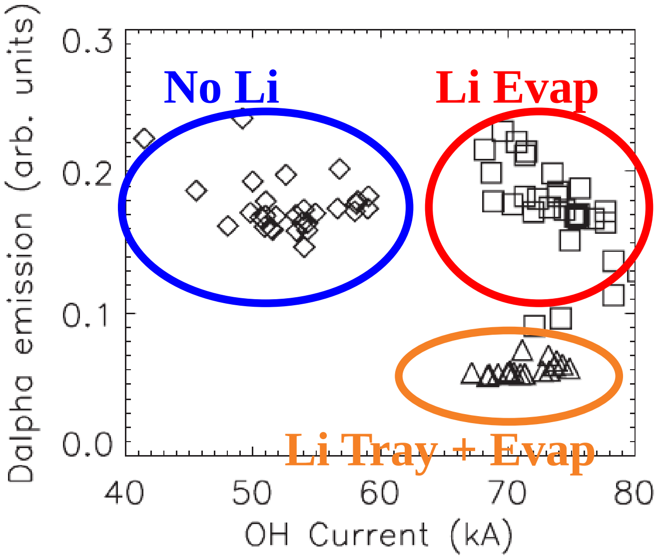
$T_e(0) \sim 100$ eV
$n_e(0) < 6\times10^{19}$ m^{-3}

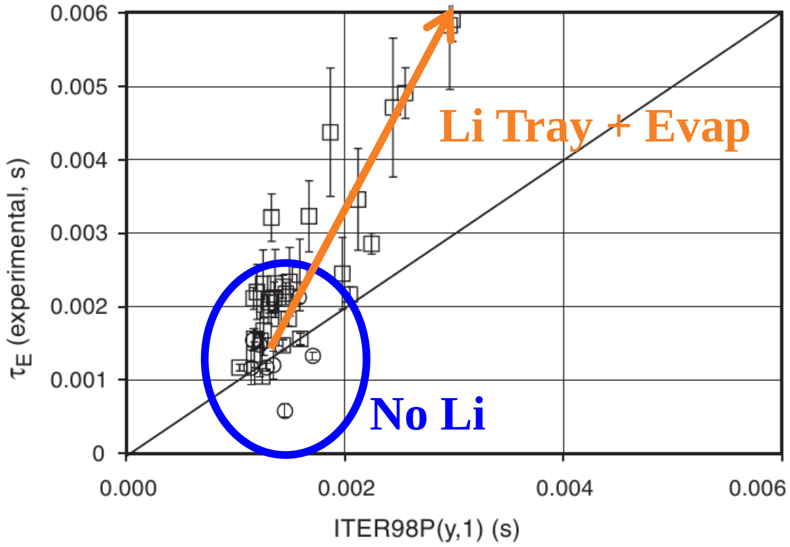


R. Majeski, R. Kaita

CDX-U improved performance with lithium limiter and wall conditioning

- Tray limiter part of series of increases in areal coverage by lithium
- D-alpha (proxy for recycling) progressively decreased
- Energy confinement-time enhancement observed





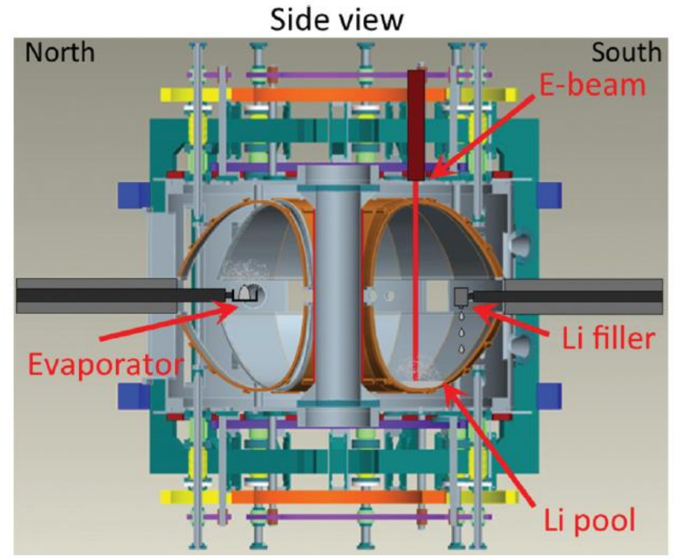
R. Majeski, et al., PRL **97** (2006) 075002.

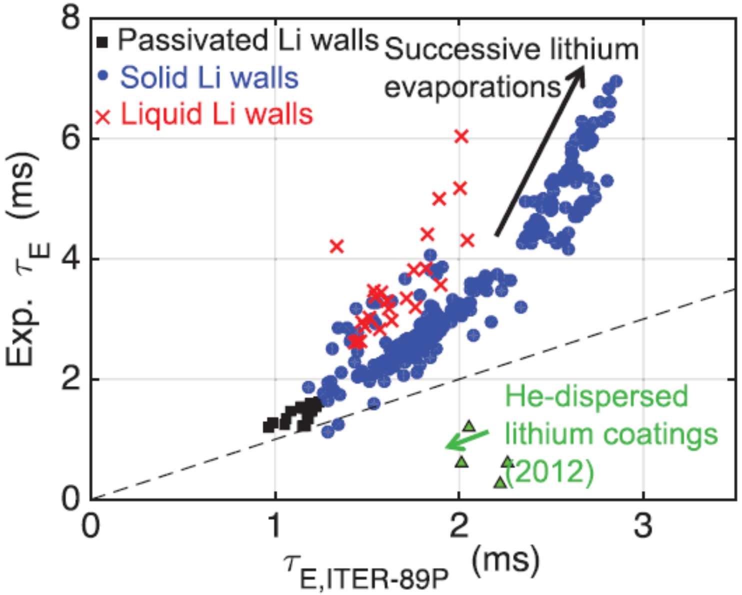
LTX repeated CDX-U result of improved energy confinement with Li

- Successor device to CDX-U featuring
  - R_0=0.4m, a=0.26m, B=0.17T, I_p=75kA, ohmic heating
  - Heated shells
  - Multiple Li application methods

- Successive Li evaporations improved performance with solid and liquid coatings

- Core temperature exhibits flattening profiles (Boyle 2017 *submitted*)





Schmitt, et al., Phys. Plasmas **22** (2016) 056112.

Diverted tokamak experience

- Maybe liquid PFCs, but why *lithium*?
  - Key observations on PPPL experiments
  - TFTR, CDX-U, LTX
- Experience gained on NSTX
  - Evaporative coatings
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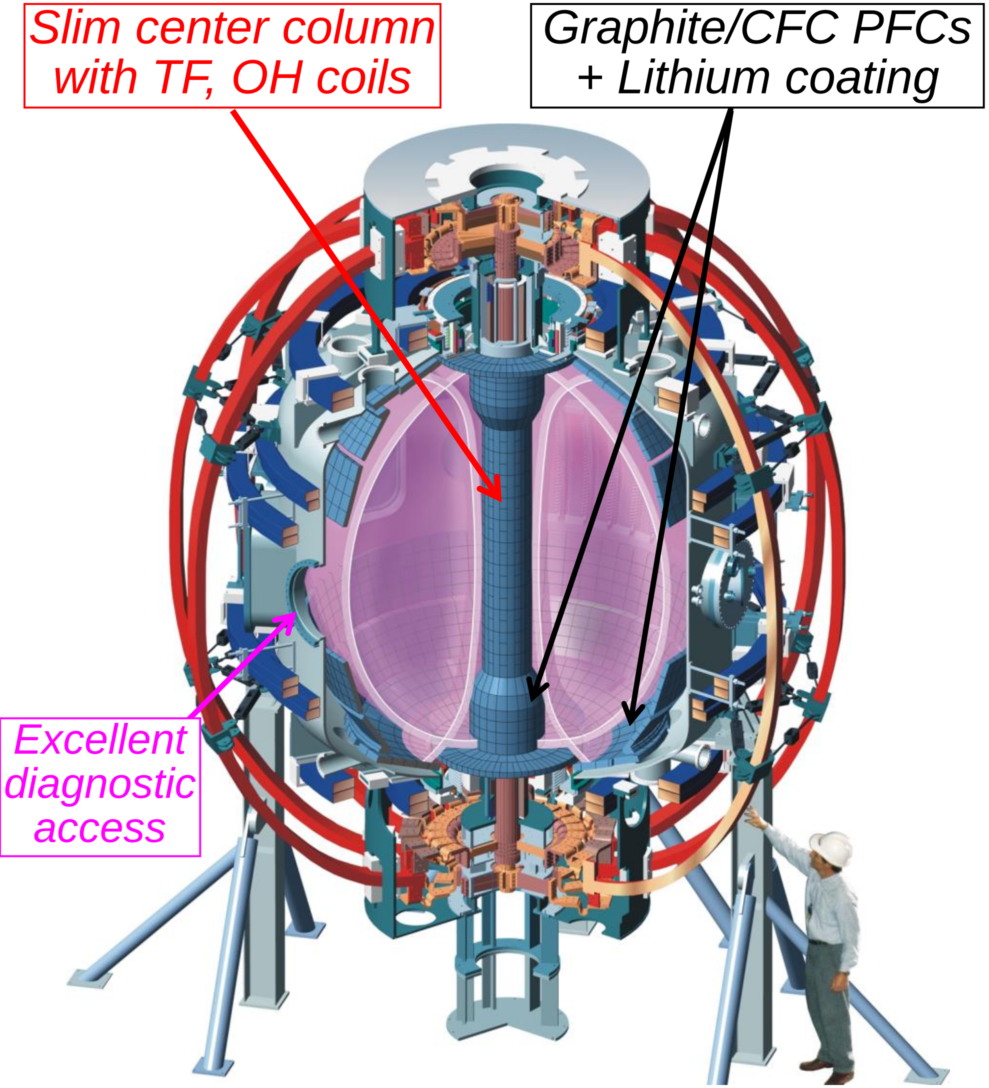
NSTX designed to study low-aspect ratio plasmas



Slim center column with TF, OH coils

Graphite/CFC PFCs + Lithium coating

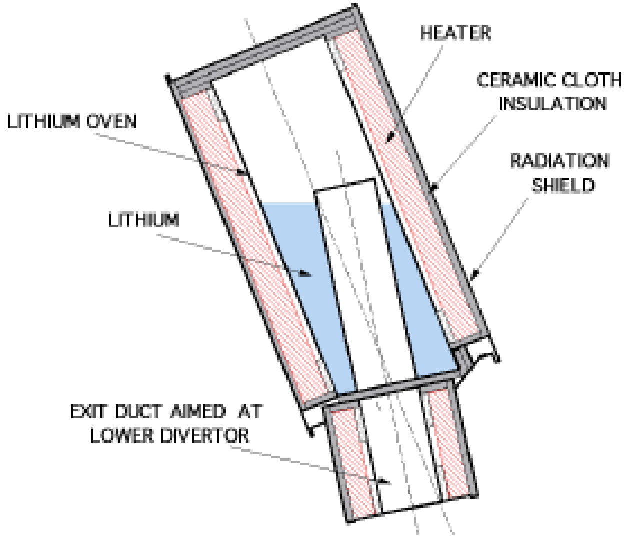
Excellent diagnostic access

Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	1.5MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2 \times 10^{20} m^{-3}$

