Design Considerations for NSTX-U Divertor Upgrade and Future Liquid-Metal PFCs*

MA Jaworski[1], A. Brooks, K. Tresemer,
S. Gerhardt, R. Kaita, J. Menard, J. Nichols,
M. Ono, R. Maingi (PPPL), P. Rindt,
N. Lopes-Cardozo (TU/Eindhoven), T.K. Gray (ORNL)

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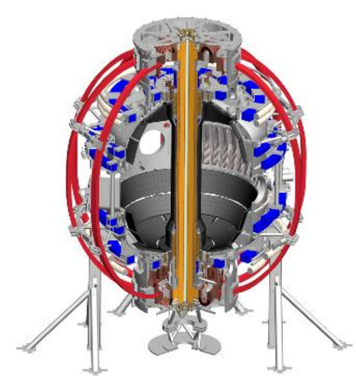


How do we test the potential of liquid metal plasma facing components?

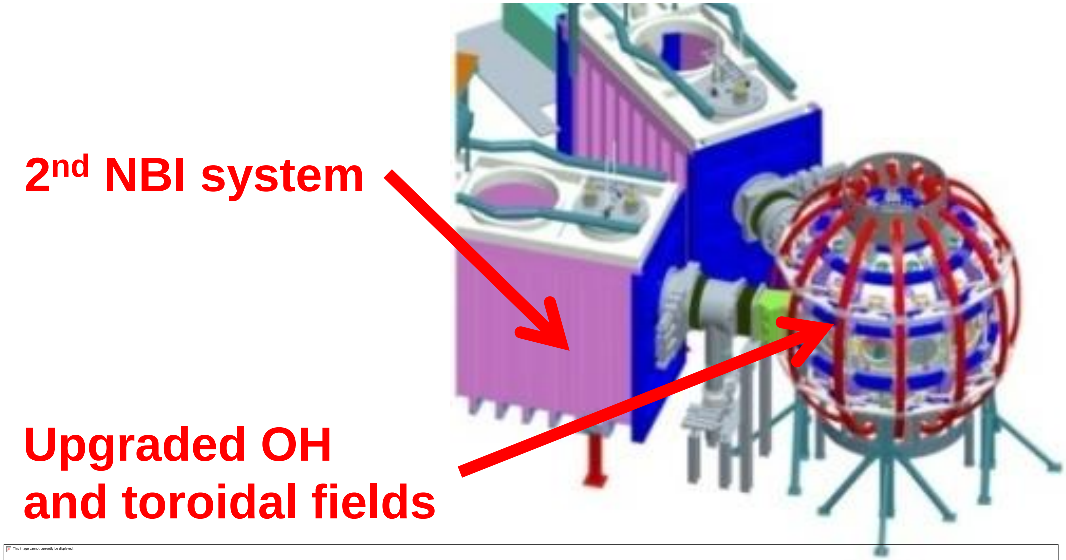
- What is an upgrade path to experimentally test these potential advantages?
- High-Z PFCs as test of separation of PMI from substrate
- Pre-filled targets to begin testing heat-flux reduction in divertor

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

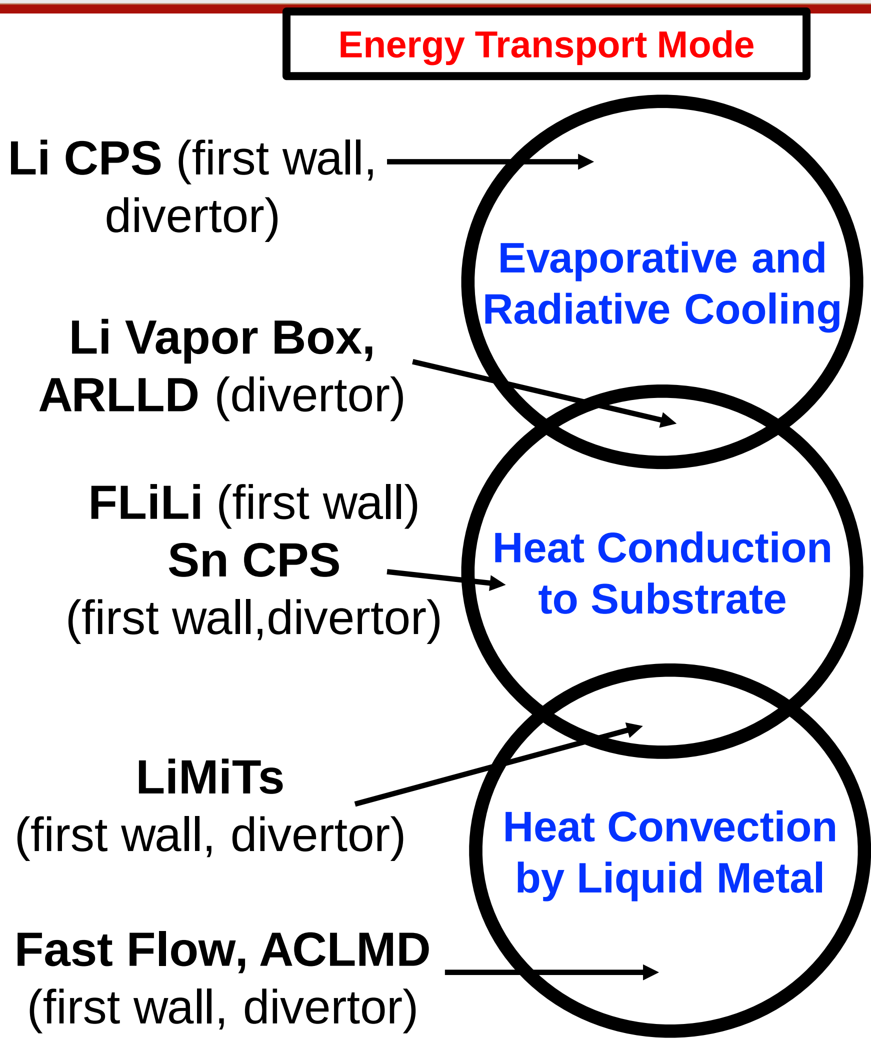
- NSTX-U is the newest US machine
  - 2x NBI heating power (<13MW)
  - 2x current (<2MA) and field (<1T)
  - 5x pulse length (<5s)

- Experimental capabilities push toward DEMO-relevance

- Open divertor provides unique opportunities for experiments



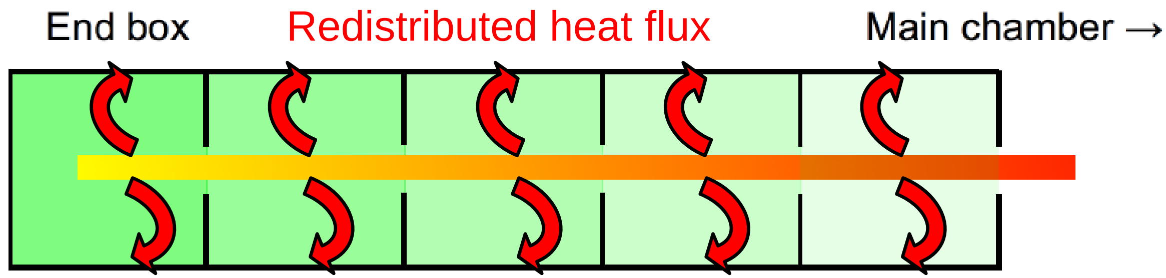
Liquid metal PFCs provide additional pathways for energy transport



