Incremental upgrades toward high-heat flux, liquid lithium PFCs in the NSTX-U*

MA Jaworski[1], P Rindt[2], K Tresemer[1], A Brooks[1], S Gerhardt[1], TK Gray[3], R Kaita[1], N Lopes-Cardozo[2], J Menard[1], M Ono[1], CH Skinner[1]

[1]Princeton Plasma Physics Laboratory
[2]TU/Eindhoven
[3]Oak Ridge National Laboratory

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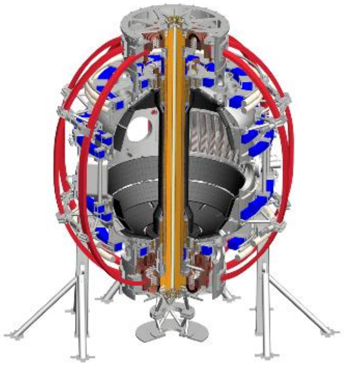
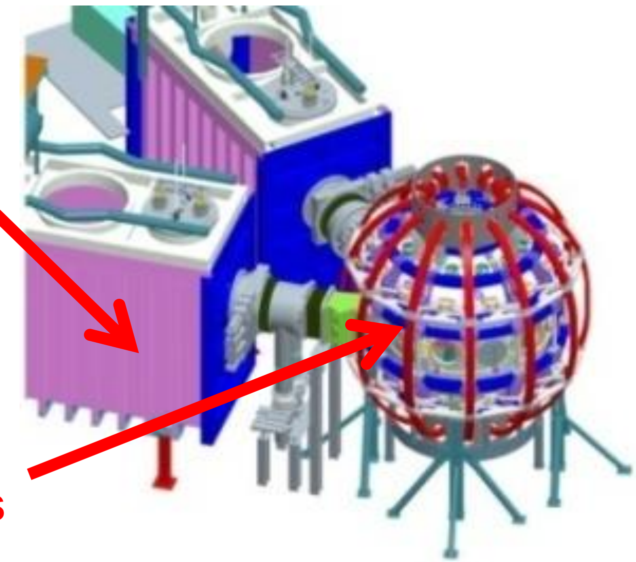


Outline

- What is a possible upgrade path to flowing liquid-metal PFCs in NSTX-U?
- How does the NSTX-U High-Z Divertor Upgrade 1 project inform liquid metal PFC development?
- What is the current concept for pre-filled, liquid metal PFCs for NSTX-U?

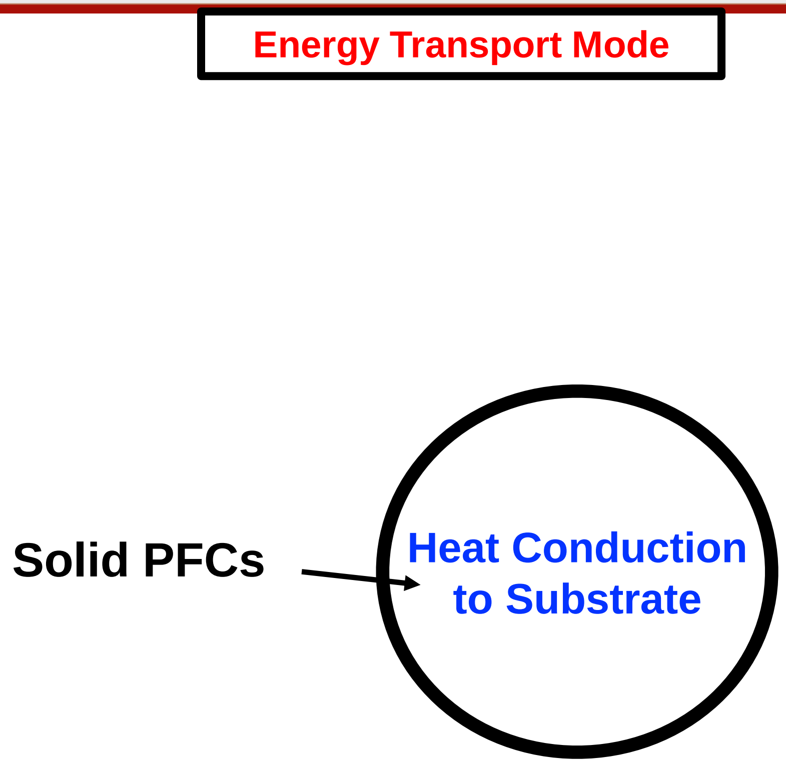
NSTX-U plasma-facing components (PFCs) will be subjected to significant heat and particle fluxes

- 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



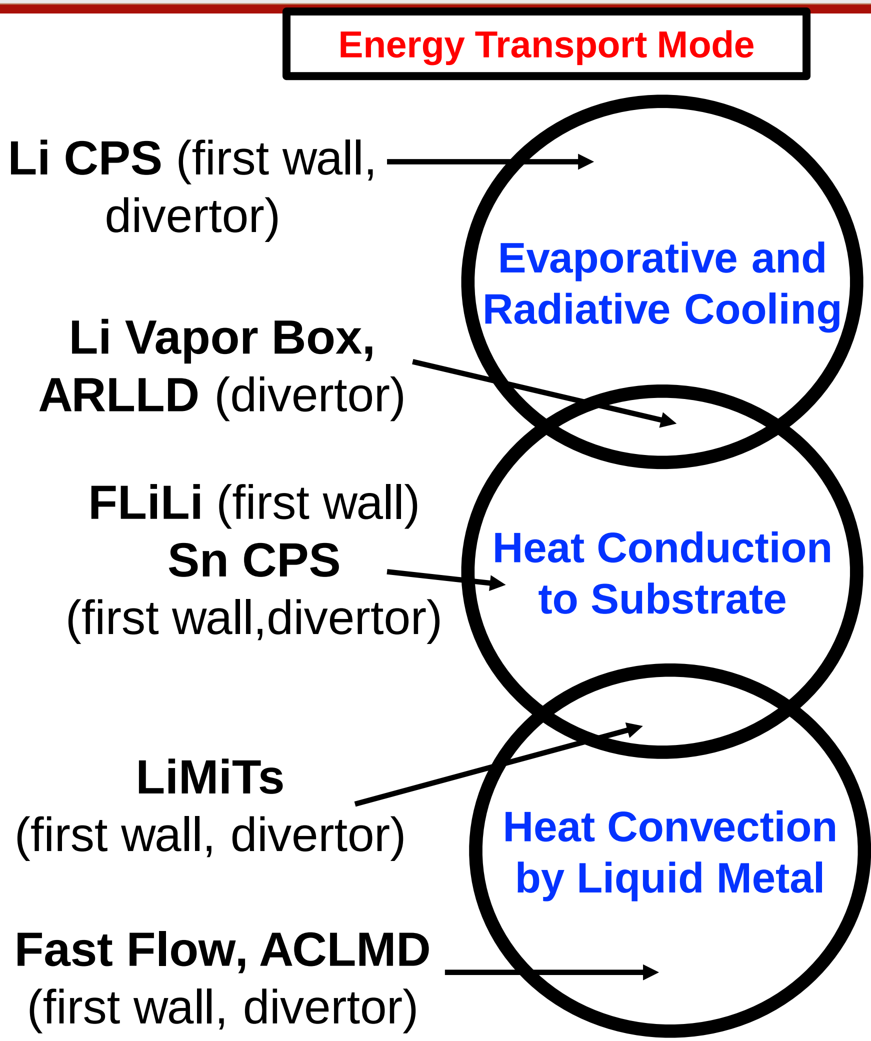
Machine	R_0 [m]	$P_{SOL}(P_{AUX})$ [MW]	P/R [MW/m]	P/S [MW/m^2]	τ_{pulse} [s]
NSTX*	0.86	6.8	8	0.2	1
NSTX-U*	**0.93**	**19**	**21**	**0.6**	**5**
JET†	2.95	12 (35)	4.1 (12)	0.03 (0.2)	20
DIII-D†	1.74	5 (20)	2.9 (11)	0.1 (0.4)	6
AUG†	1.65	5 (27)	3 (16)	0.1 (0.6)	10
CMOD†	0.7	3 (6)	4 (9)	0.4 (0.7)	2
MAST†	0.87	5 (7.5)	6 (9)	0.2 (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**	∞