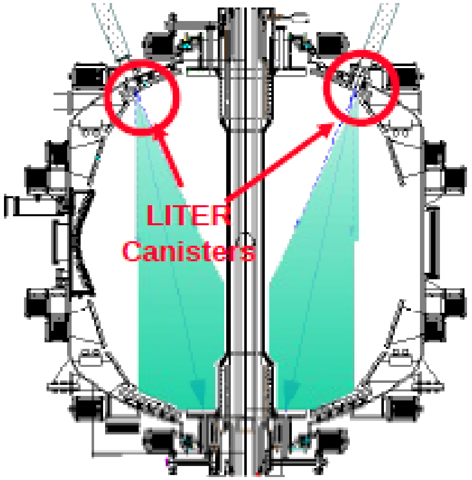
M. Bell

Confinement program not geared toward technology development

- US machines favored evaporation of Li
  - NSTX developed LITER system
  - Pair of evaporators to coat lower vessel PFCs
- CDX-U and LTX have used toroidal trays
- Contrast to T11-M, FTU and TJ-II which utilize capillary-porous systems as limiter



NSTX LITER evaporator

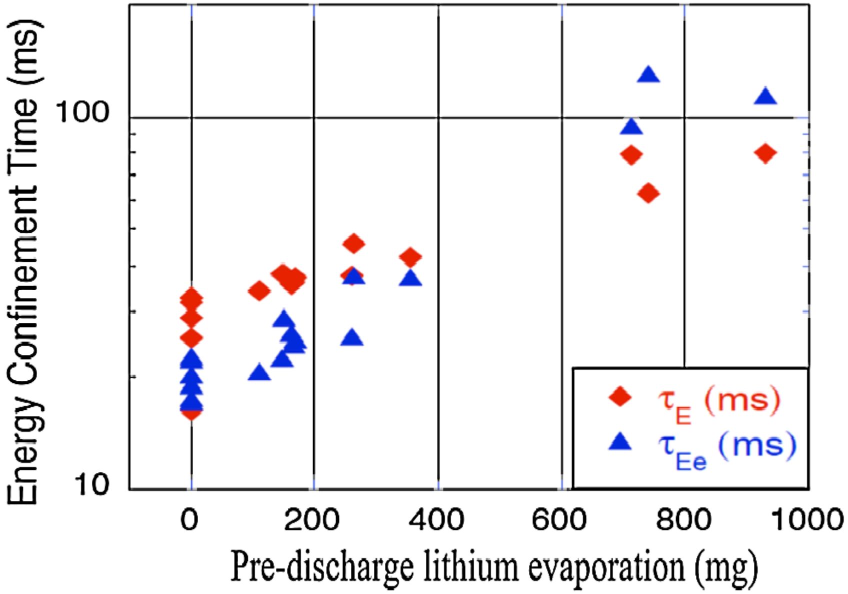


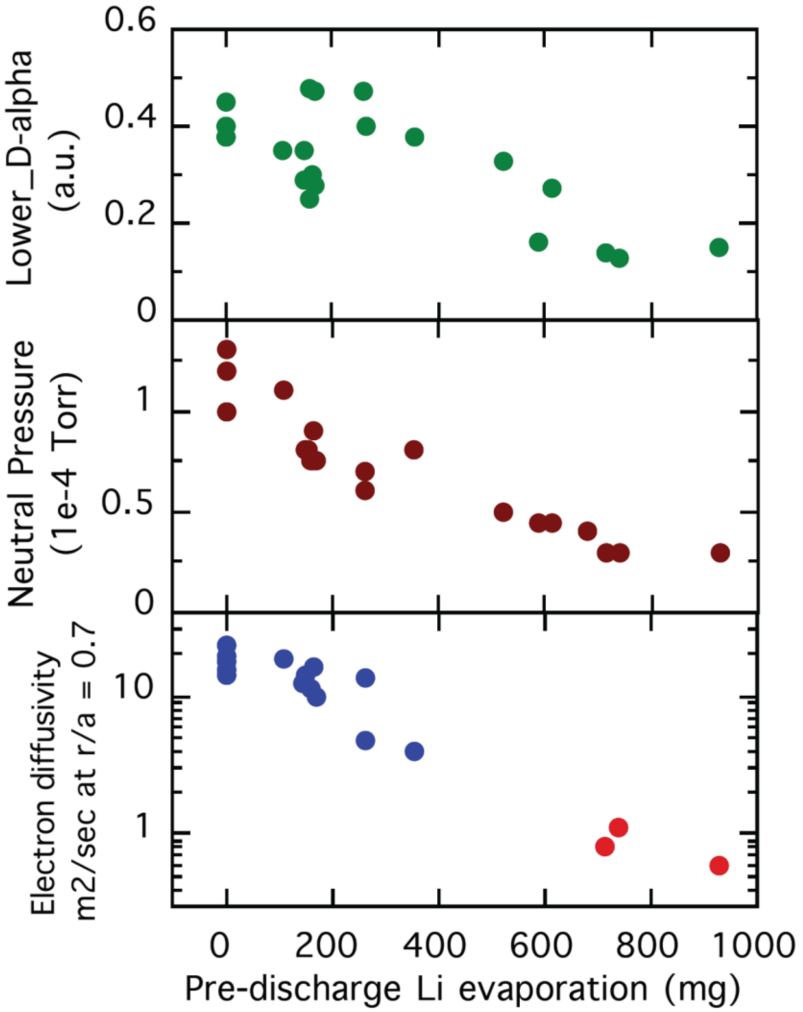
H. Kugel, M. Bell

NSTX sees continuous improvement in confinement with additional lithium

- Increase in confinement observed in electron channel

- Linked with reduced divertor D-alpha emission

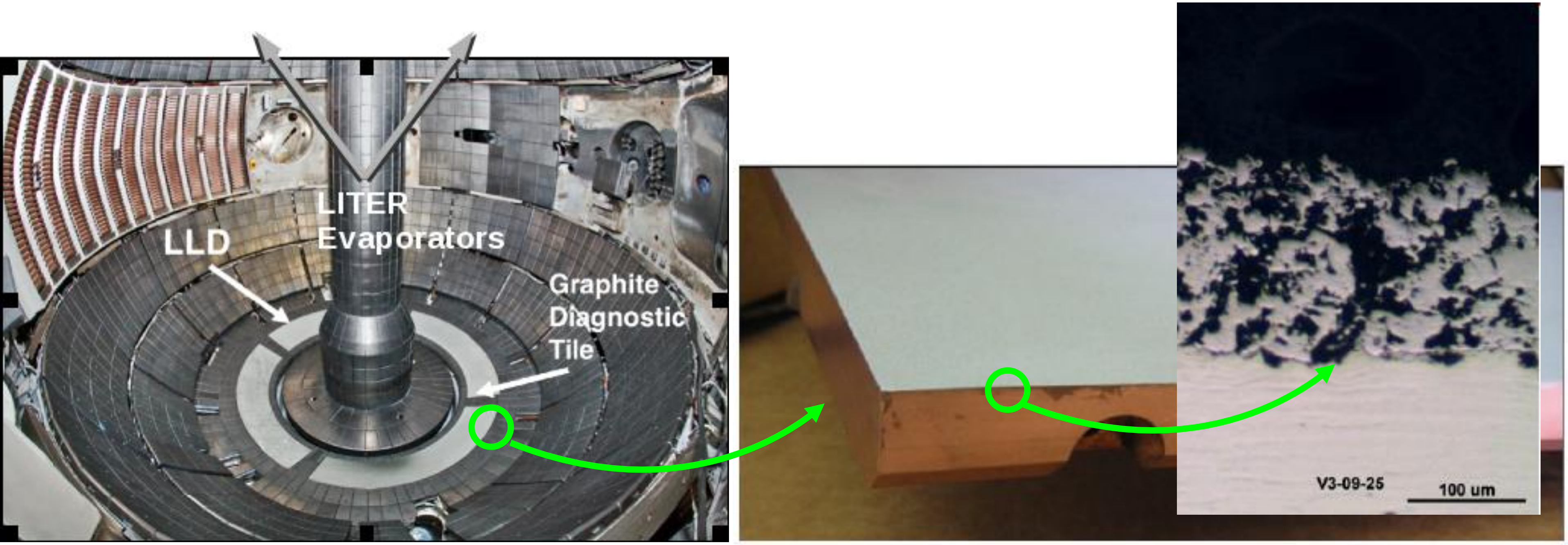




R. Maingi, et al., PRL 107, 145004 (2011)

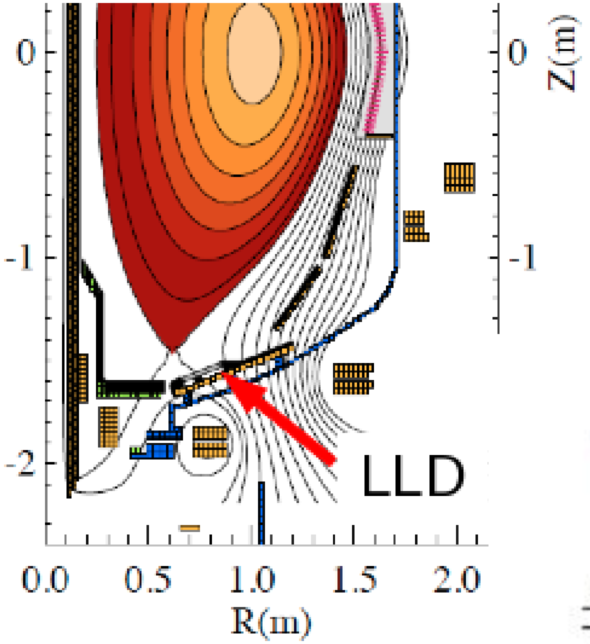
NSTX performed liquid-metal PFC experiments with the Liquid Lithium Divertor (LLD)

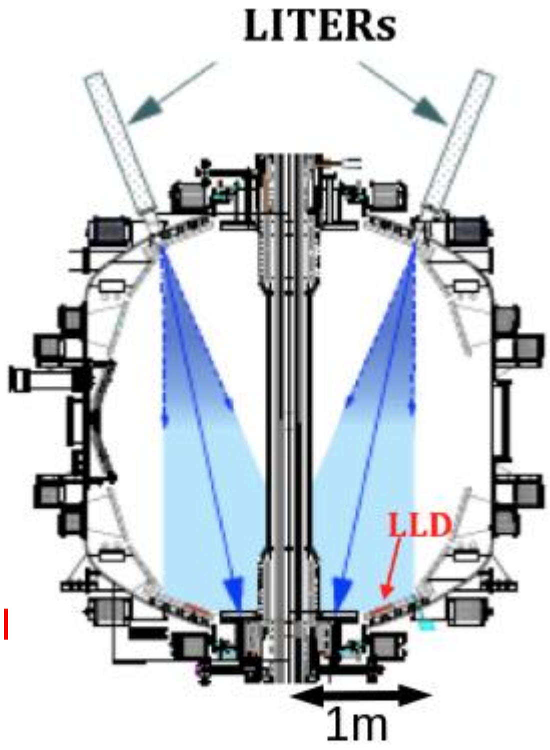
- Liquid lithium divertor installed for FY2010 run campaign to improve confinement & particle control
- 2.2cm copper substrate, 250um SS 316, ~150um flame-sprayed molybdenum porous layer; LITER loaded
- 37g estimated capacity, 60g loaded by end of run



Experimental overview for testing the LLD

- Experiments diverting onto the LLD conducted throughout run campaign
- Comparison made either diverted onto LLD or immediately inboard on graphite
- Li evaporator used as filling method
  - 7% filling efficiency
  - *Always coating entire lower divertor region!*