- 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

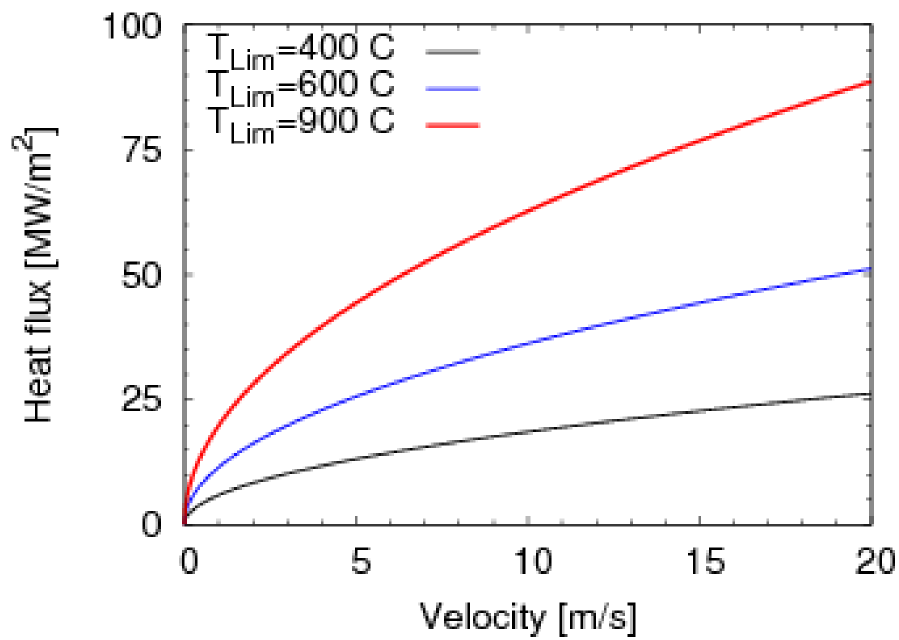
Vapor-box concept – Goldston et al., Phys. Scripta 2015
See: TP12.00122



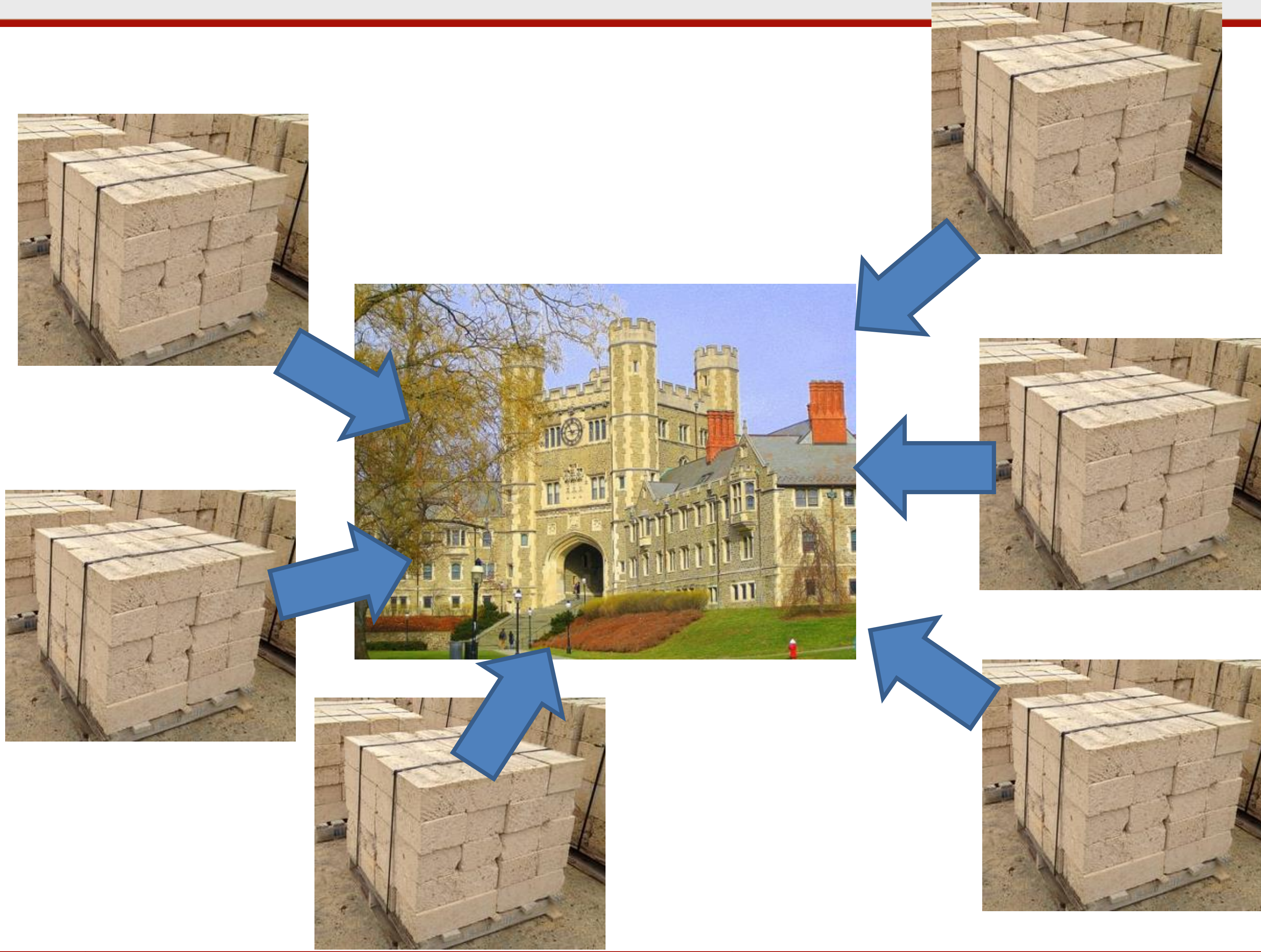
T (wall) ºC	950	787.5	625	462.5	300

- Vapor-box localizes Li for plasma detachment
- Fast-flow concept can also benefit from increased surface temperature
- Hydrogen pumping limited to <400C

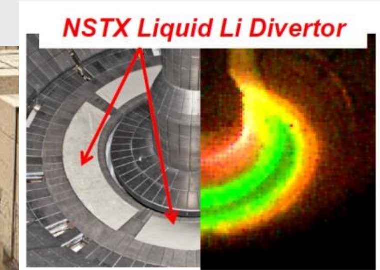
$$q_0 = \frac{\Delta T_{Lim} k}{2}\sqrt{\frac{\pi v_{LM}}{\alpha L_{char}}}$$