Liquid metal PFCs provide additional pathways for energy transport



- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation

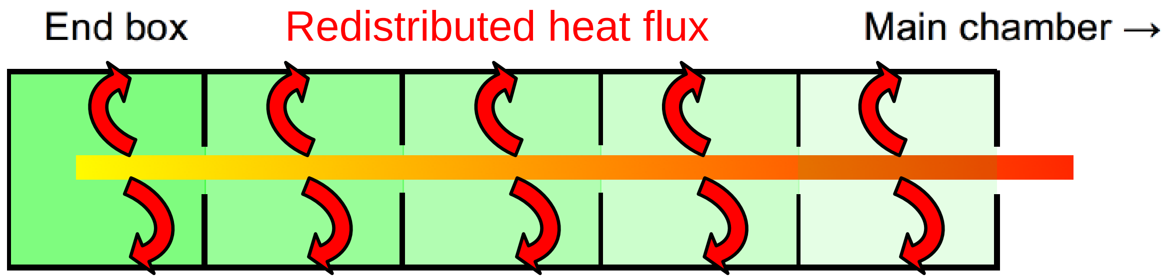
Liquid metal PFCs provide additional pathways for energy transport



- 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

Ultimate temperature limit of liquid lithium surface has large impact on power extraction potential

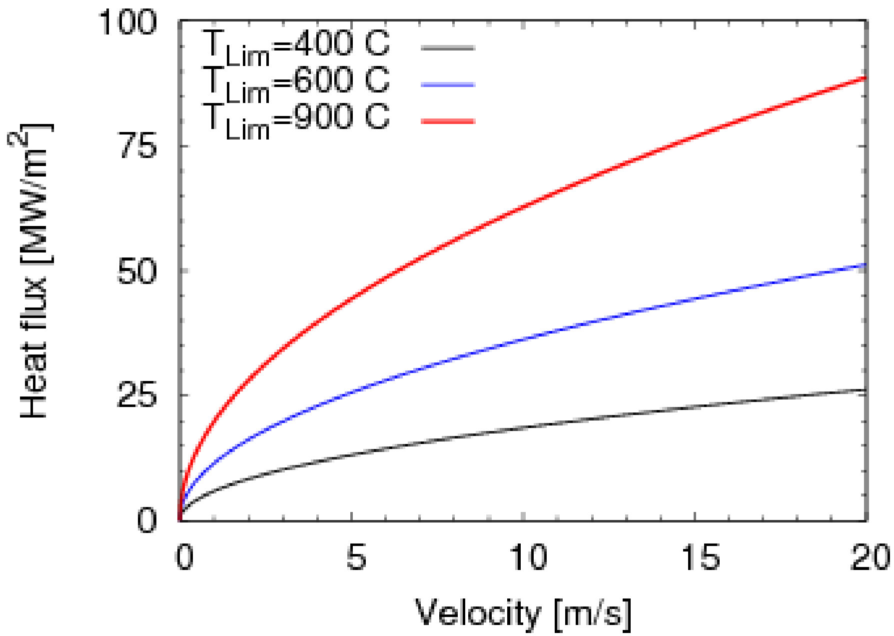
Vapor-box concept – Goldston et al., PFMC 2015, Phys. Scripta submitted



T (wall) °C	950	787.5	625	462.5	300

- Vapor-box utilizes neutral gas to redistribute incident heat
- Fast-flow concept can also benefit from increased surface temperature
- Hydrogen pumping limited to <400C

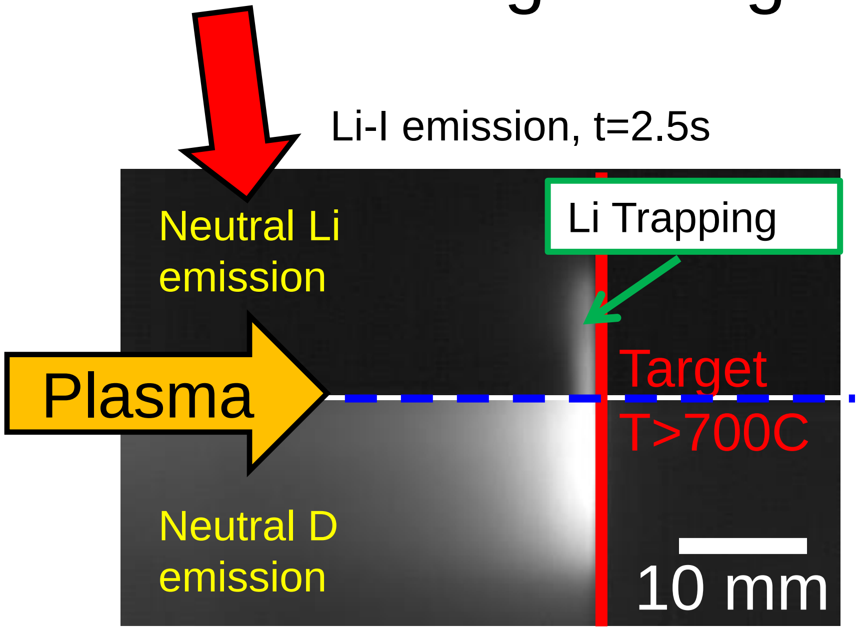
$$q_0 = \frac{\Delta T_{Lim} k}{2} \sqrt{\frac{\pi v_{LM}}{\alpha L_{char}}}$$