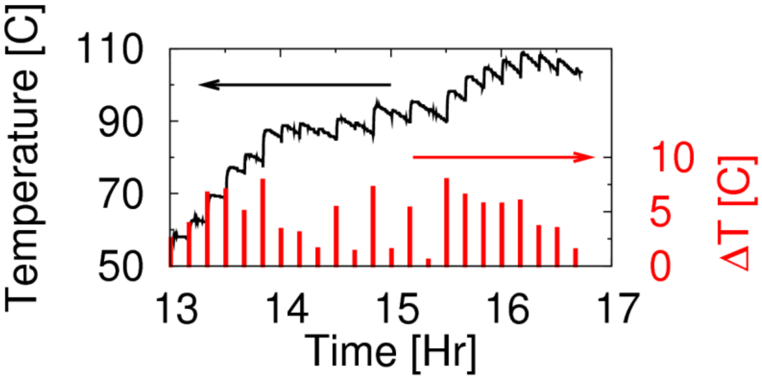


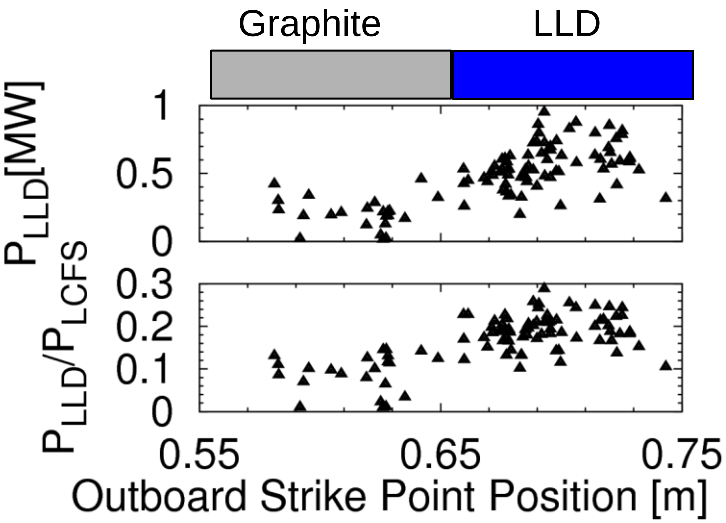


No boronization campaign prior to lithium introduction
Database already starts with 60g inventory in vessel

Significant power deposited on LLD measured via plate calorimetry

- Each LLD plate segment consists of 43kg of copper
  - $\Delta E = m\, c_p\, \Delta T$ per plate
  - $P_{LLD} \sim 4\Delta E/\tau_{pulse}$
  - $P_{LCFS} = P_{NBI} + P_{OHM} - P_{RAD} - dW/dt$
- LLD absorbing approximately 25% of exhaust power (~1MW in some cases)
- No molybdenum observed in plasma after Li melt temperatures reached (Soukhanovskii, RSI, 2010)

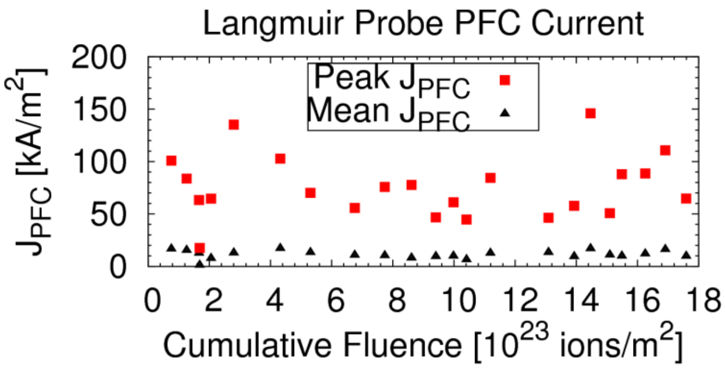


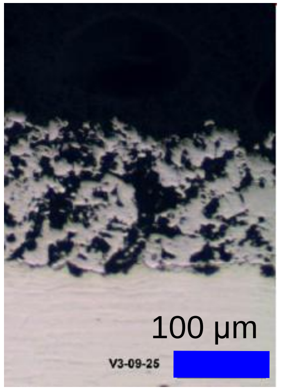


Jaworski, et al., NF 2013

No macroscopic ejection events observed from LLD during experiments

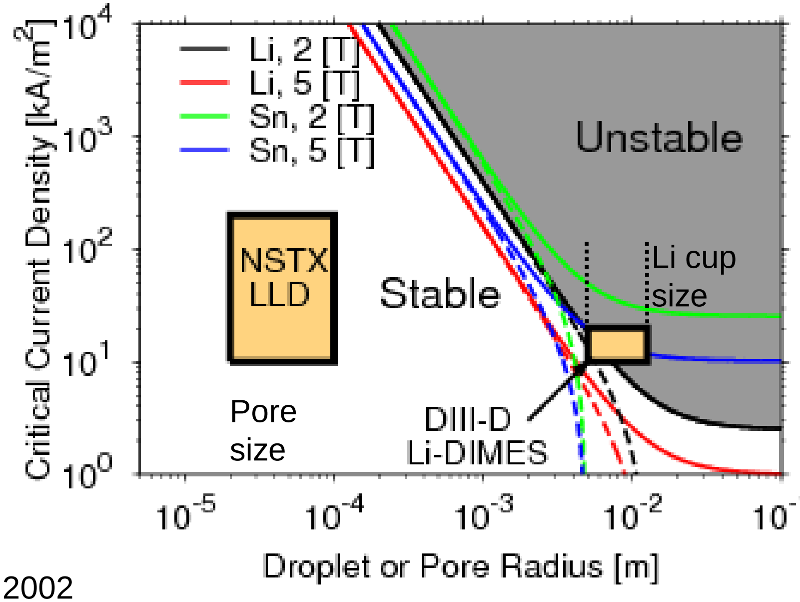
- Up to 10x more current measured with Langmuir probes; LLD porous geometry limits droplet size
- Rayleigh-Taylor analysis provides marginal stability curves; NSTX LLD stable
- CPS tests also reduced droplet ejection with smaller pore sizes*





$$j_{cr} = \frac{1}{B}\left(\frac{4\pi^2}{\lambda^2}\Sigma + \rho g\right)$$

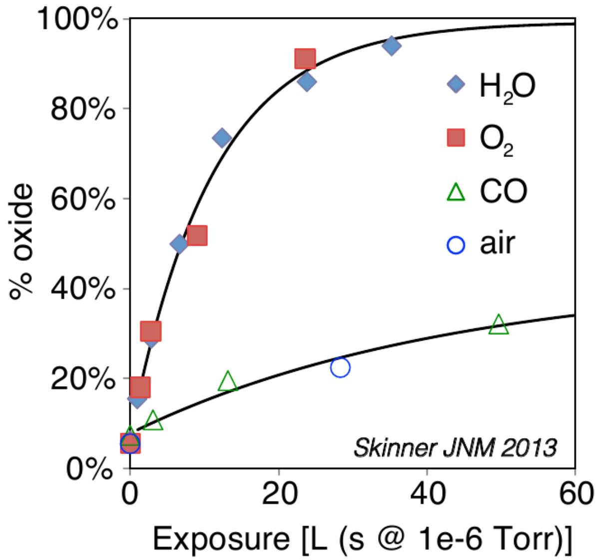
For the fastest growing modes

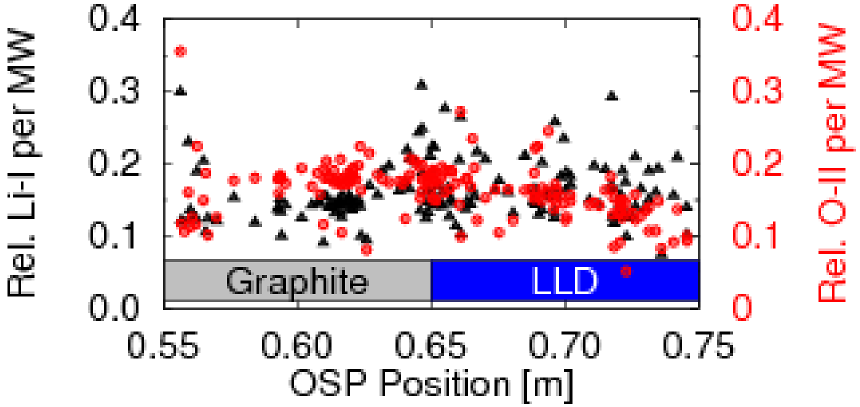


Jaworski JNM 2011, Jaworski NF 2013 , Whyte FED 2004, *Evtikhin JNM 2002

Oxygen identified as important constituent at plasma-material interface

- Oxygen uptake by lithium films quantified in laboratory experiments
  - Oxide layer formation in ~200s in NSTX (~600s inter-shot time)
  - Consistent with Liquid Lithium Divertor (LLD) results showing little change in impurity emission
- Influence of oxygen contaminants under investigation
  - Molecular dynamics simulations of Li-C-O show increased D uptake (Krstic, PRL 2013)
  - Non-zero **oxygen** sputter yield from contaminated surfaces


Oxygen uptake by Li coating on Mo

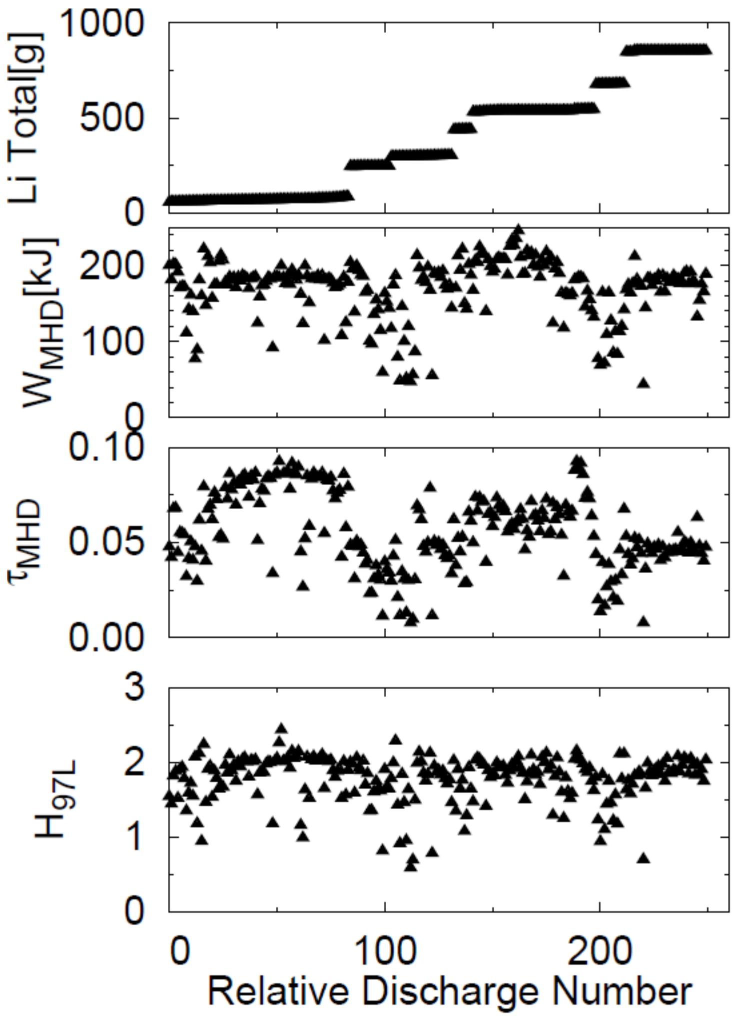

NSTX whole-divertor impurity emission

Skinner JNM 2013, Jaworski NF 2013

Performance independent of Li quantity in LLD – maintained standard (Li) confinement