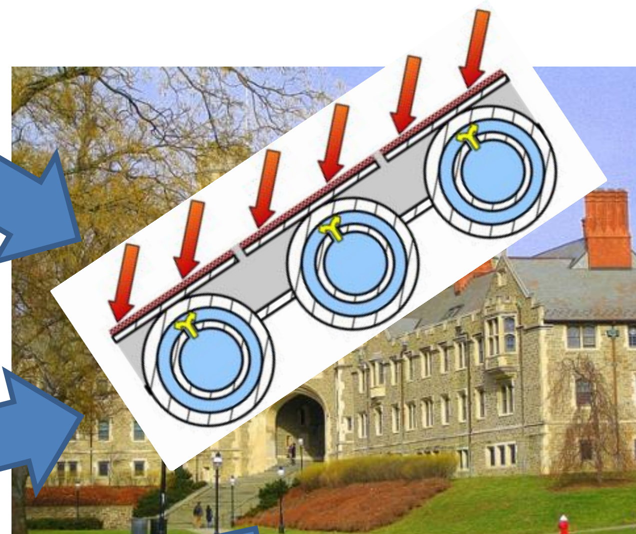
Multiple required elements complex projects



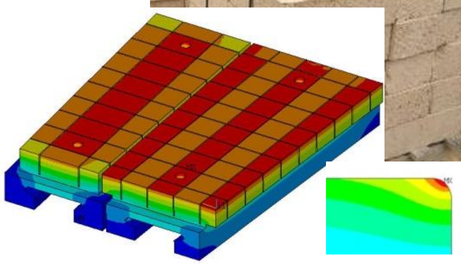
Required elements for flowing, liquid metal PFCs