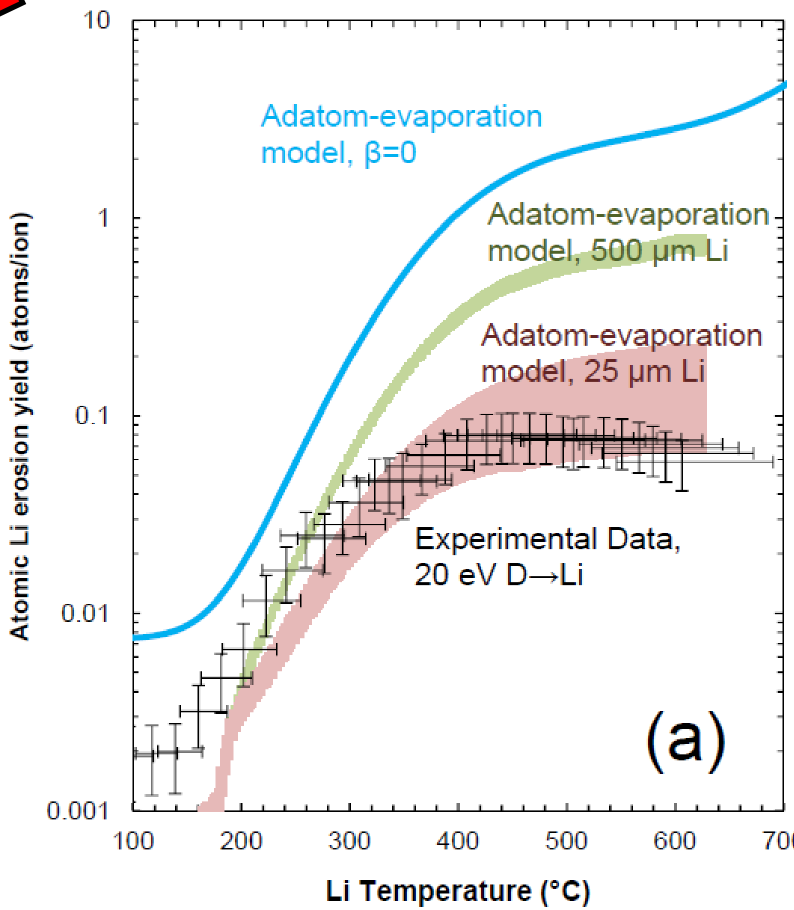
Recent results suggest higher temperatures are possible

- Suppressed erosion under high-flux D bombardment observed
- Near-surface trapping of lithium resulting in long