- FY2010 LLD experimental set
  - Experiments span 60g to nearly 1kg of deposited lithium
  - Includes 75hr deposition at mid-year
  - Calculate ITER 97L H-factor *average* from 400-600ms for each discharge
- Discharges look nearly identical between start and end of run
  - Consistent with surface contamination hypothesis

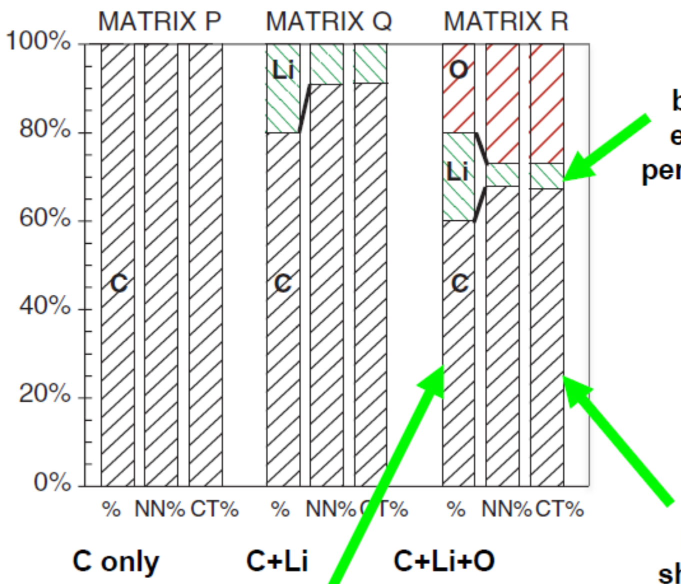
Fully-flowing PFC can provide a means of sweeping away gettered material and creating “stationary” surface conditions.



Jaworski NF 2013

Lithium compounds exhibit complex, substrate-dependent chemistry

- Quantum modeling by Krstic indicates preferential bonding of deuterium to **oxygen** in carbon matrix
- Laboratory studies by Capece show increased absorption by **oxidized Li**, but lower thermal decomposition temperature

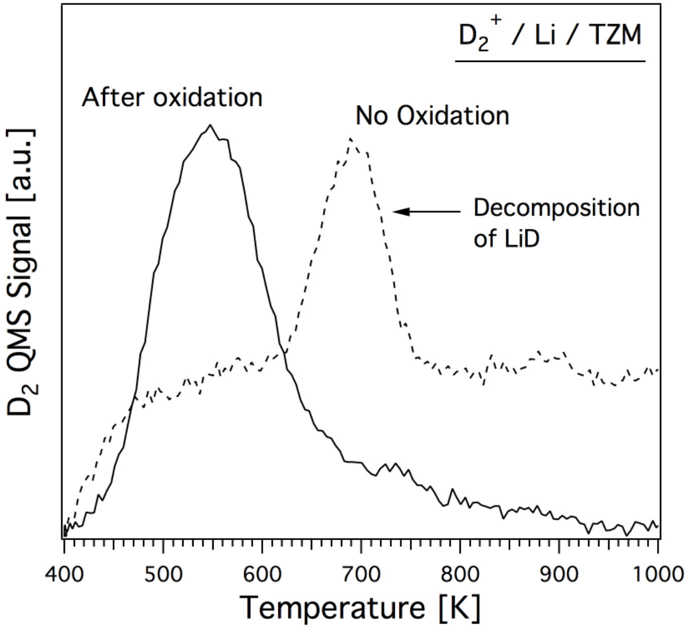


Amount of D bound by Li is even less than percentage of Li in PFC matrix

Atomic composition of matrix

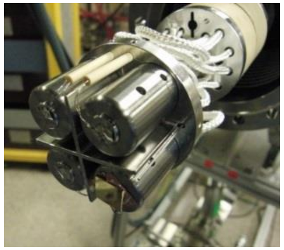
Fraction of D sharing charges with matrix constituents

Krstic, 2013 PRL

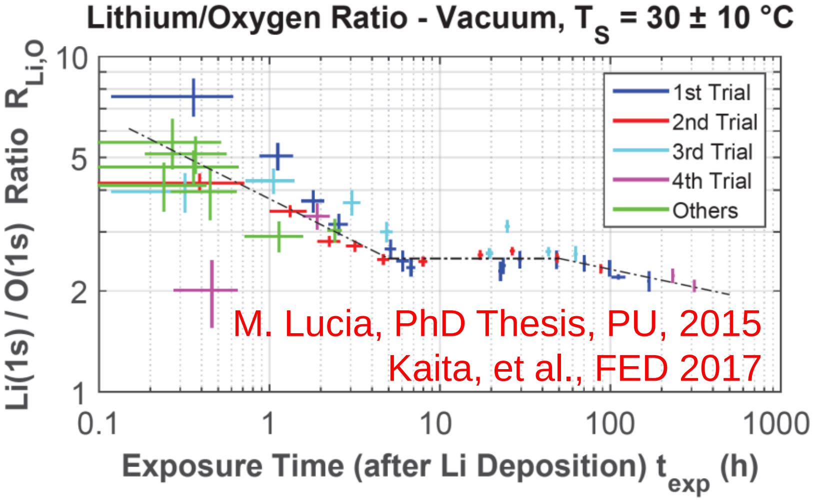


Capece, 2015 JNM

High-Z progression highlights mixed-material PMI and coordinated lab studies



- Material Analysis and Particle Probe enables compositional analysis
  - Measurements of C, Li, Mo, B, O via XPS
  - D retention via TPD

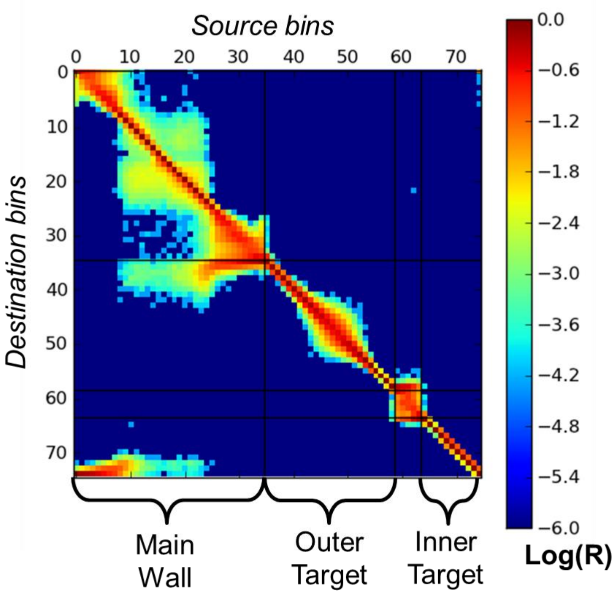


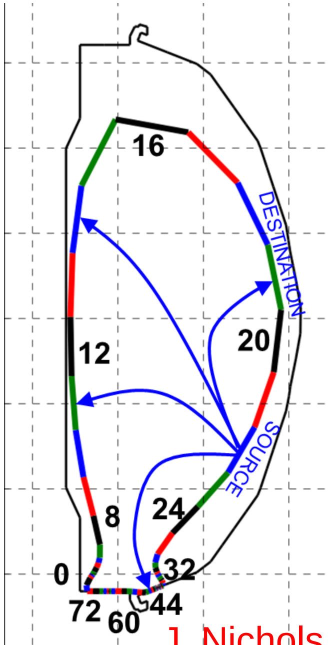
M. Lucia, PhD Thesis, PU, 2015

Kaita, et al., FED 2017

- Material migration modeling with WallDYN
  - PPPL PhD thesis, collaboration with IPP-MPG & PPPL
  - QCM and witness plate measurements in vacuum vess.
  - Mixed-material erosion model development with **surf. sci. lab**

Charge-integrated Li redistribution matrix





J. Nichols

DEMO PFC concept studies return to an old idea

- Maybe liquid PFCs, but why *lithium*?
  - Key observations on PPPL experiments
  - TFTR, CDX-U, LTX

- Experience gained on NSTX
  - Evaporative coatings
  - The Liquid Lithium Divertor experiments

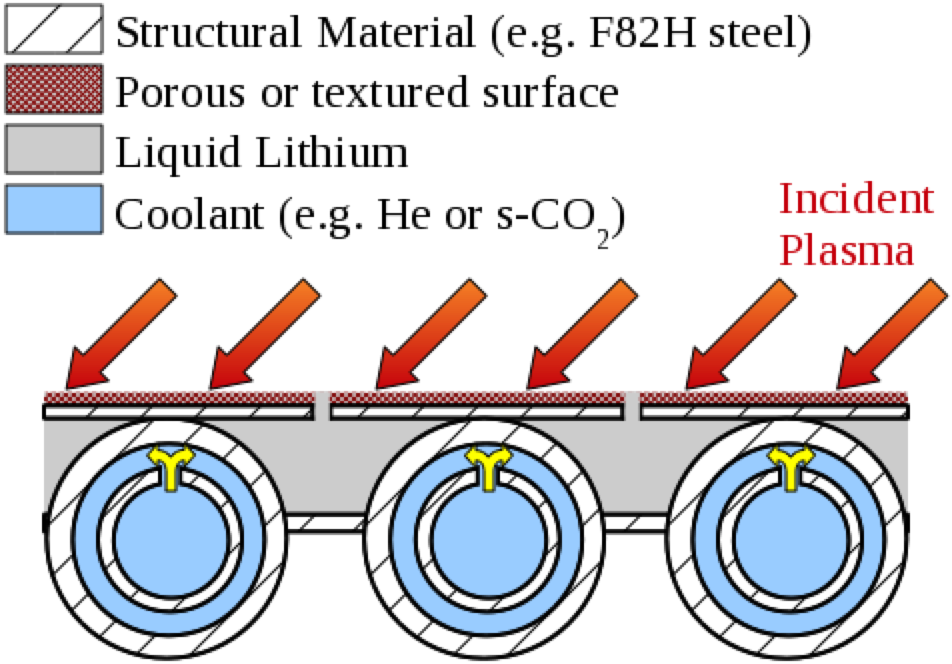
- Necessity of high-temperature lithium studies