Integrated, flowing LM PFC

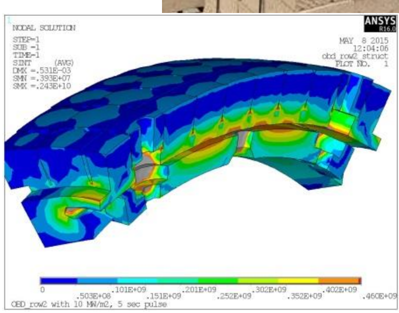


Heat flux handling



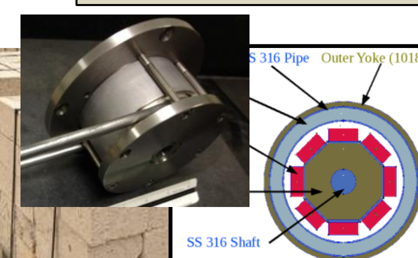
Plasma scenarios and operation

Substrate and structural



Safety testing & engineering

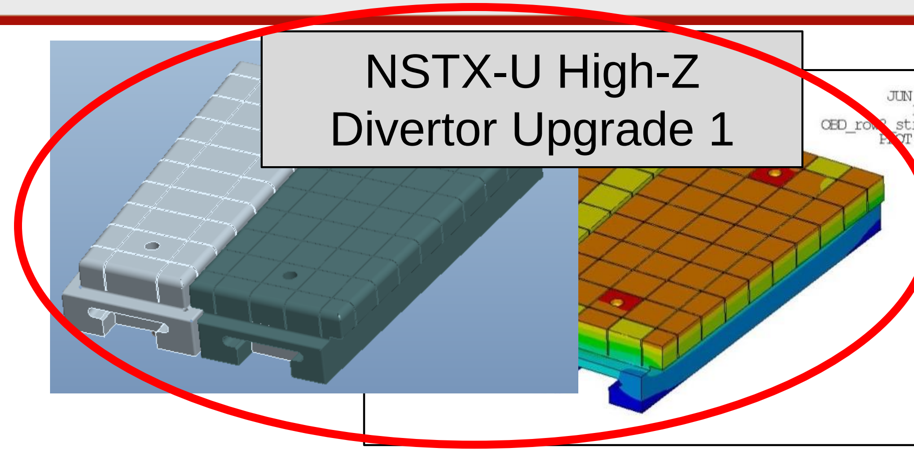
Liquid metal wetting and coverage

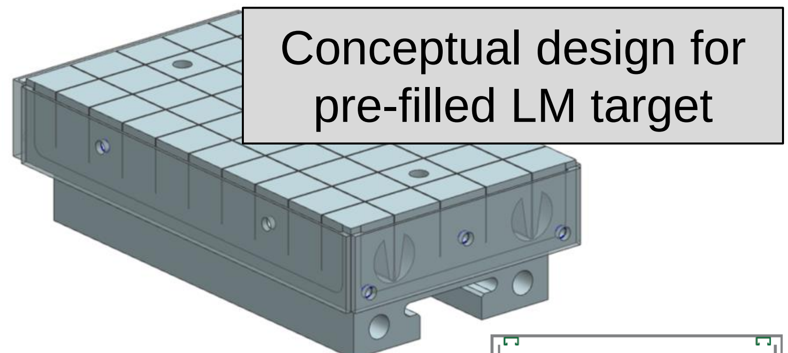


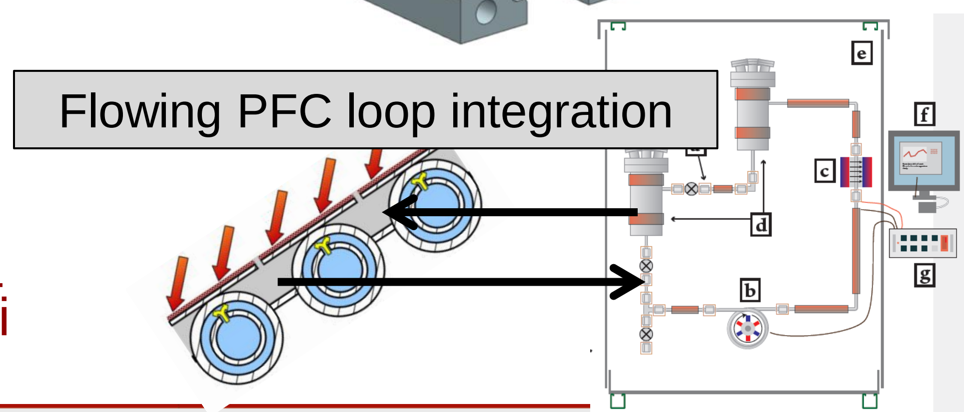
Pump and loop technologies

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

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

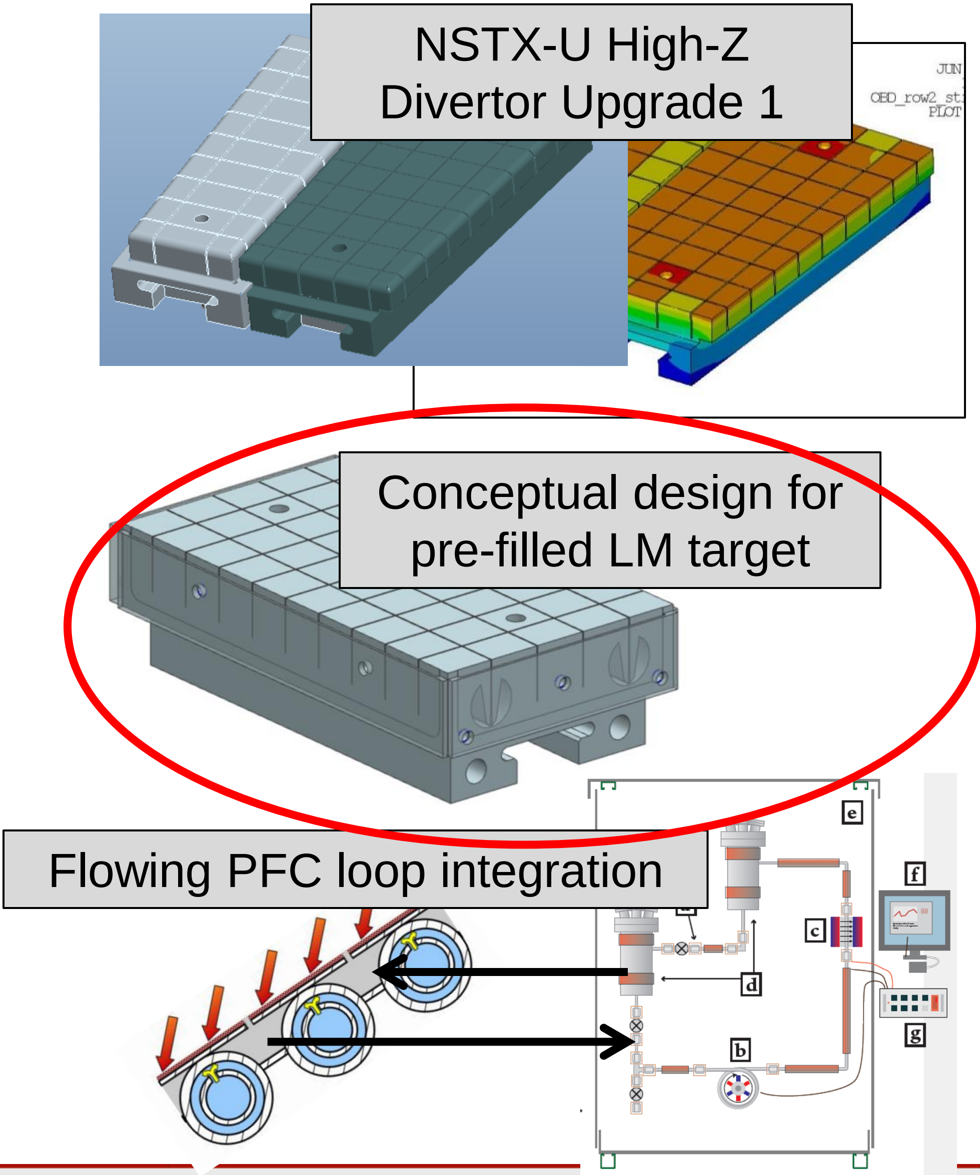






Pre-filled targets test LM coverage, resupply and impact of significant Li source

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

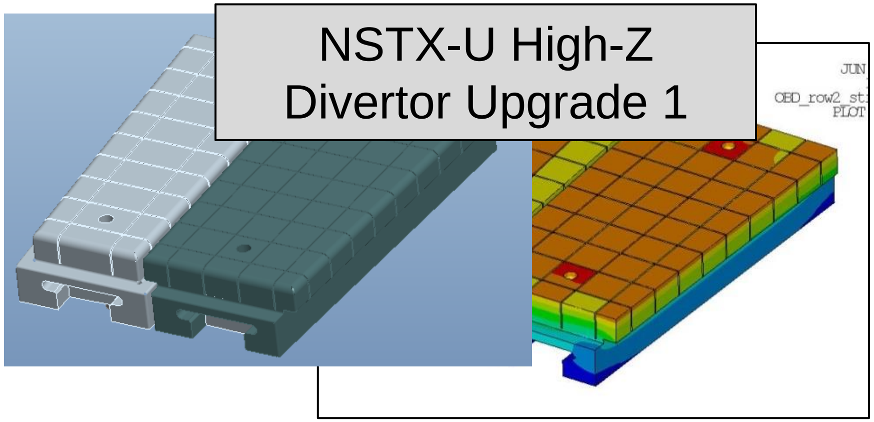


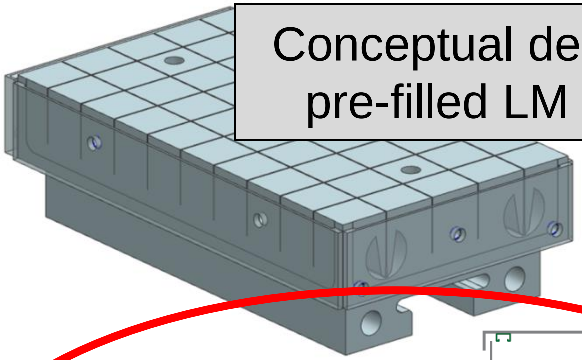
Final integration demonstrates LM introduction/extraction and inventory control