T. Abrams 2014 PhD Princeton U. &
T. Abrams 2015 Nucl. Fusion submitted.

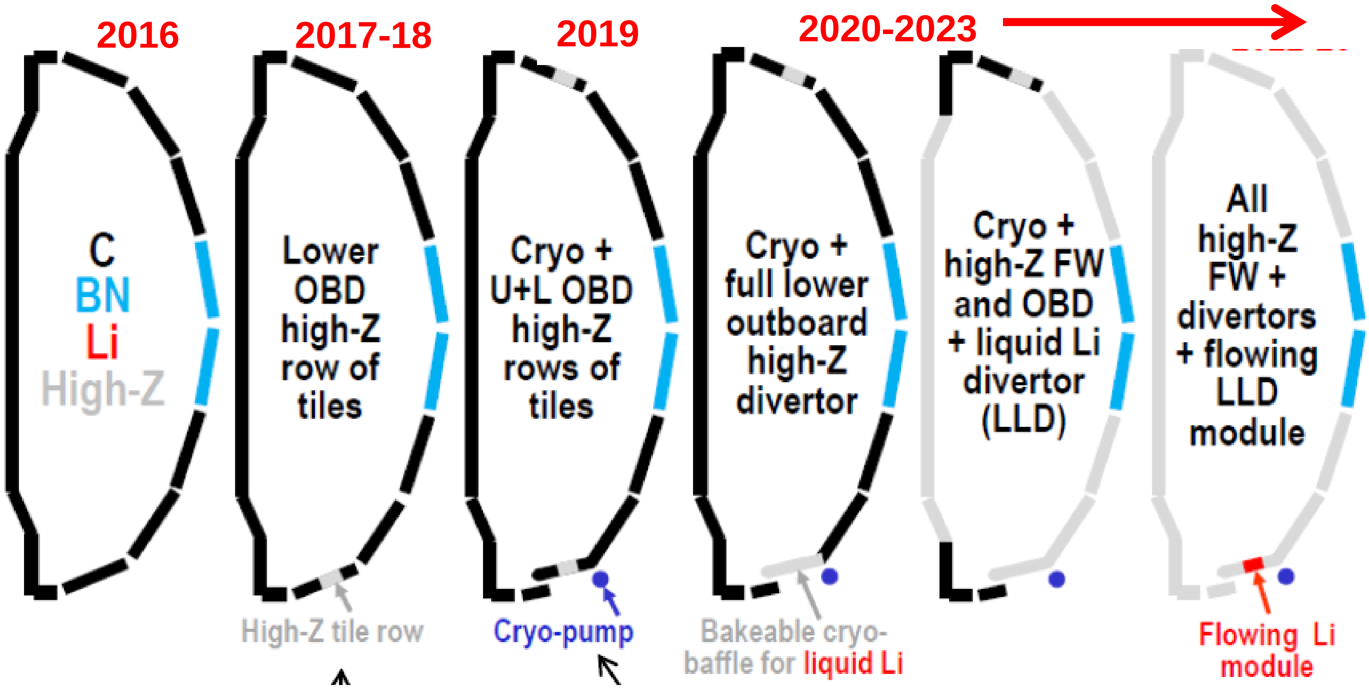


Jaworski, 3rd ISLA, 2013

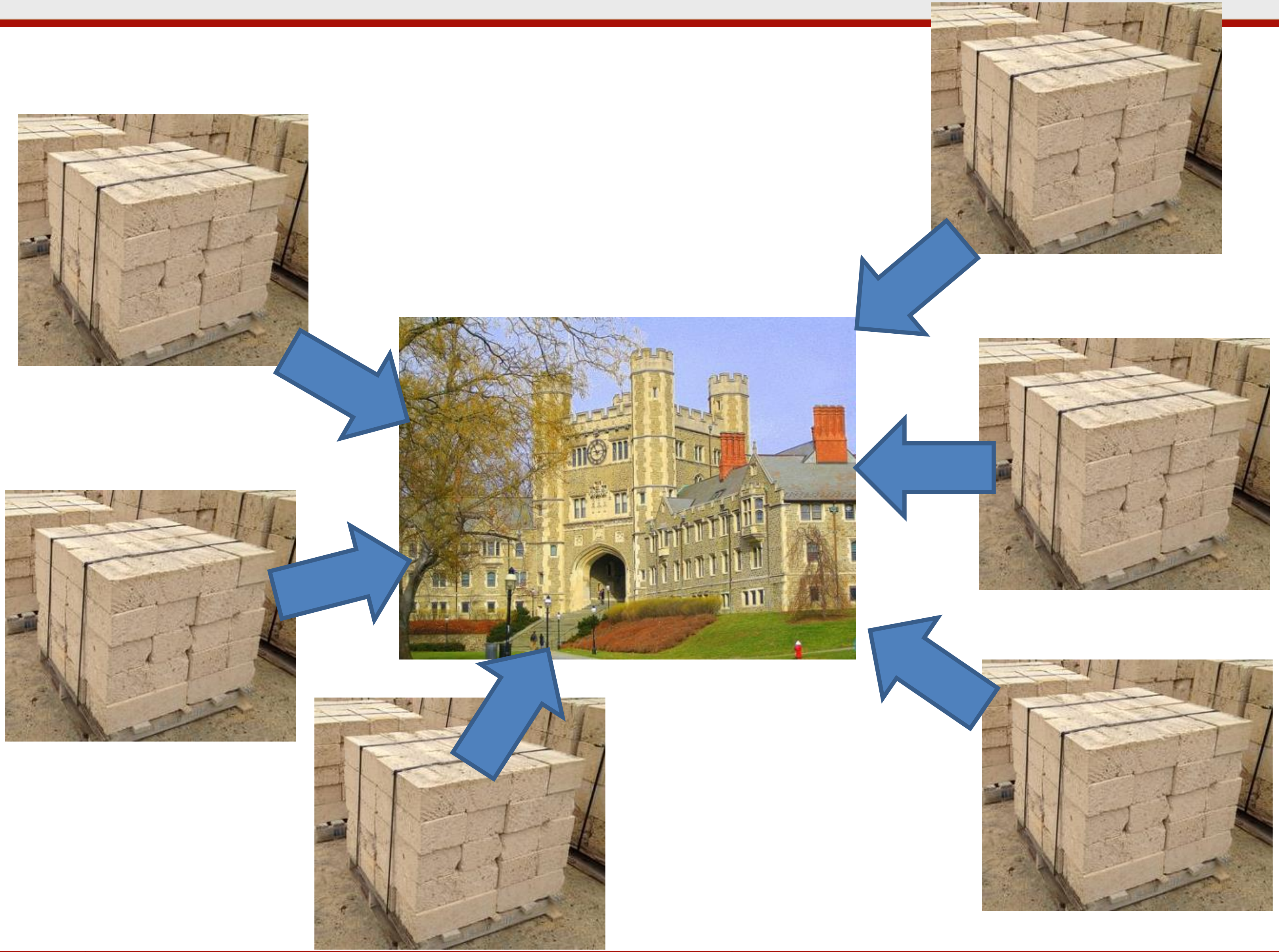


NSTX-U long-term objective is to perform comparative assessment of high-Z and liquid lithium PFCs

- Conversion to all-metal PFCs enables study of the role of PFCs on integrated scenarios
- Flexible divertor configurations allows exploration of novel PFCs and advanced magnetic configurations
- Addition of cryo-pump allows comparative assessment of cryo- vs. Li-based hydrogenic control

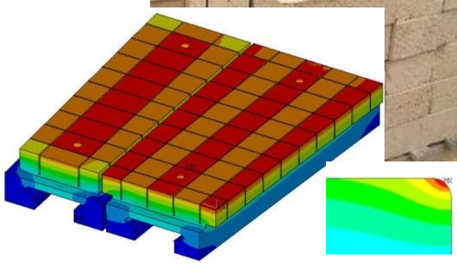


Required elements for complex projects…

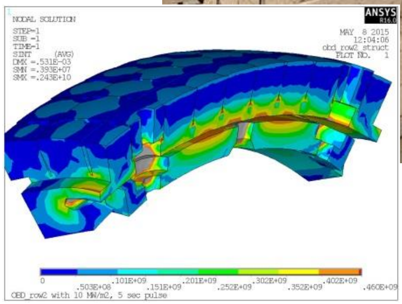


Required elements for flowing, liquid metal PFCs

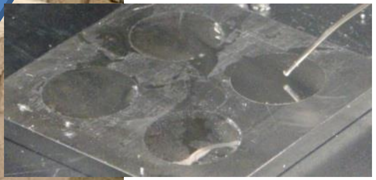
Heat flux handling

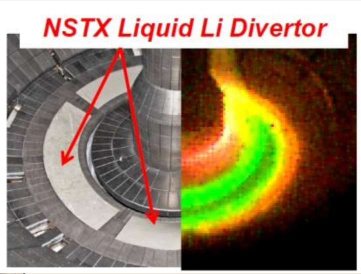


Substrate and structural



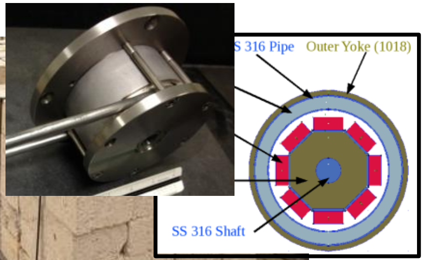
Liquid metal wetting and coverage





Plasma scenarios and operation

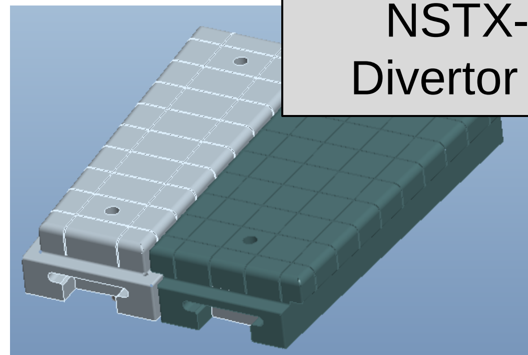
Safety testing & engineering

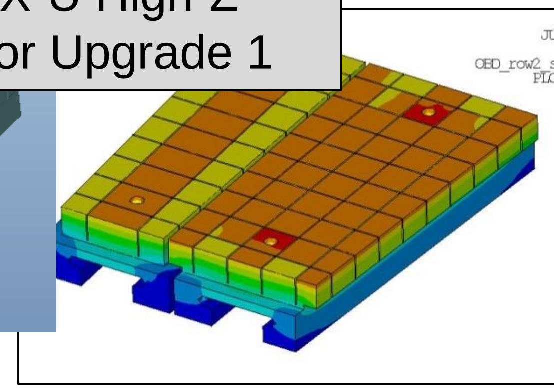


Pump and loop technologies

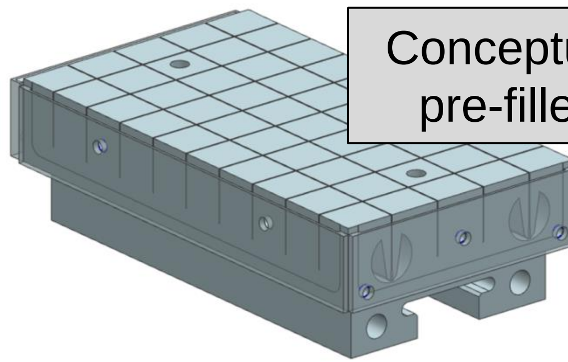
A three-step progression can achieve flowing, liquid metal PFCs

1. High-Z divertor tiles
   - Heat-flux handling
   - Substrate and structural (thermomechanical)
2. Pre-filled liquid-metal target
   - Builds from high-Z divertor tile design
   - Demonstrates liquid-metal wetting/reservoir
3. Flowing LM PFC
   - Integrates liquid lithium loop
   - Safety engineering updates