- Proposed technical and scientific program for NSTX-U

- Open questions and possibilities for liquid metals

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

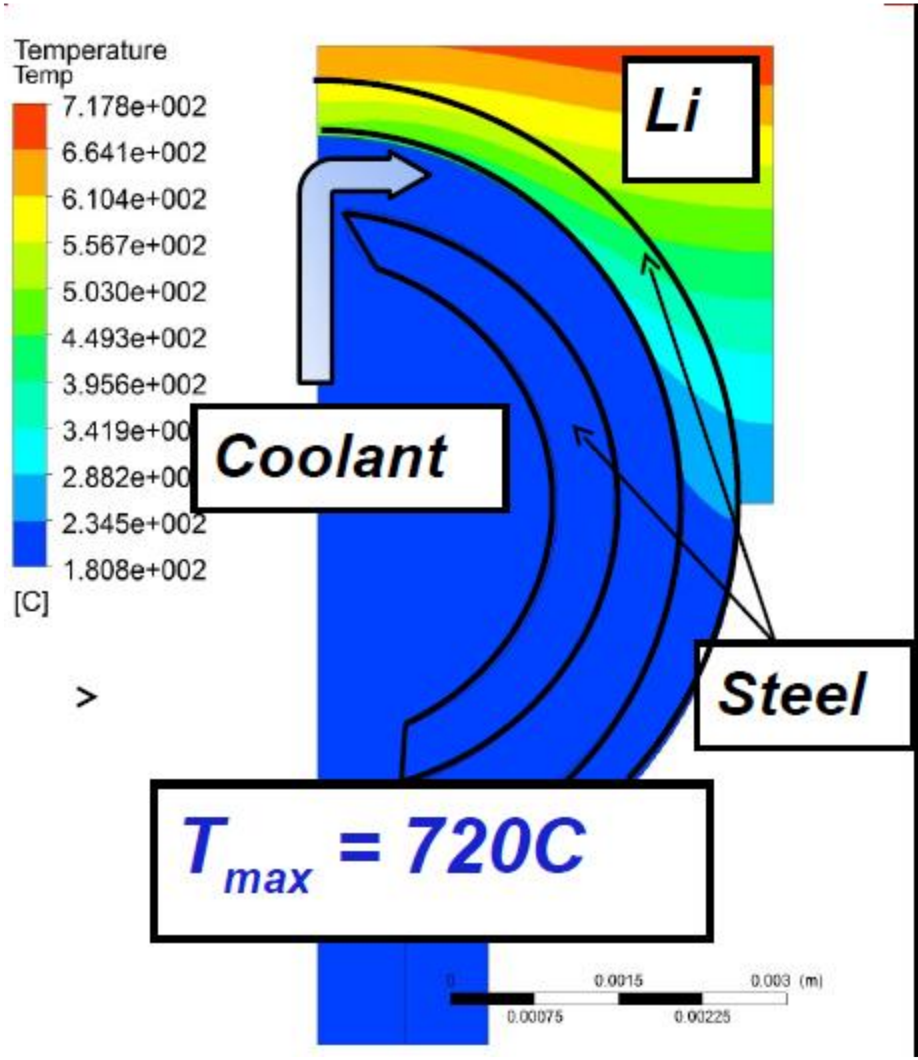
- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Multiple coolant options exist (T-tube impinging jets shown as example)



Jaworski PPCF 2013;
c.f. Coenen Phys. Scr. 2014

Advanced cooling techniques can be optimized for LM-PFCs for steady-state cooling

- T-tube[1] uses impinging gas jets to increase local heat transfer coefficient
- Altered T-tube for these simulations to have:
  - Smaller radius
  - Steel structure, s-CO2 coolant **(No tungsten)**
  - 10 MW/m^2 incident
  - Consistent with strength limits of ODS-RAFM steel
- Previous studies considered <400C as limit for hydrogen retention



[1] Abdel-Khalik FST 2008.

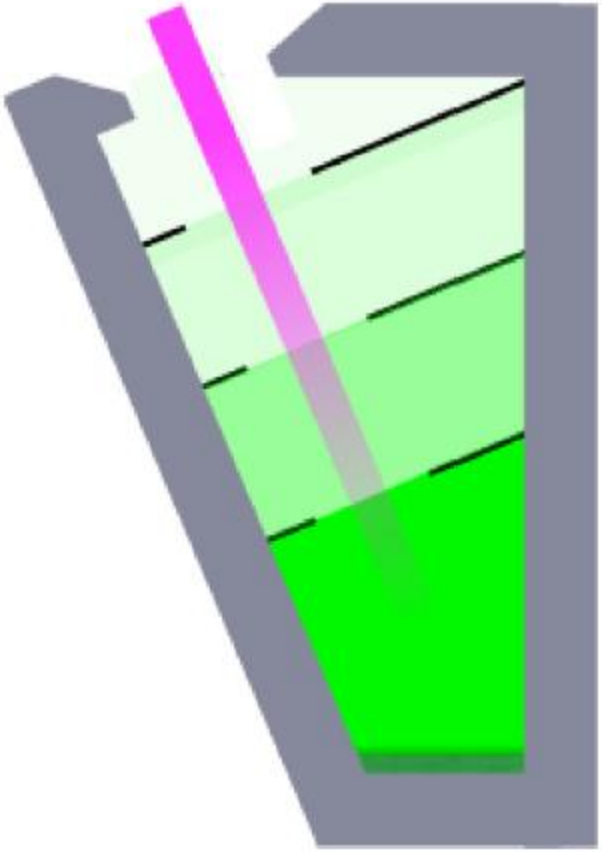
Jaworski PPCF 2013; Khodak IEEE TPS 2014

Li Vapor-box divertor is a heat-flux mitigation scheme using condensable vapor

- Li VBD creates a dense Li vapor cloud as divertor target

- VBD spreads heat-flux over broader area through:
  - Radiative dissipation
  - Collisional processes

- VBD traps Li in divertor
  - Temperature-controlled surfaces control condensation
  - Avoids flooding main chamber

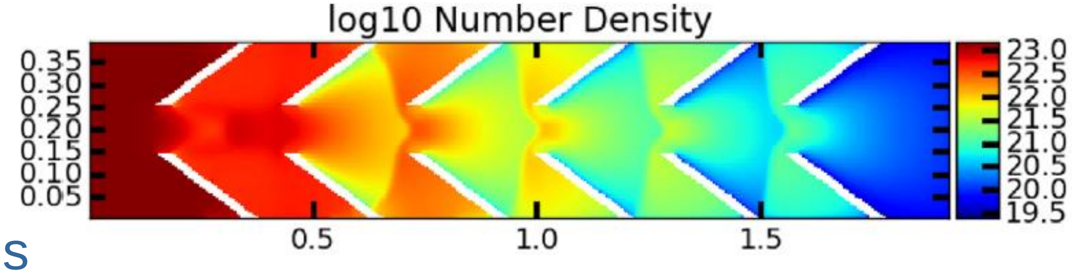


Poloidal cross-section of Li-VBD

Goldston, Nucl. Mater. Energy 2017

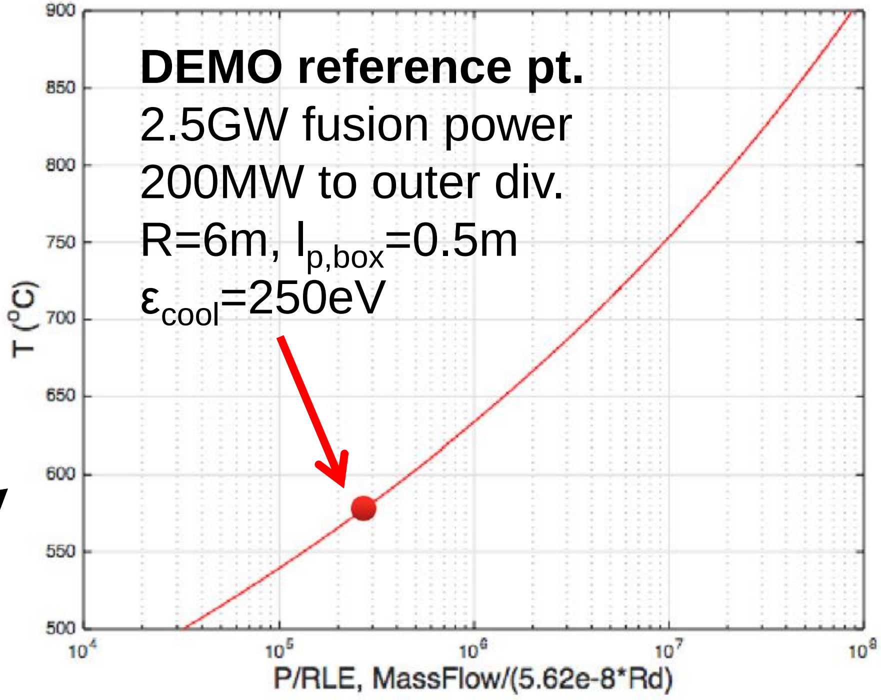
0th-order estimates show modest component temperatures for power dissipation

- Mass-flow reduction via series of condensing chambers
  - Latent heat transferred to walls
  - Radiation transferred to walls



- Cooling rate per atom calculated form atomic physics databases
  - ADAS Coll. Rad. model
  - Ionization and radiation

- Power balance yields estimated, maximum density/flux of Li



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

Both figures: Goldston, Nucl. Mater. Energy 2017

Li VBD is conventional divertor turned to “11”

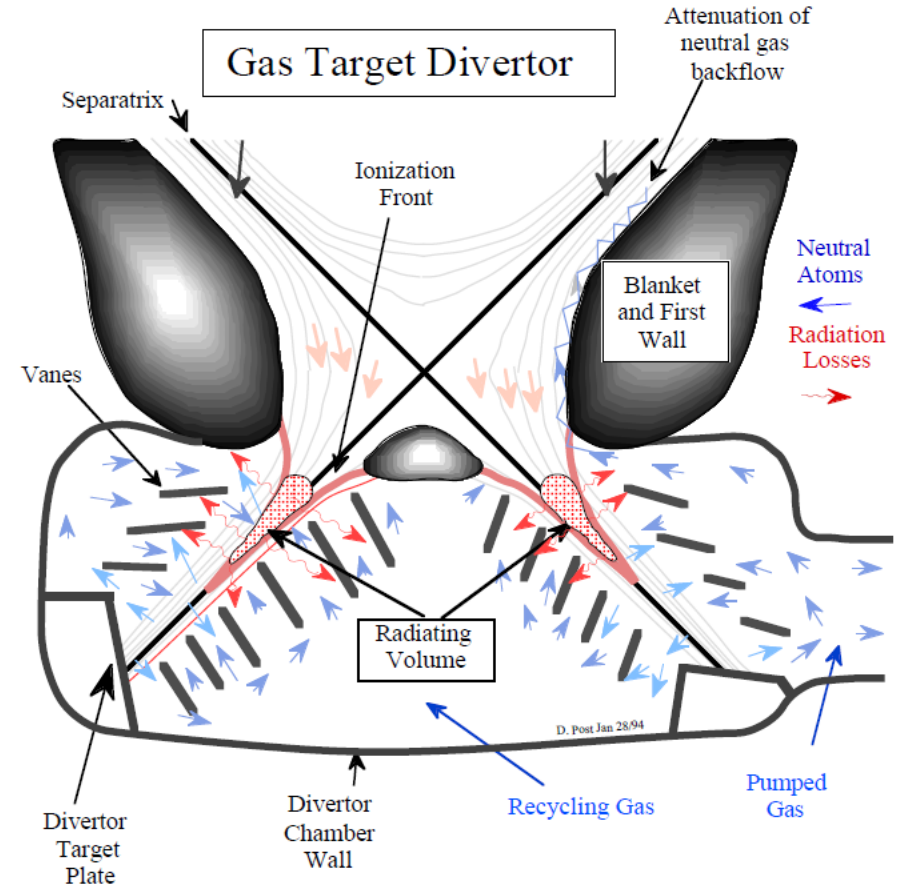


Figure 2. Schmatic Illustration of Dynamic Gas Target Divertor.