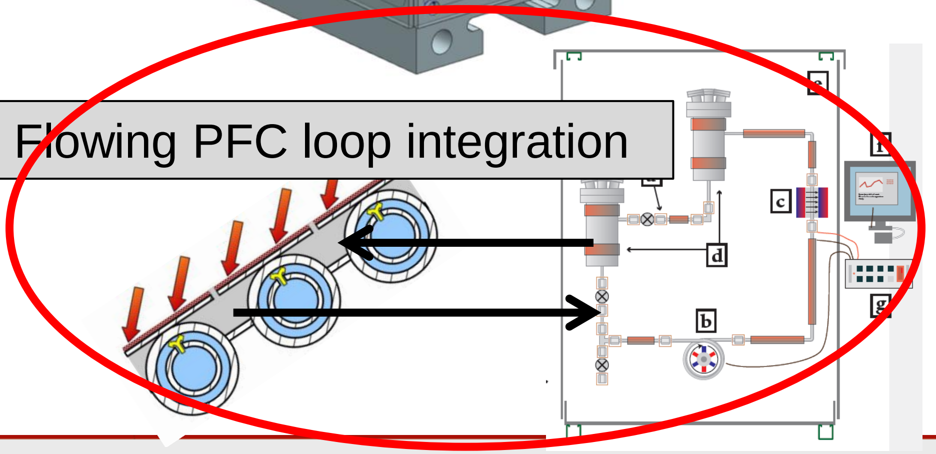
3. Flowing LM PFC

– 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>

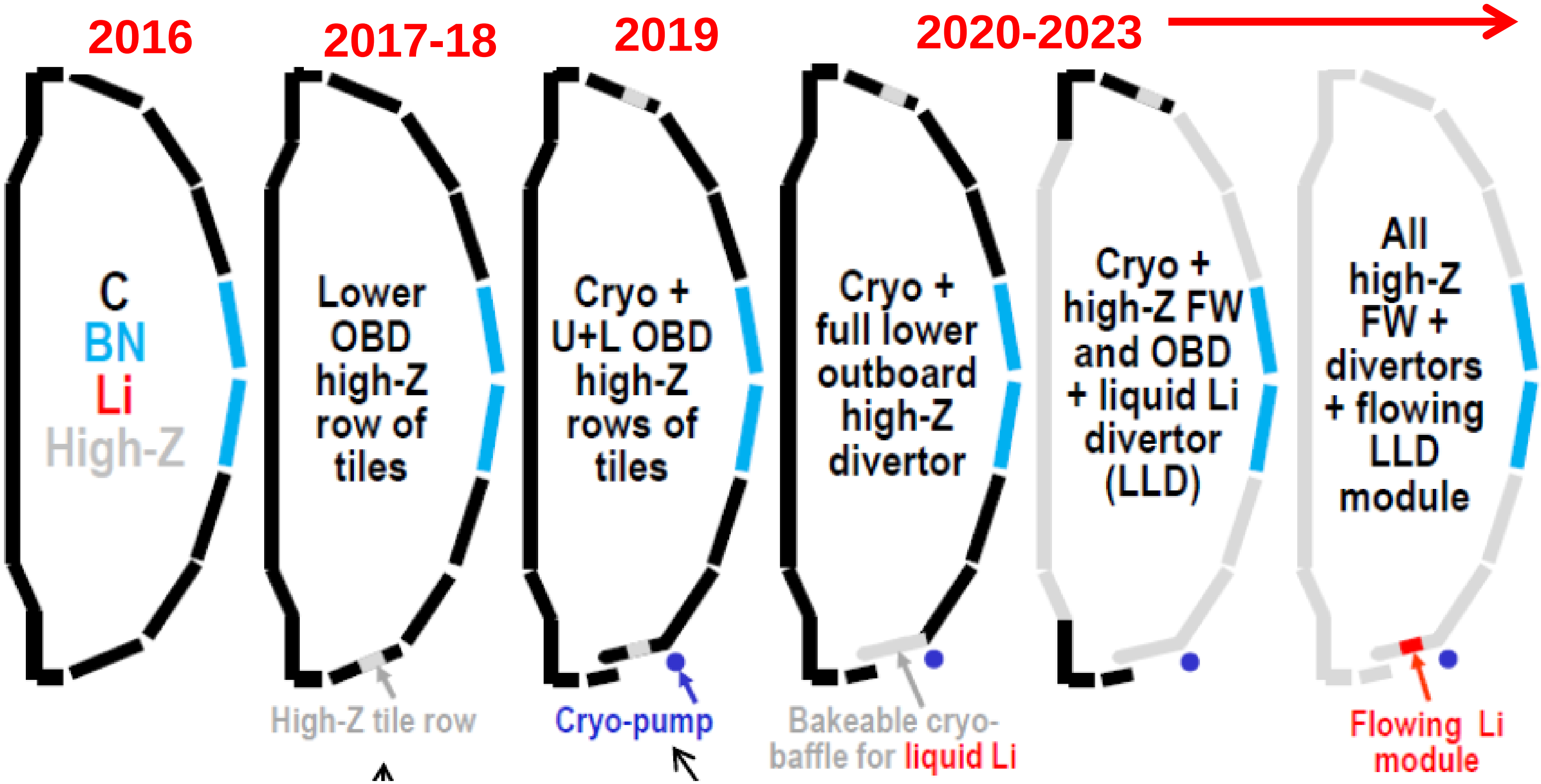

NSTX-U High-Z Divertor Upgrade 1


Conceptual design for pre-filled LM target


Flowing PFC loop integration

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



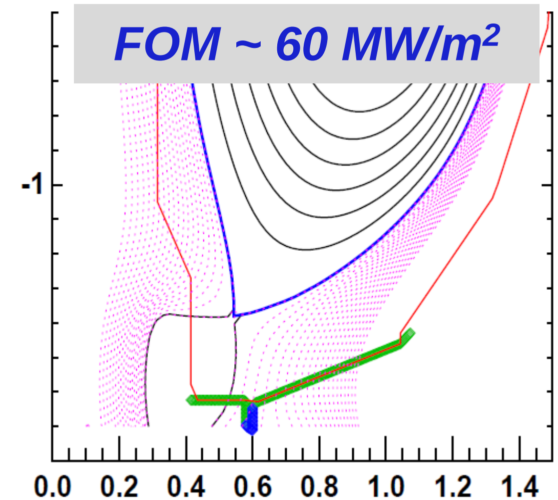
High-Z incremental upgrade will provide design and engineering assessments

- Replace continuous row of graphite tiles with high-Z
  - Avoid Li intercallation for longer-pulse experiments
  - Examine protection of high-Z substrate w/ low-Z coatings
- 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

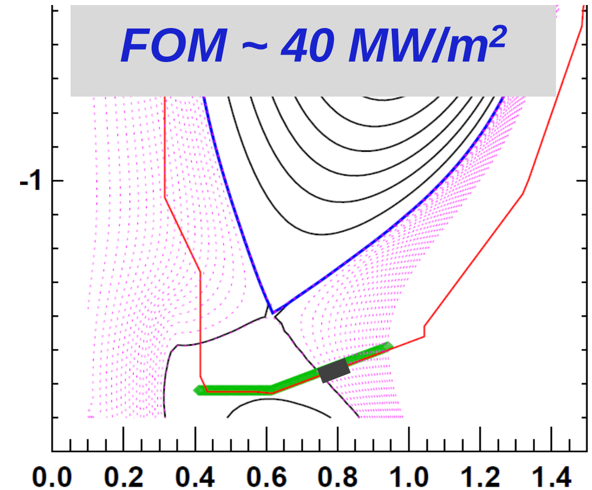
Replacement of outboard row of tiles provides significant heat-flux and maintains operational flexibility

- Shape developed to perform dedicated tests on outboard PFCs
  - ISOLVER free-boundary solver utilized with specified β_N
  - 0D-analysis obtains heating power for some assumed confinement (ITERH98)
- Zero-radiation power exhaust provides heat flux figure-of-merit (FOM)
  - FOM calculates incident power accounting for magnetic shaping only
  - High-Z shape FOM is 66% of full-power, high-triangularity scenario

High-performance discharge

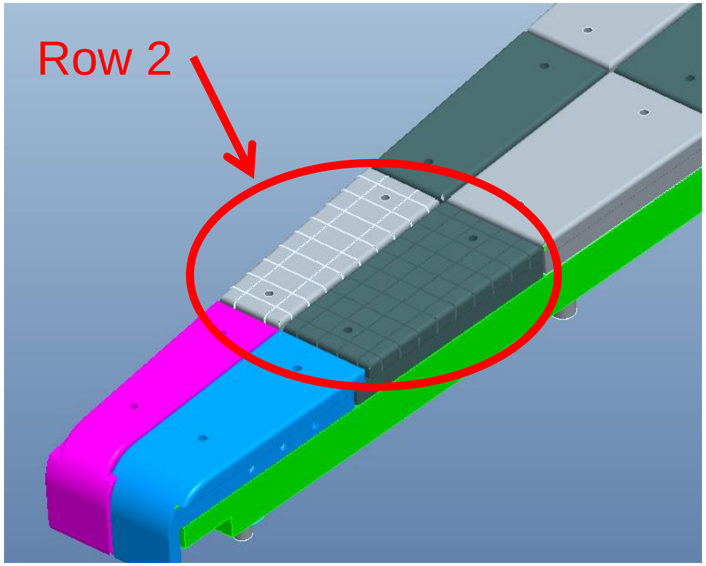


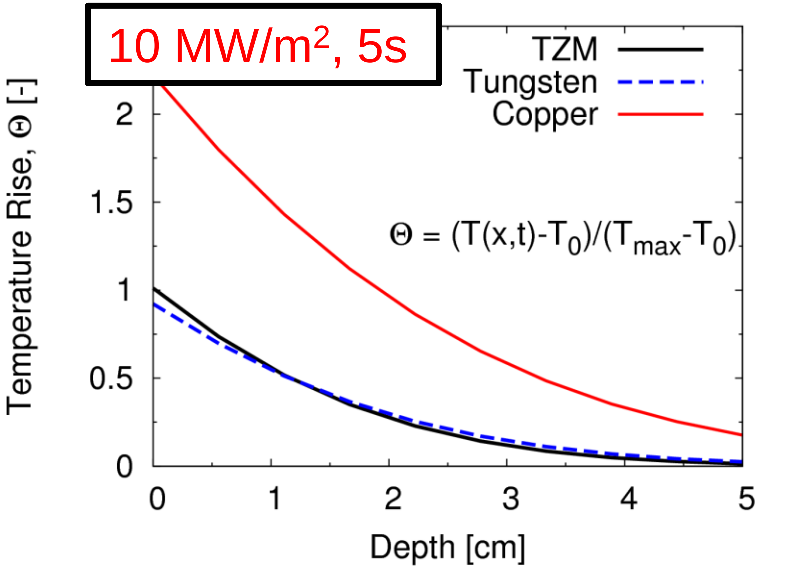
High-Z reference discharge



Rapid experiments facilitated by direct replacement of graphite tiles

- Machine installation time minimized with 1-for-1 replacement
- Surface castellation 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)