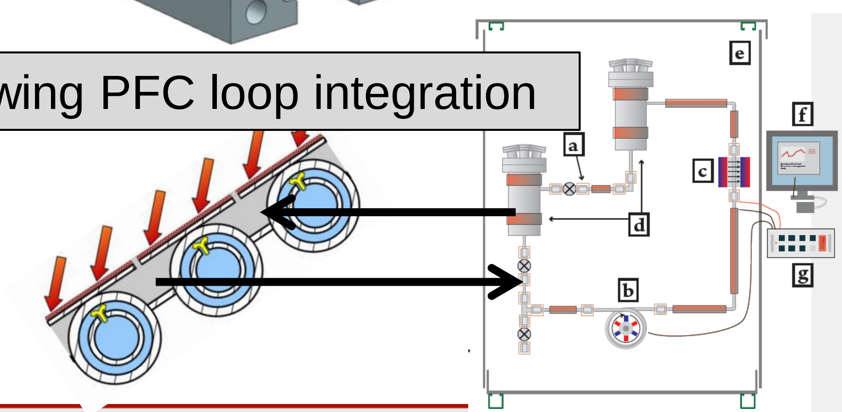




NSTX-U High-Z Divertor Upgrade 1



Conceptual design for pre-filled LM target



Flowing PFC loop integration

High-Z incremental upgrade will provide design and engineering assessments

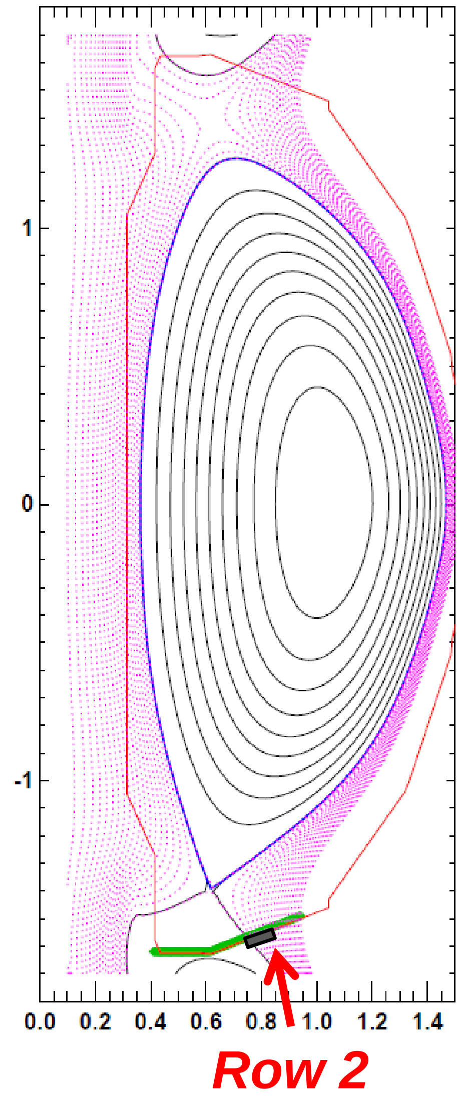
- Replace continuous row of graphite tiles with high-Z
- Provide operational experience and validate engineering design and analysis with an eye to future upgrades
- Continue experiments on evaporated Li films on high-Z substrate in diverted configuration
- Refine high-Z, high-heat flux design criteria for NSTX-U

Replacement of outboard row of tiles provides significant heat-flux and maintains operational flexibility

- Shape developed to perform dedicated tests on outboard PFCs
  - ISOLVER free-boundary solver utilized with specified β_N
  - 0D analysis obtains heating power consistent with shape and requested β_N
- Heat flux figure-of-merit (FOM) indicates significant power density on target tiles
  - FOM calculates incident power accounting for magnetic shaping only
  - High-Z shape FOM is 66% of full-power, high-triangularity scenario

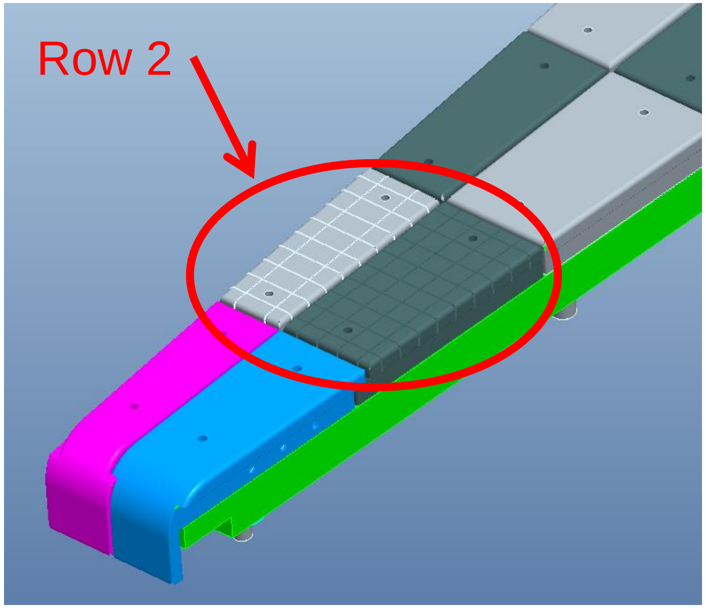
ISOLVER + 0D analysis
Bt = 0.78T
Ip = 1.25MA
BetaN = 4.5
q95 = 6.8
Elong. = 2.37
Lower triang. = 0.53

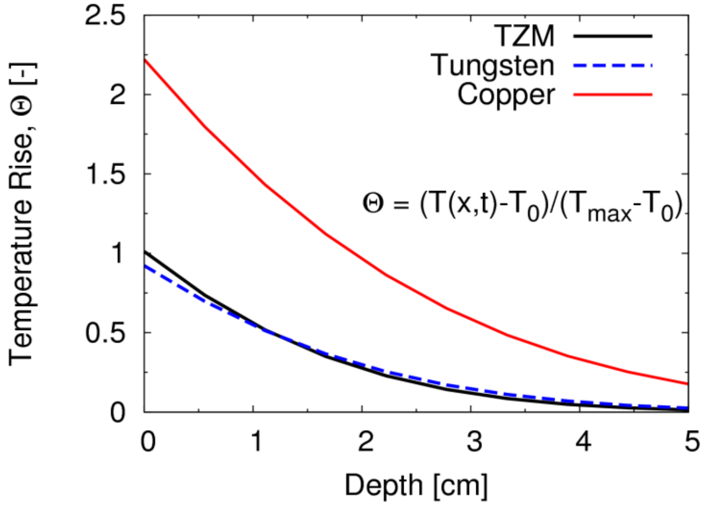
tauE = 0.049s
fGW = 0.75
N20 = 0.98
Te=Ti = 1.05keV
Pinj = 9.8MW



Rapid experiments facilitated by direct replacement of graphite tiles

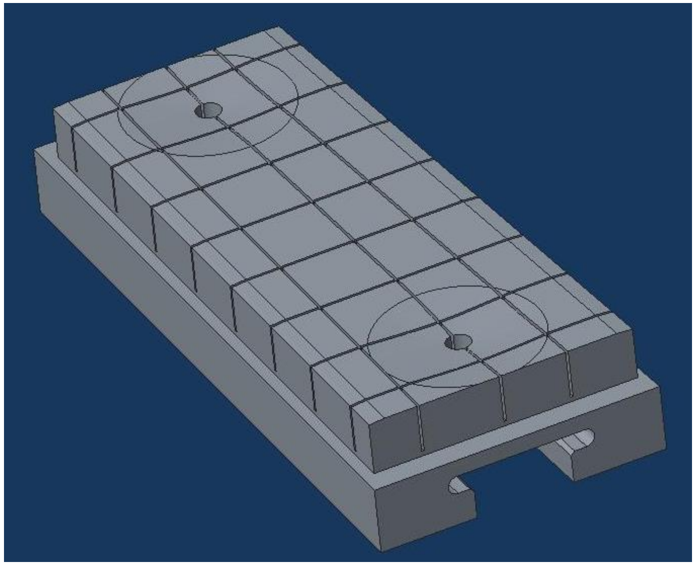
- Machine installation time minimized with 1-for-1 replacement
- Surface castellations relieve thermo-mechanical stresses
- TZM-alloy provides high-Z, Li-compatible substrate and machinability
- Copper (LLD-like) construction not possible due to large expected temperature rise (exceeds recrystallization limit of Cu)