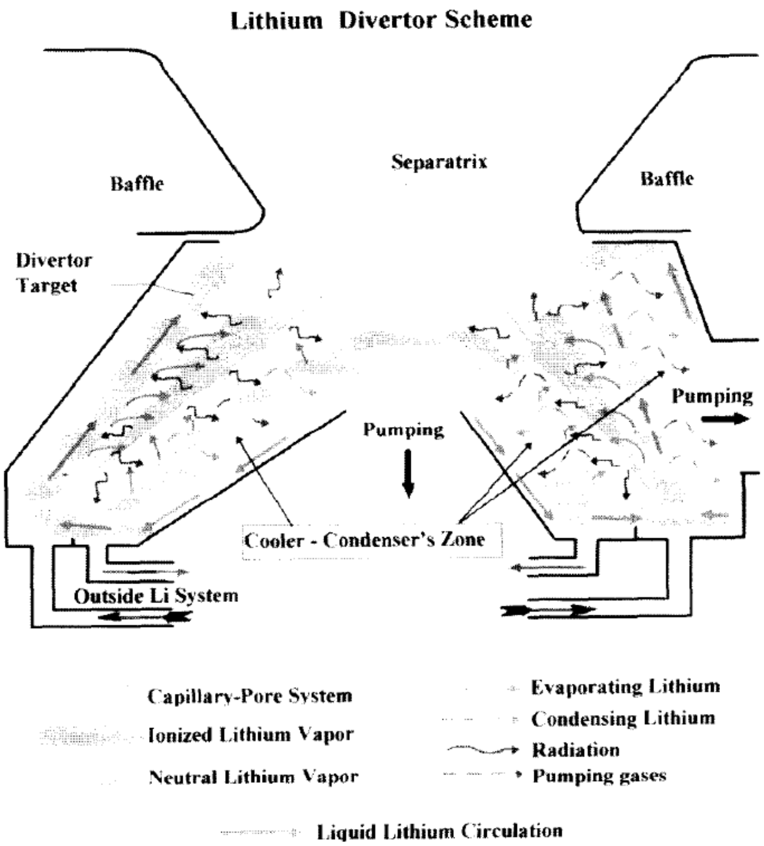


Fig. 2. The scheme of LMD energy transformation and lithium circulation.

Post 1995 Phys. Plasmas

Golubchikov 1996 J. Nucl. Mater.

The current NSTX-U 5-year plan for developing liquid metals (est. 2014)

- Maybe liquid PFCs, but why *lithium*?
  - Key observations on PPPL experiments
  - TFTR, CDX-U, LTX

- Experience gained on NSTX
  - Evaporative coatings
  - The Liquid Lithium Divertor experiments

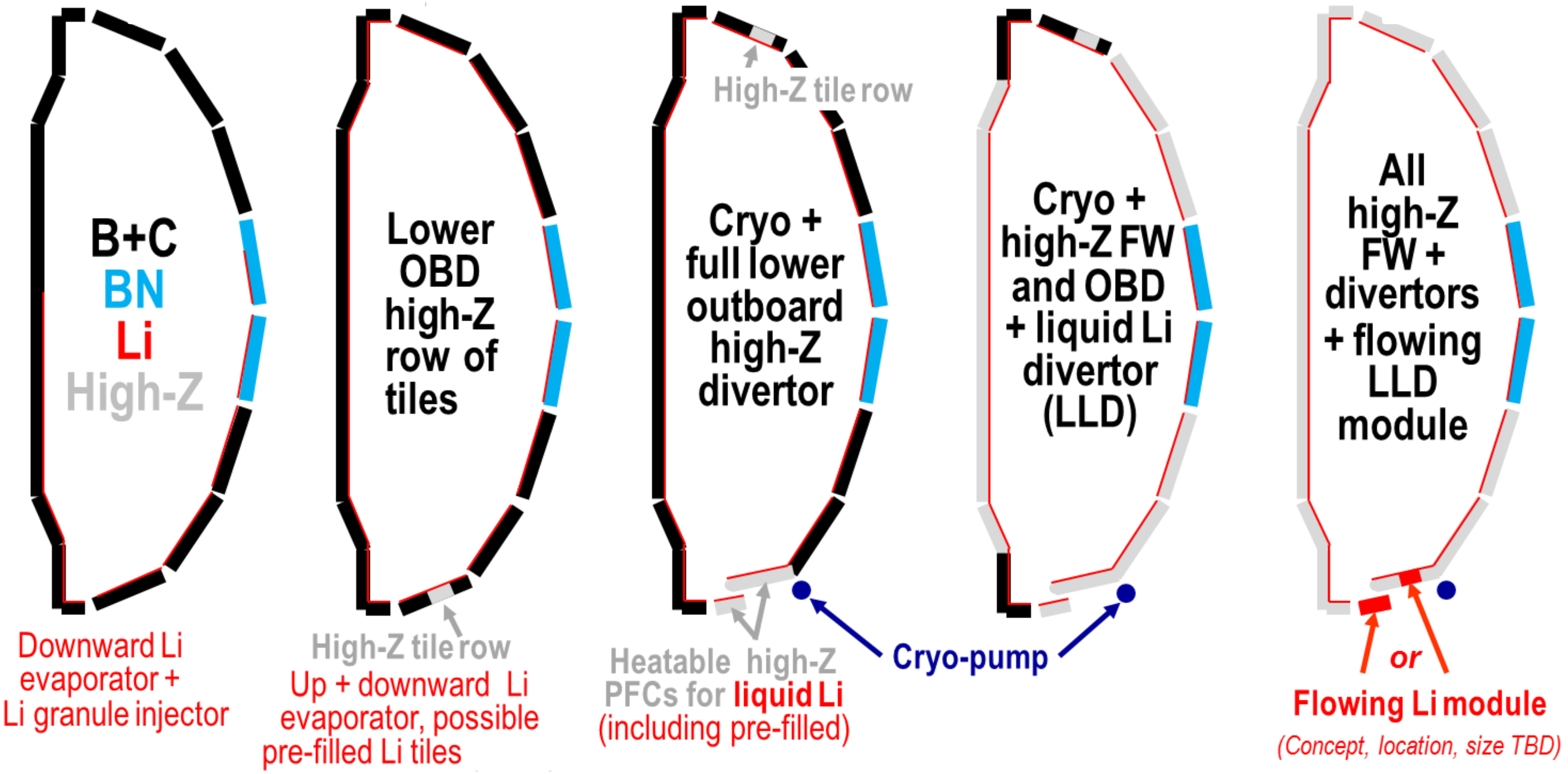
- Necessity of high-temperature lithium studies

- Proposed technical and scientific program for NSTX-U

- Open questions and possibilities for liquid metals

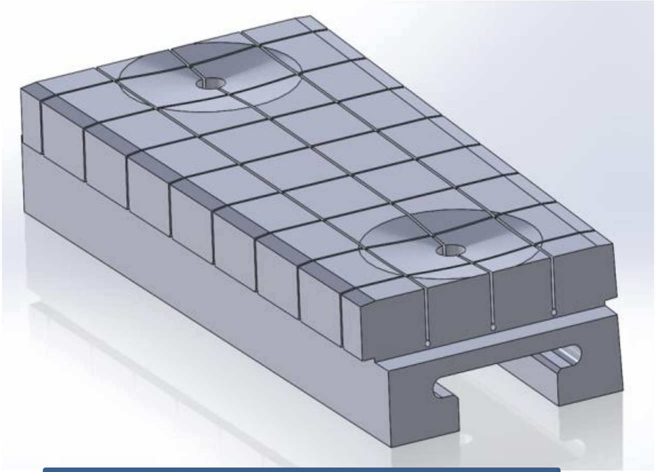
Staged conversion mitigates risk and enables comparative assessment of both high-Z and liquid Li

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

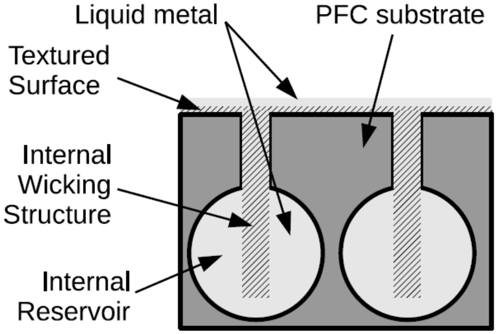


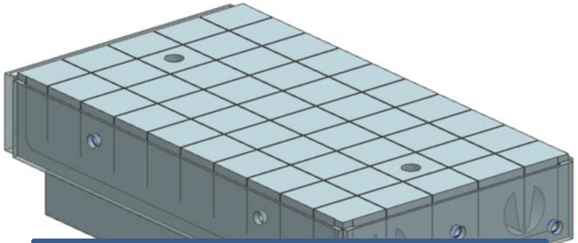
Development path for NSTX-U suggested by most mature liquid-metal PFC technology