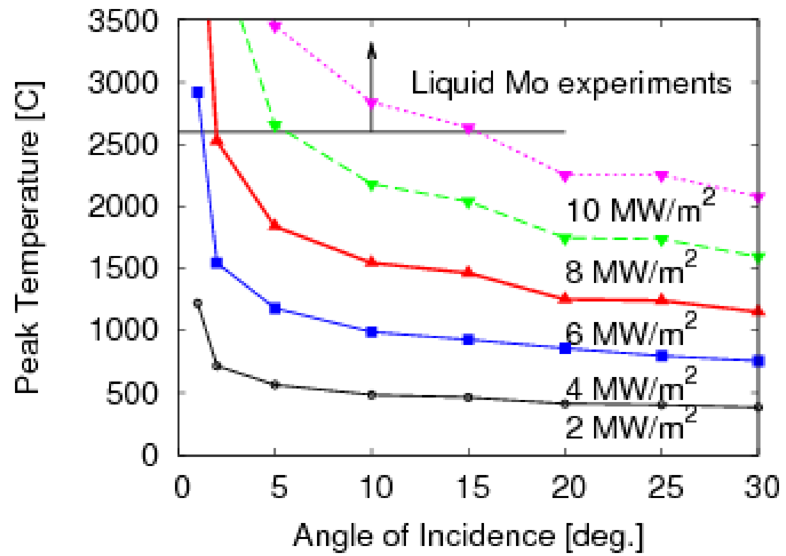
Leading edge heating is a critical issue for high-Z PFCs and motivates alternate geometries

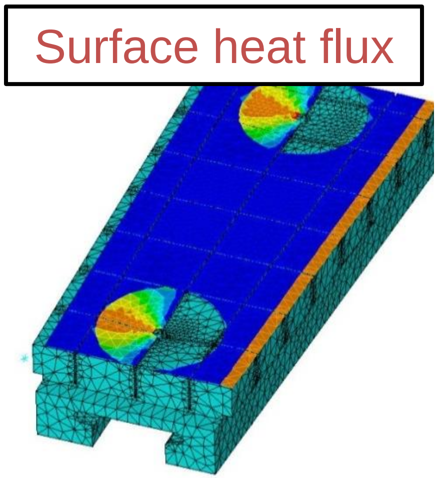
- Leading edges lead to heat-flux enhancement factor

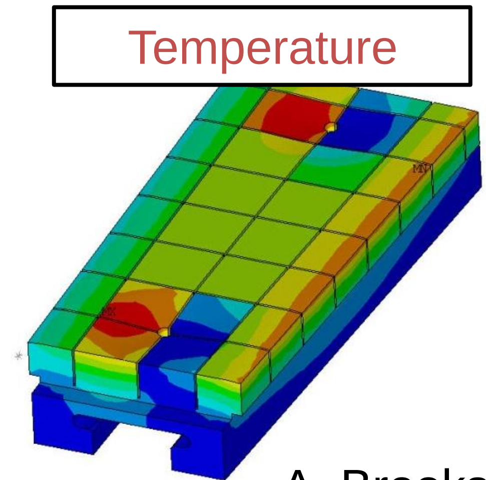
- Tile-to-tile gap and front-side access require chamfers

- Chamfer scheme reduces peak temperature ~30%
  - T_{peak} = 2470C vs. 3450C for 10 MW/m², 5° inc.