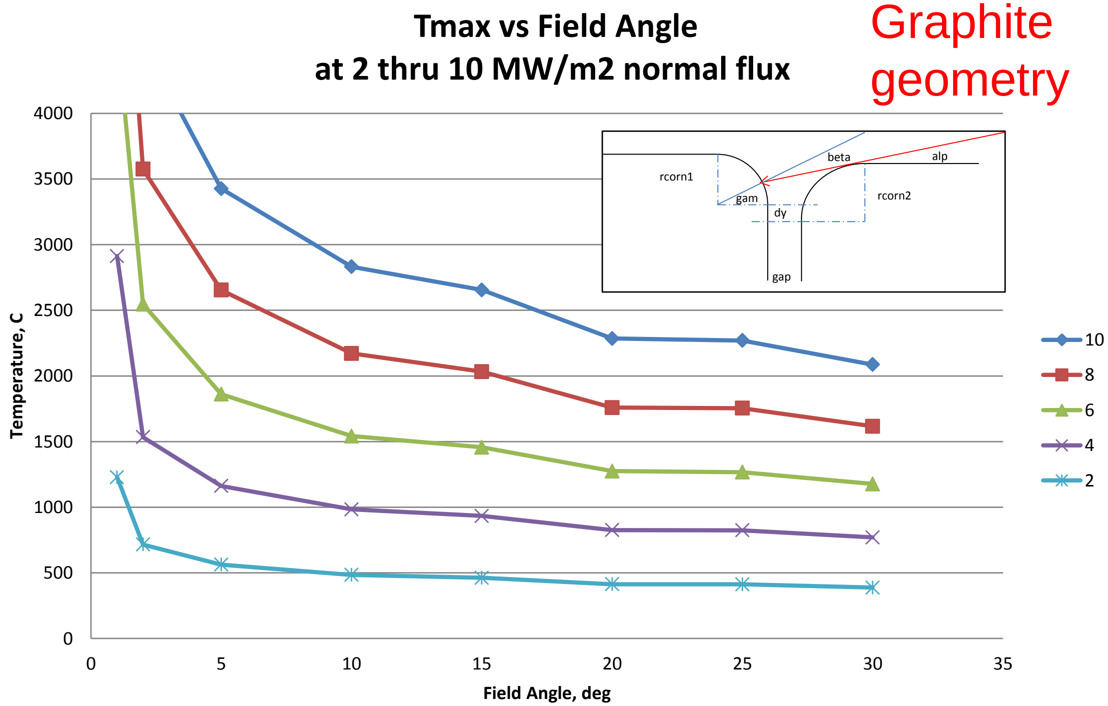


Leading edge heating is a critical issue for high-Z PFCs and motivates alternate geometries

- Leading edges lead to heat-flux enhancement factor
- Wire-EDM fabrication method leads to minimal gap between castellations
- Tile-to-tile gap and front-side access require chamfers

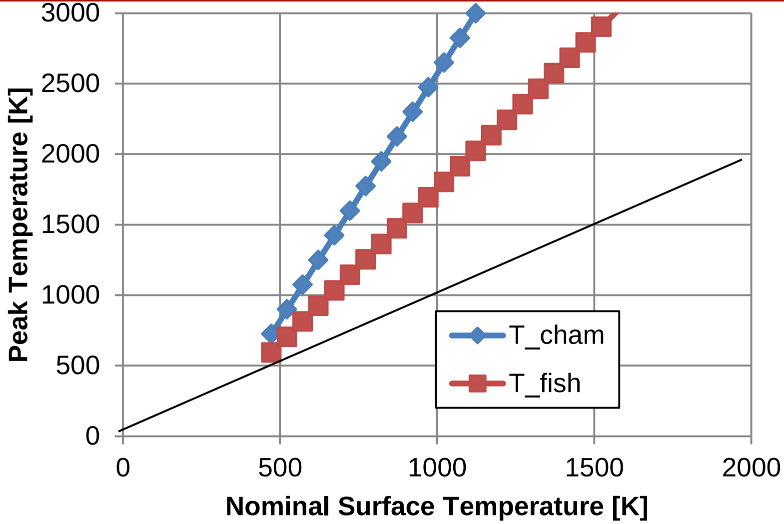


Graphite geometry



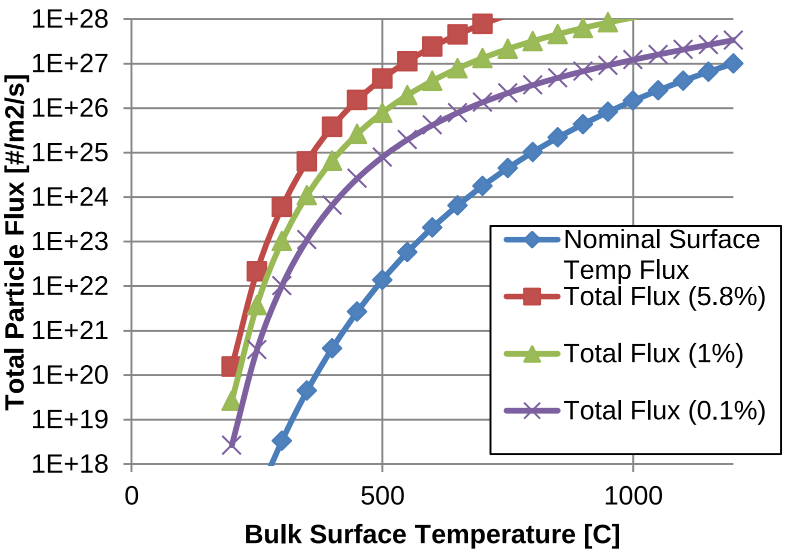
Inhomogeneous surface temperatures result in larger total particle flux

- Leading edges result in larger average temperature
  - Chamfers localize heating
  - Fish-scaling increases average heating