- 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

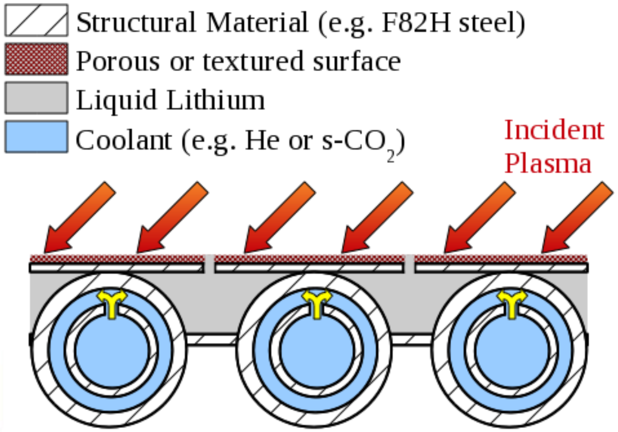


High-Z PFC design





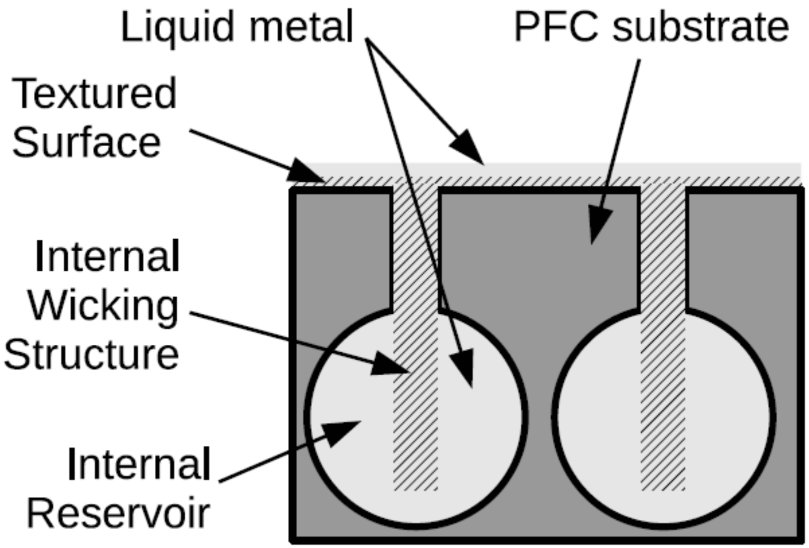
Pre-filled target concept

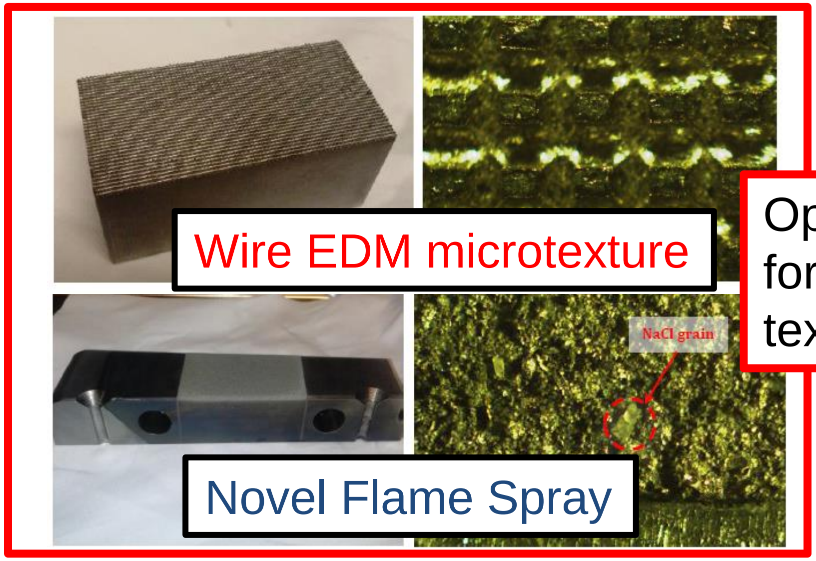


DEMO-relevant PFC concept

Pre-filled target concept aims to improve "reactor relevancy" of experiments

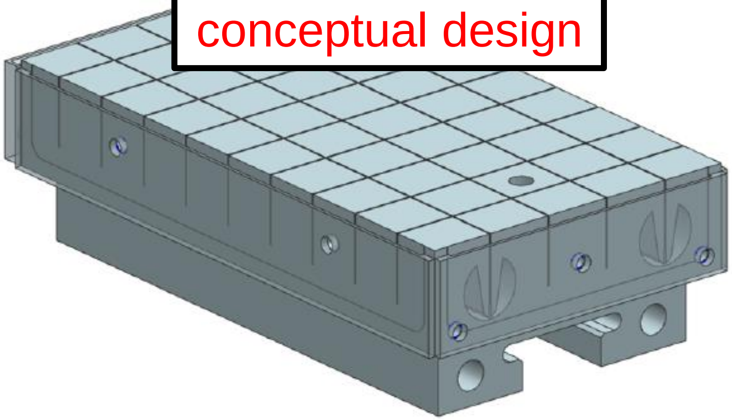
- Liquid reservoir mimics actively-fed PFCs
- Achieves in-vessel lithium surfaces without evaporation
- **Pre-filling** avoids *in-vacuo* manipulation and alleviates wetting concerns after install





Options for surface texturing

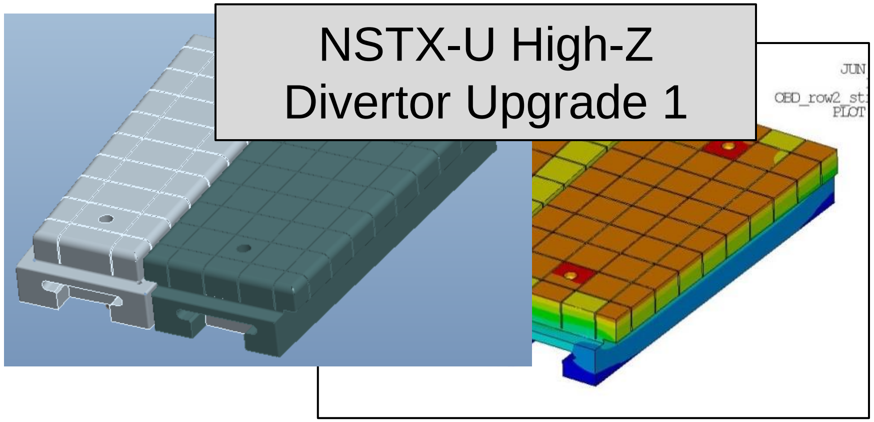
Pre-filled target conceptual design



Jaworski FED 2016; Rindt FED 2016

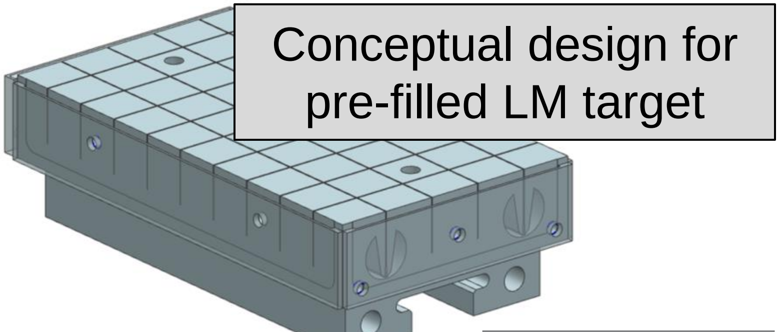
A three-step progression leads to flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER



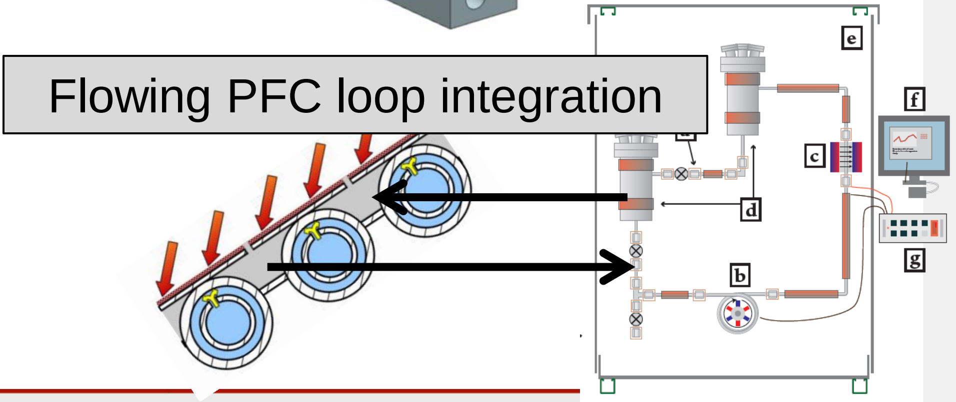
NSTX-U High-Z Divertor Upgrade 1

2. Pre-filled liquid-metal target



Conceptual design for pre-filled LM target

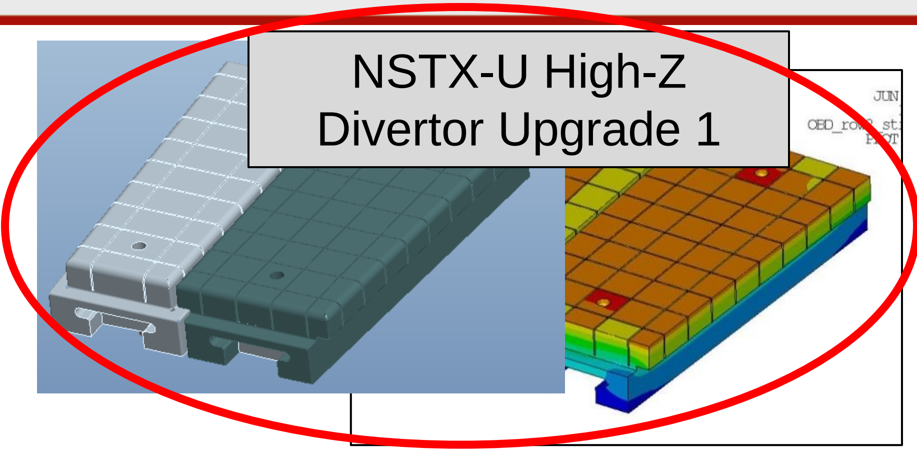
3. Flowing LM PFC



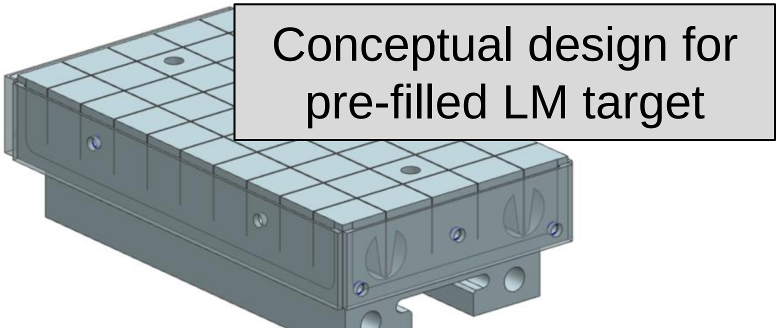
Flowing PFC loop integration

High-Z divertor tiles + Li evaporated coatings examine C-free PMI processes at high temperature

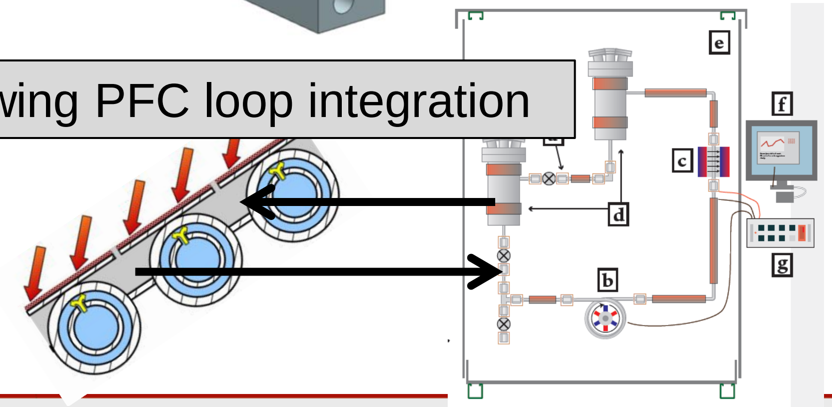
1. High-Z divertor tiles + LITER
   - Technical goals:
     - Establish non-intercalating substrate for evaporated Li
     - Provide high-heat flux substrate for Li experiments
   - Scientific goals:
     - Quantify maintenance of Li on high-temperature substrate and protection of substrate
     - Re-examine suppression of erosion in high-flux divertor
     - Understand impact and core-edge compatibility of <u>high-temp. target</u> with limited inventory of Li



NSTX-U High-Z Divertor Upgrade 1



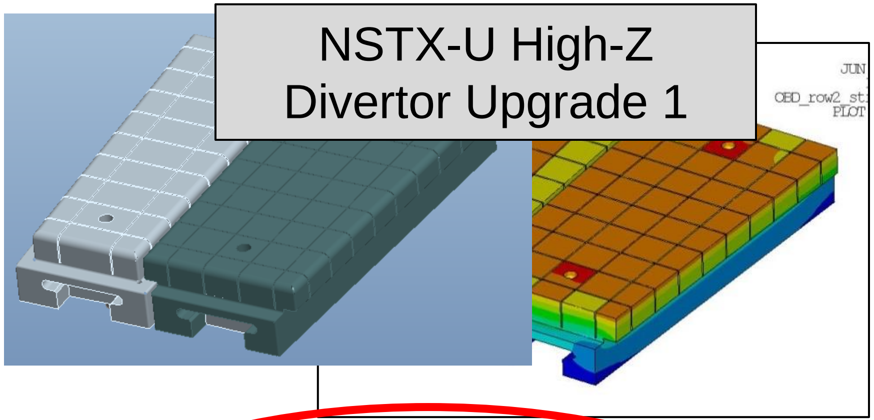
Conceptual design for pre-filled LM target