Graphite Geometry



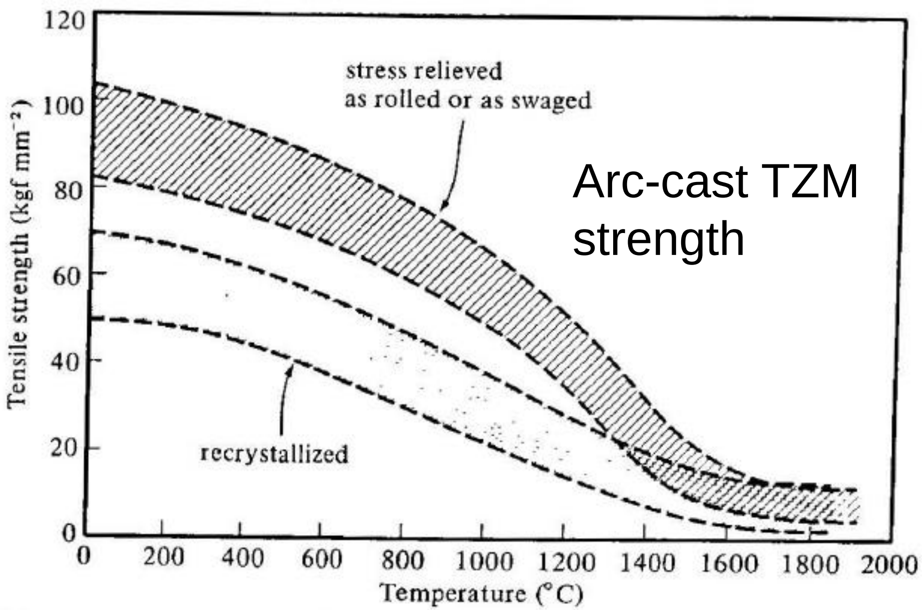




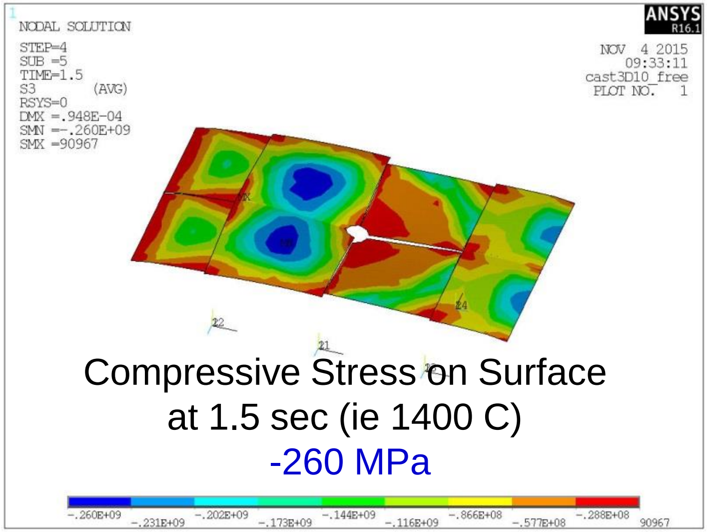
A. Brooks

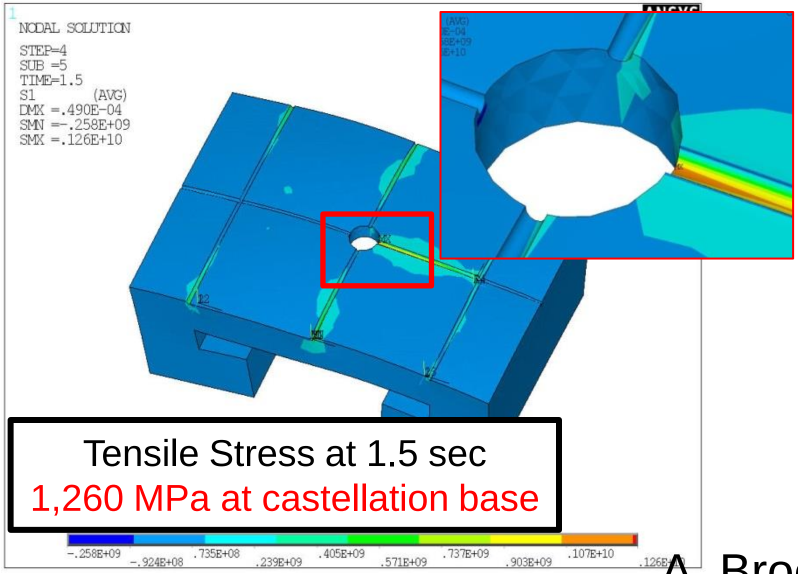
Castellations separate peak stress from peak temperature

- TZM weakens at high temperatures
- Castellations reduce surface stress (2-4x)
- Avoiding surface cracking and potential high-Z dust production in PFC desirable



Briggs, J., *High Temp.-High Press.* **3** (1971) p. 363-409.