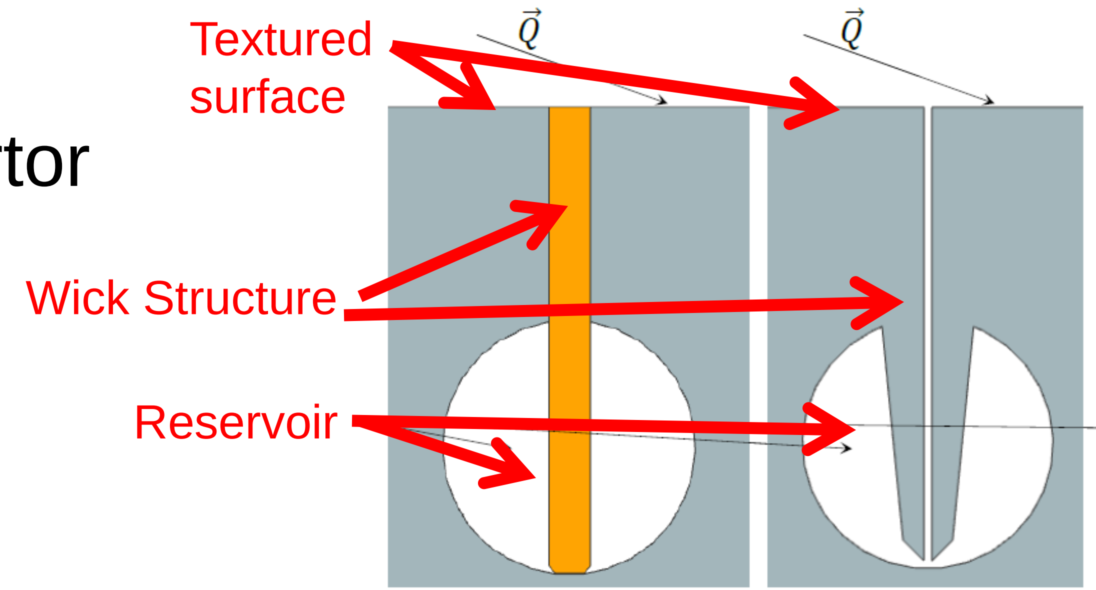
- Exponential vapor pressure produces strong increase in particle flux

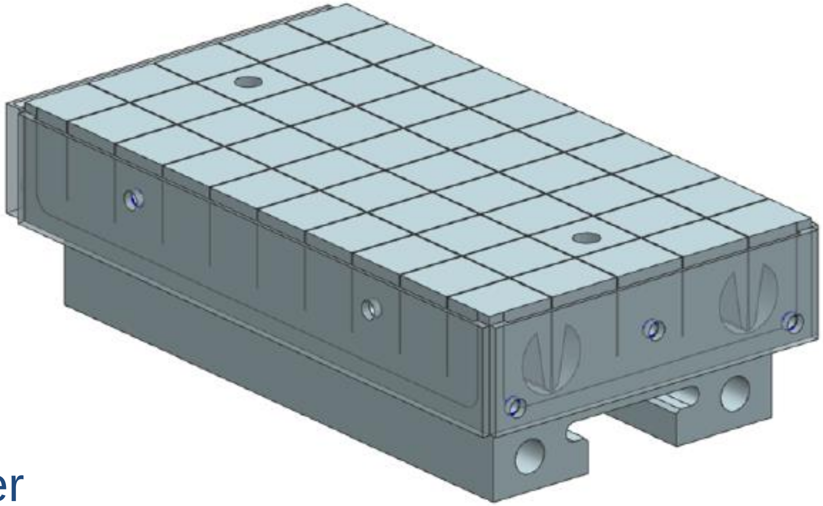
- Lithium likely to erode fastest from areas of enhanced heating



Pre-filled target concept integrates Li reservoir with high-Z tile scheme

- Similar to CPS device but applicable as divertor PFC
- Utilizes wire-EDM fabrication to obtain complex geometry
- Emphasizes passive replenishment via capillary action





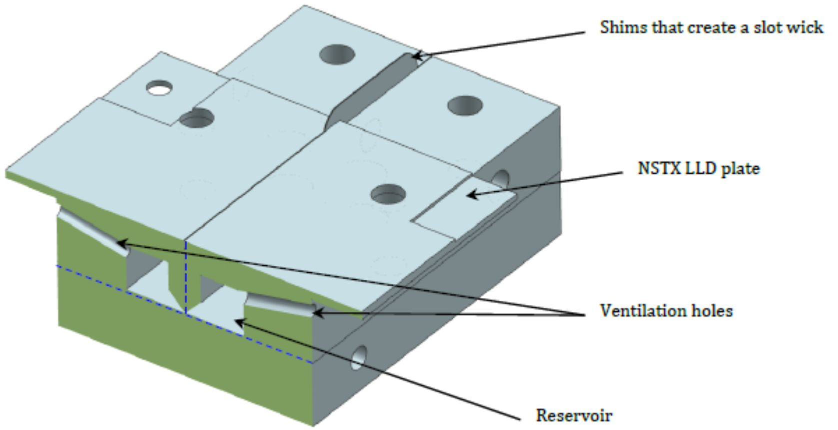
P. Rindt, TU/Eindhoven Thesis Project, see poster

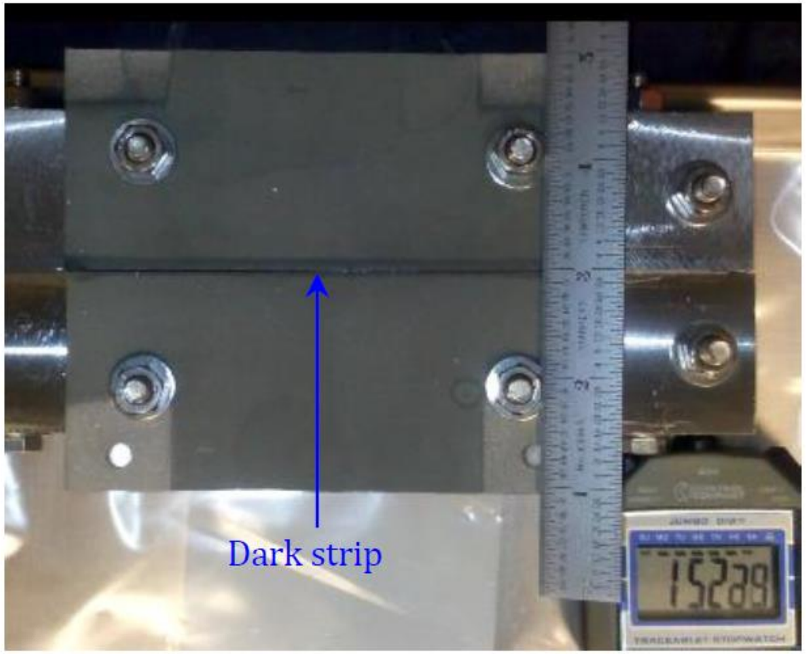
Preliminary tests indicate basic concept is feasible

- Prototype testing used isopropyl alcohol as surrogate

- Initial tests demonstrated wicking to surface and feasibility to empty reservoir via surface wick

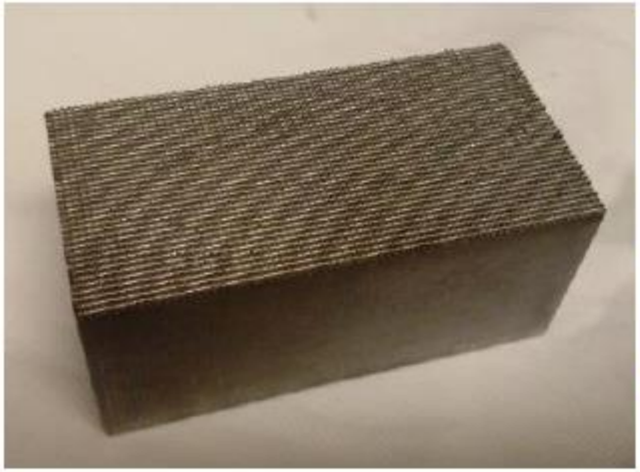
- Effectiveness highly dependent on surface capillary structure and texturing