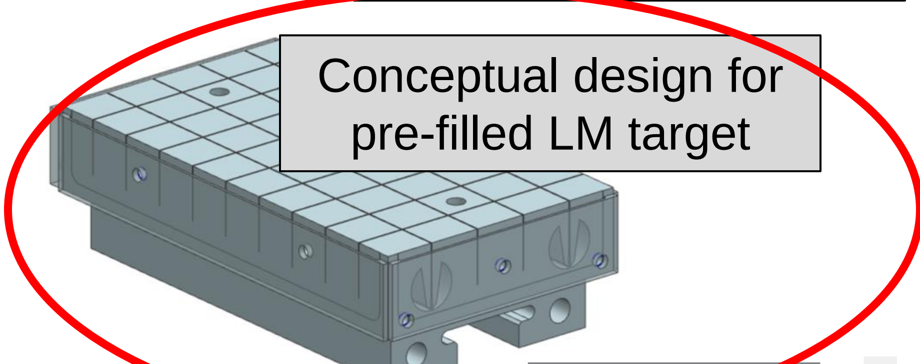


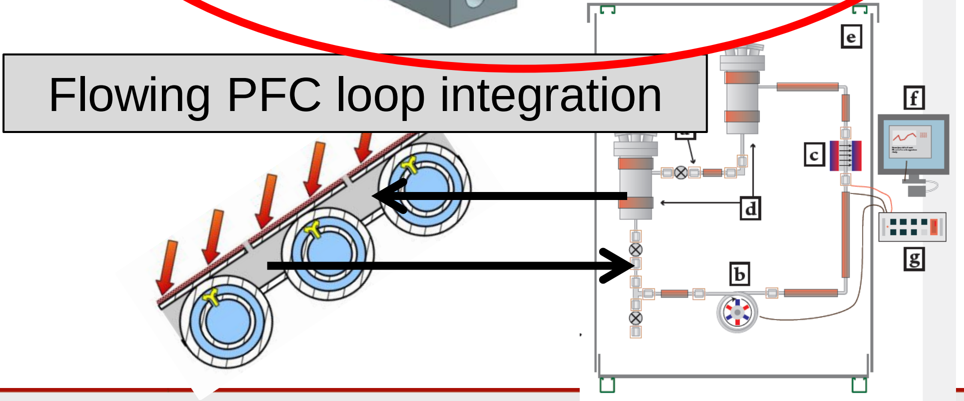
Flowing PFC loop integration

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

2. Pre-filled liquid-metal target
   - 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 <u>high-temp. target</u> with **larger** inventory of Li


NSTX-U High-Z Divertor Upgrade 1

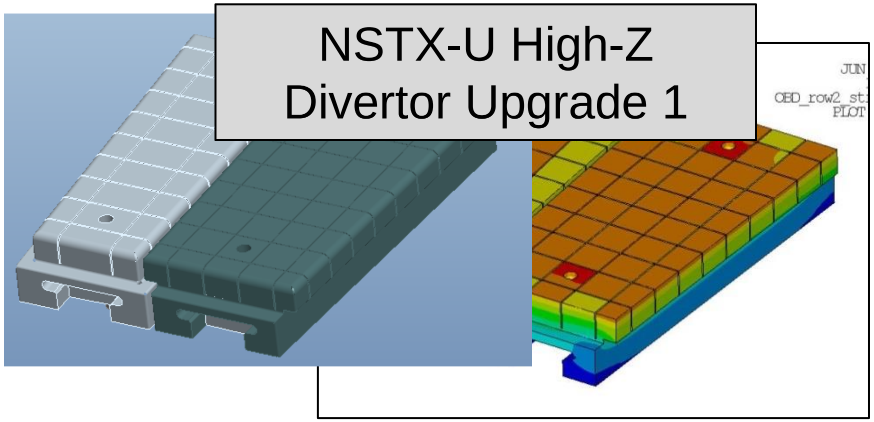

Conceptual design for pre-filled LM target

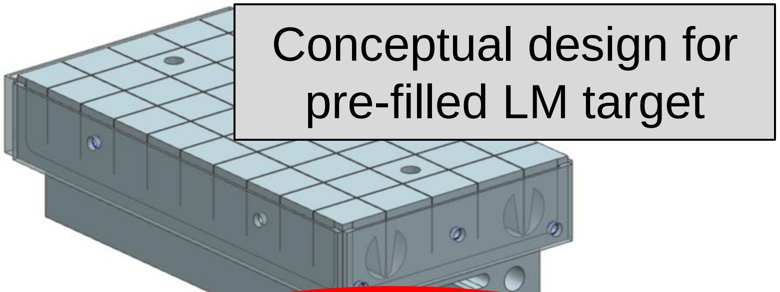

Flowing PFC loop integration

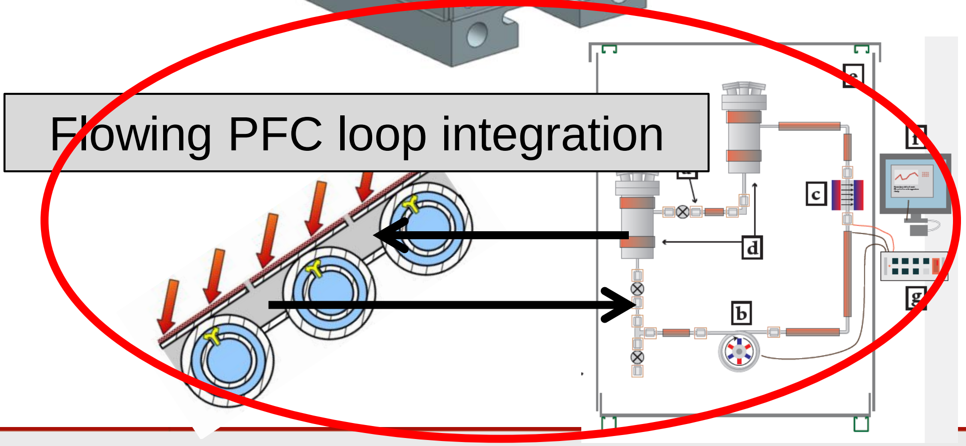
Final integration demonstrates LM introduction/extraction and inventory control

3. Flowing LM PFC

- 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>


NSTX-U High-Z Divertor Upgrade 1


Conceptual design for pre-filled LM target


Flowing PFC loop integration

The current NSTX-U 5-year plan for developing liquid metals

- Maybe liquid PFCs, but why *lithium*?
  - Key observations on PPPL experiments
  - TFTR, CDX-U, LTX

- Experience gained on NSTX
  - Evaporative coatings
  - The Liquid Lithium Divertor experiments

- Necessity of high-temperature lithium studies

- Proposed technical and scientific program for NSTX-U

- Open questions and possibilities for liquid metals

Demonstration of integrated scenario (core+edge+PFCs)

- **Ultimate configuration still debated!** (e.g. hot-walls + vapor-box divertor + added impurity seeding?)

- Larger areal coverage at representative temperatures

- Representative surface compositions

- Material redistribution and mixing means first-wall still needs attention for whole-machine assessment

- **Broader concept exploration can identify critical issues with each configuration**

Demonstration and analysis of fuel-cycle impact

- Liquid metals, even at small retention rates, could impact needed tritium breeding ratio in a reactor
  - E.g. Nishikawa’s Tritium balance-of-plant analysis showed significant impact on needed TBR due to codeposition even with solid PFCs (2011 FST)

- Laboratory experiments demonstrate release at large concentrations (>1%) even at low temperatures (<600C for Li-D, <400C for oxidized Li)

- Recovery demonstrated from Li at ~1ppm level relevant to fast-flow systems (see IFMIF activity; Edao 2010 FED)
  - Fast-flow concepts still developing self-consistent recovery schemes

- Similar efforts will be required for Sn and Ga concepts to ensure no surprises!

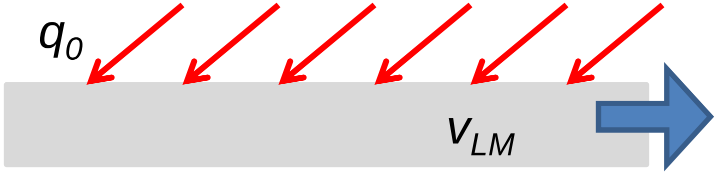
Power-handling capability is the greatest advantage of fast-flow concepts

- “Moving slab” approximation for temperature rise
  - – LM properties, conductivity *k* and thermal diffusivity *α*
  - – Characteristic path length L_{char}
  - – Limiting temperature rise ΔT_{Lim}

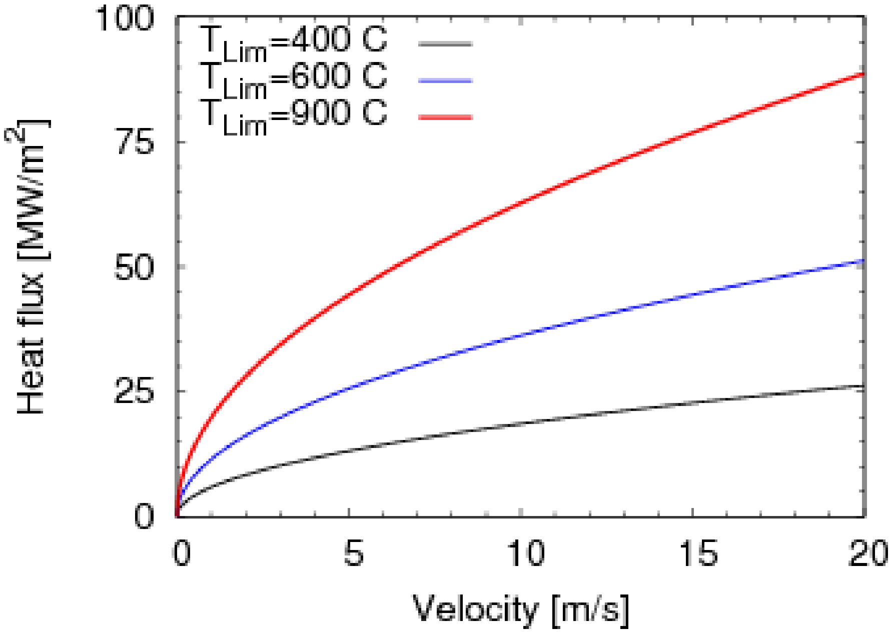
- Trades complexities (cooling vs. MHD control)

- Ongoing research via PU+PPPL collaboration (Kolemen, Majeski)

Incident heat flux vs. velocity



$$q_0 = \frac{\Delta T_{Lim} k}{2} \sqrt{\frac{\pi v_{LM}}{\alpha L_{char}}}$$



Summary

- Confinement program has long-supported liquid metal development at PPPL
  - History of confinement gains has created unique tool for experiments (conditioning)
  - Focus on deploying tools for next experimental campaign

- Logical conclusion of near-term technologies leads to new questions for integrated performance
  - High-temperature, continuously vapor-shielded targets
  - Overall performance in extreme states

- Experiments have generally **not** gone as planned
  - Li conditioning was diagnostic “accident”
  - LLD effects obscured by “the unreasonable effectiveness of lithium on graphite” – R. Kaita
  - Surface science and material transport effects increase in importance

- Scientific and technical goals proceed hand-in-hand
  - Component temperature tightly linked to engineering design
  - All liquid metals studied to date exhibit significant temperature-dependent PMI processes (e.g. temperature-enhanced sputtering)