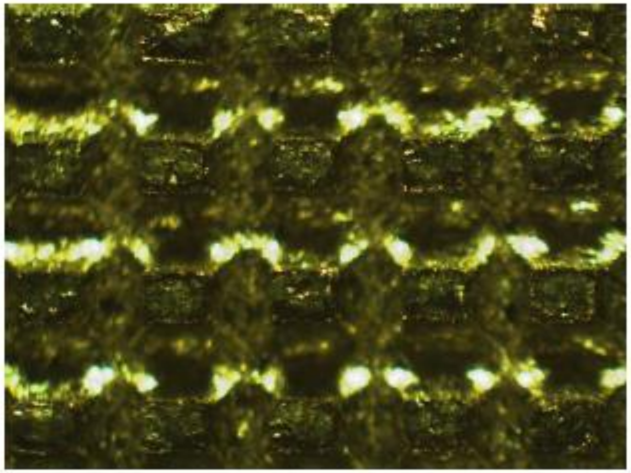


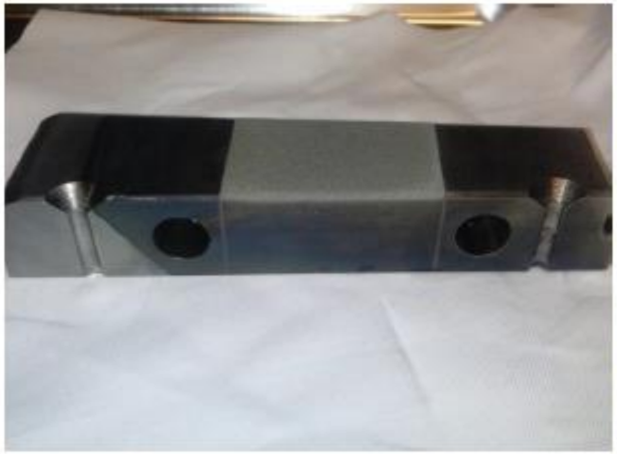


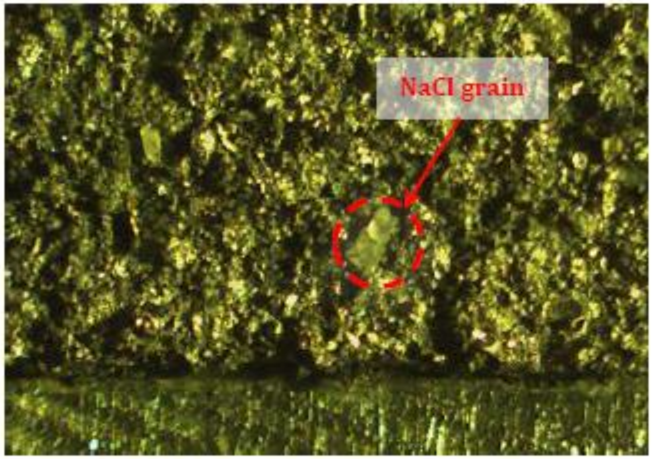
Multiple surface treatments tested for enhancement of wicking and flow (1)

- Comparison to LLD flame-sprayed material
- Wire-EDM micro-texturing
- Enhanced-porosity flame-spray



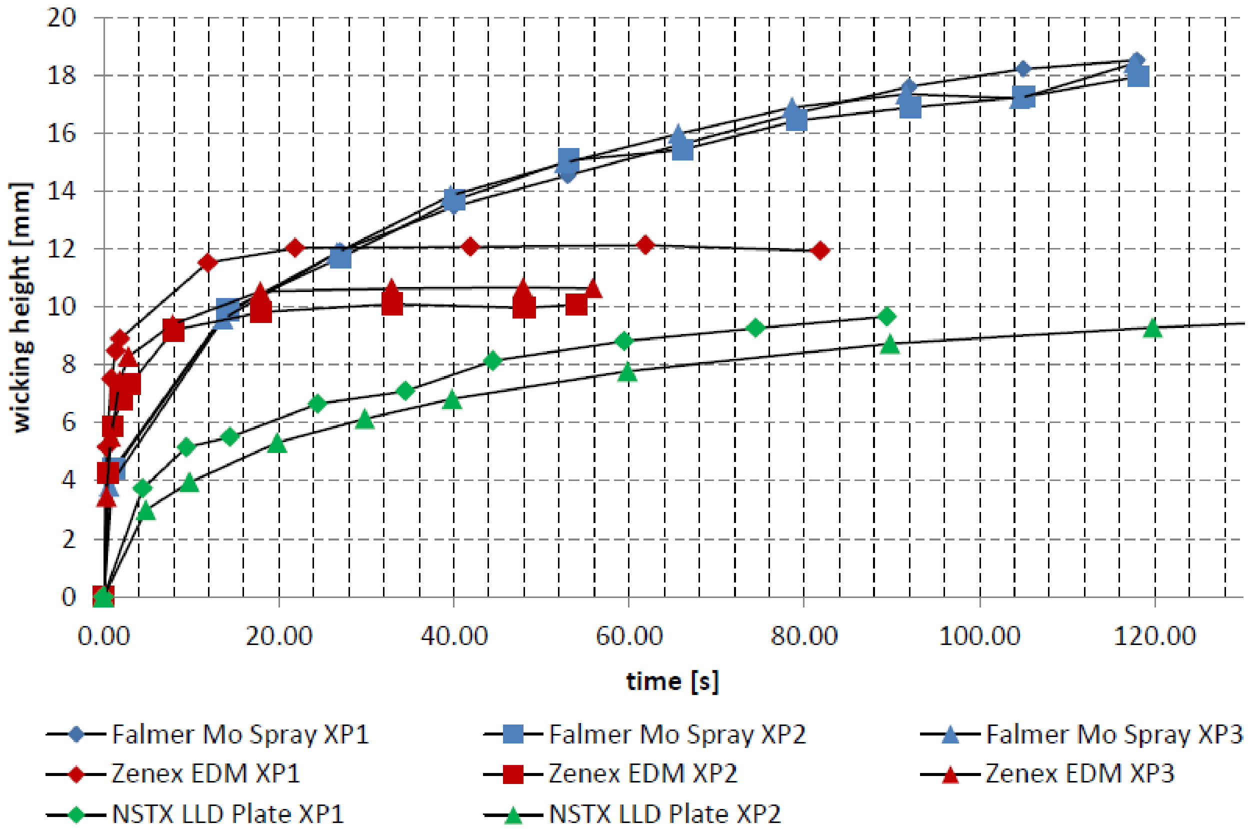






Multiple surface treatments tested for enhancement of wicking and flow (2)

- Simple wicking height apparatus used
- All samples show improved wicking over LLD flame-spray surface
- Wire-EDM micro-texturing similar to laser-texturing method developed by Lin et al. (J. Nucl. Mater. 2013)



Three-step progression provides roadmap for liquid metal PFCs in NSTX-U

- NSTX-U provides a challenging environment for PFCs and great flexibility for testing new divertor and material concepts
- Starting step of high-Z divertor upgrade provides high-heat flux target for evaporated lithium experiments over a wide temperature range
- Pre-filled targets for the divertor can provide information on LM behavior with significant reservoir capacity
- Flowing PFCs can build upon operational experience gained with pre-filled targets and parallel efforts in safety and LM handling systems