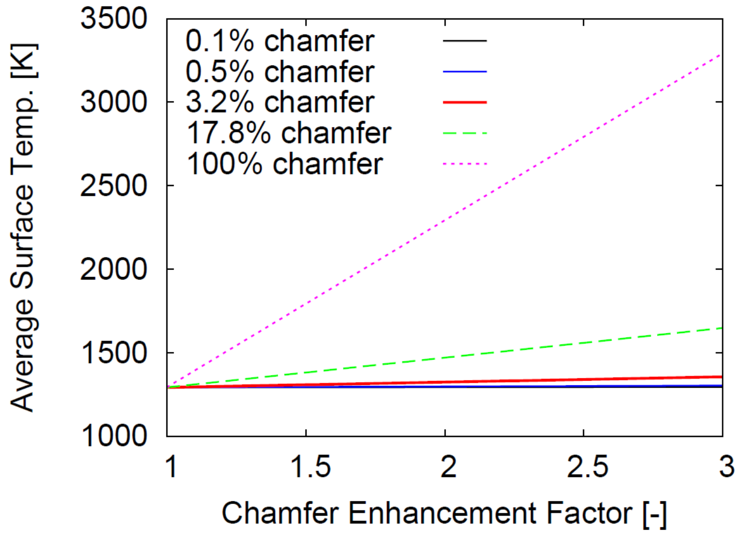


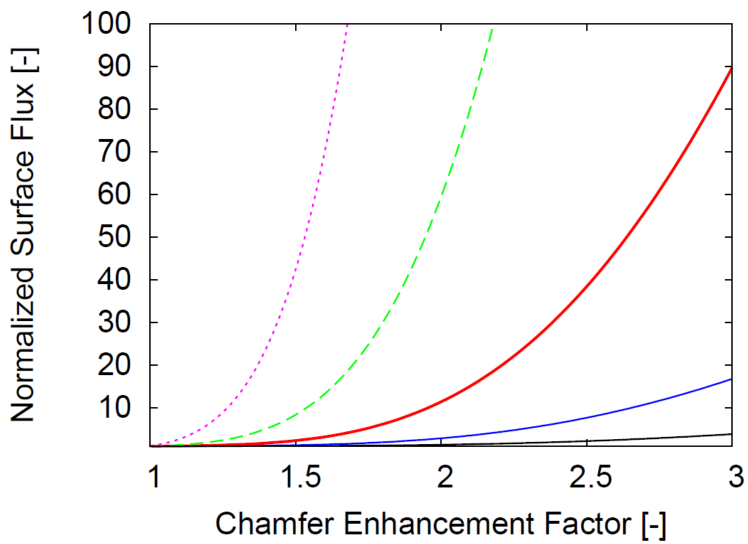


A. Brooks

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



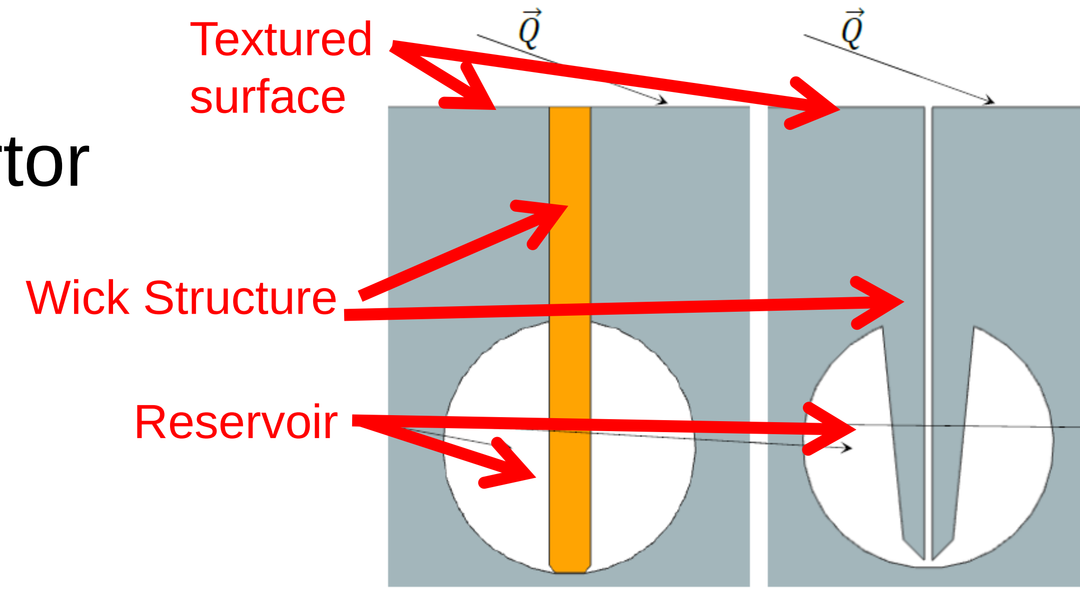


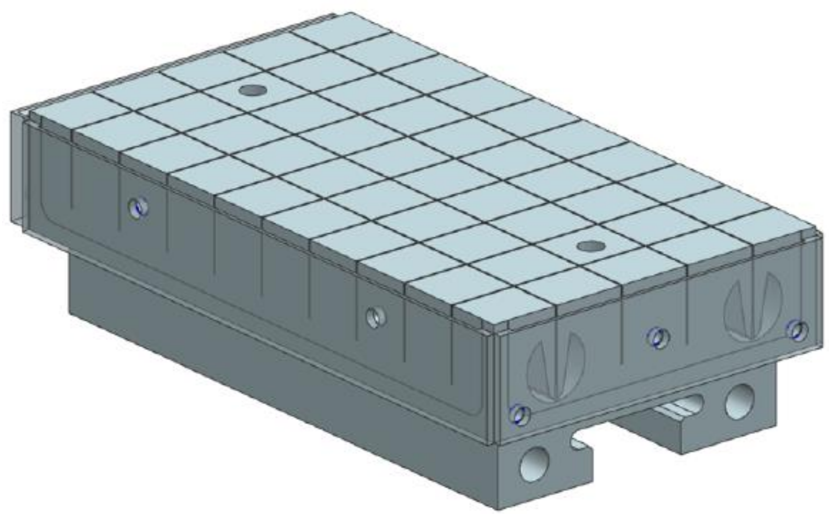
Three-step progression provides roadmap for liquid metal PFCs in NSTX-U

- NSTX-U provides test-bed 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 lithium safety (see TP12.00094) and LM handling systems

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





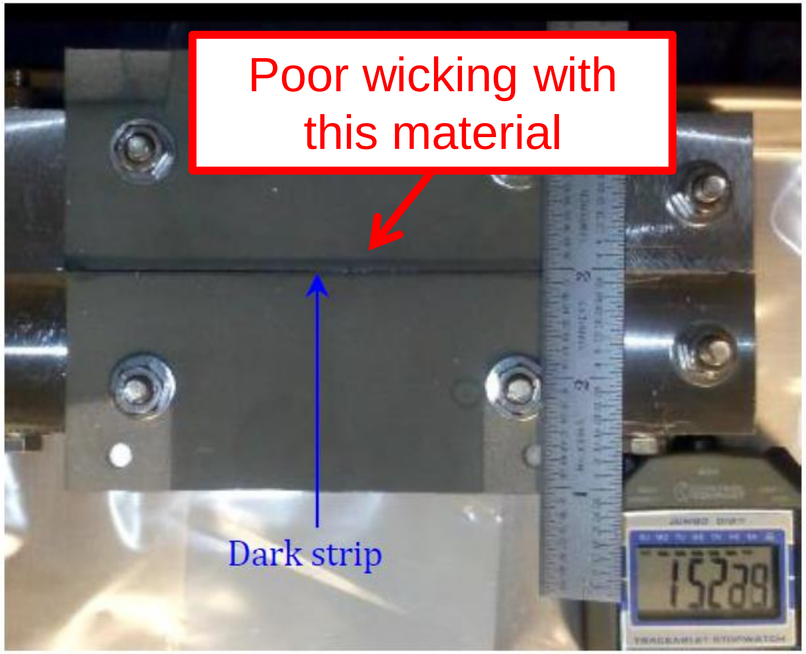
P. Rindt, TU/Eindhoven Thesis Project

Preliminary tests indicate basic concept is feasible

- Prototype testing used isopropyl alcohol as surrogate

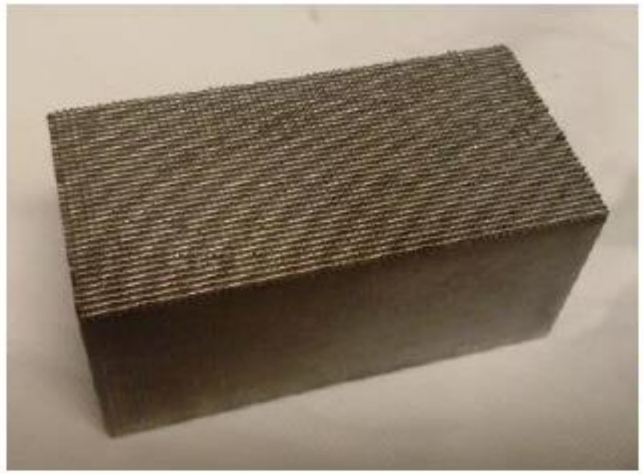
- Initial tests demonstrated wicking to surface and feasibility to empty reservoir via surface wick

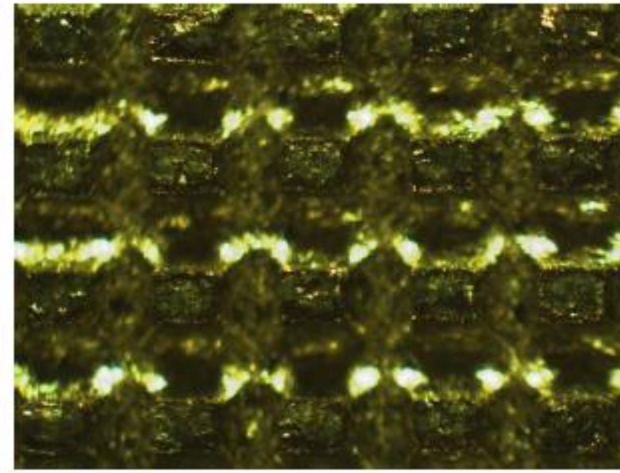
- Effectiveness highly dependent on surface capillary structure and texturing

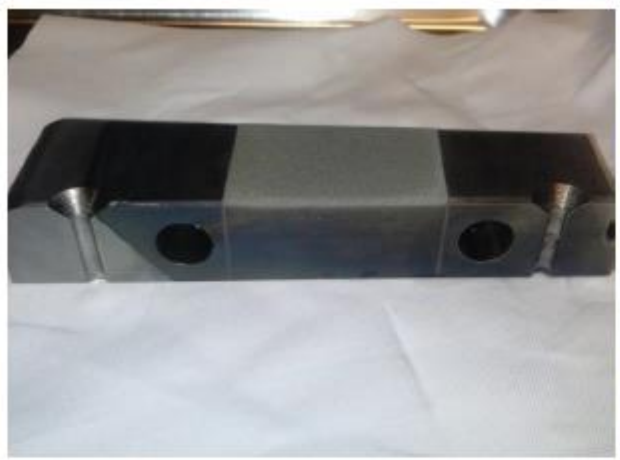


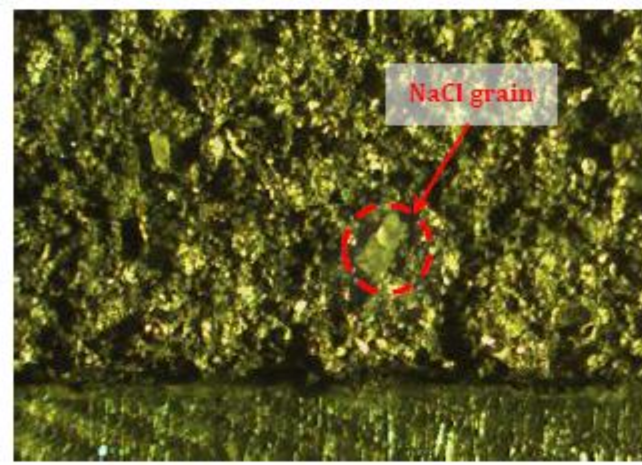
Multiple surface treatments tested for enhancement of wicking and flow (1)

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



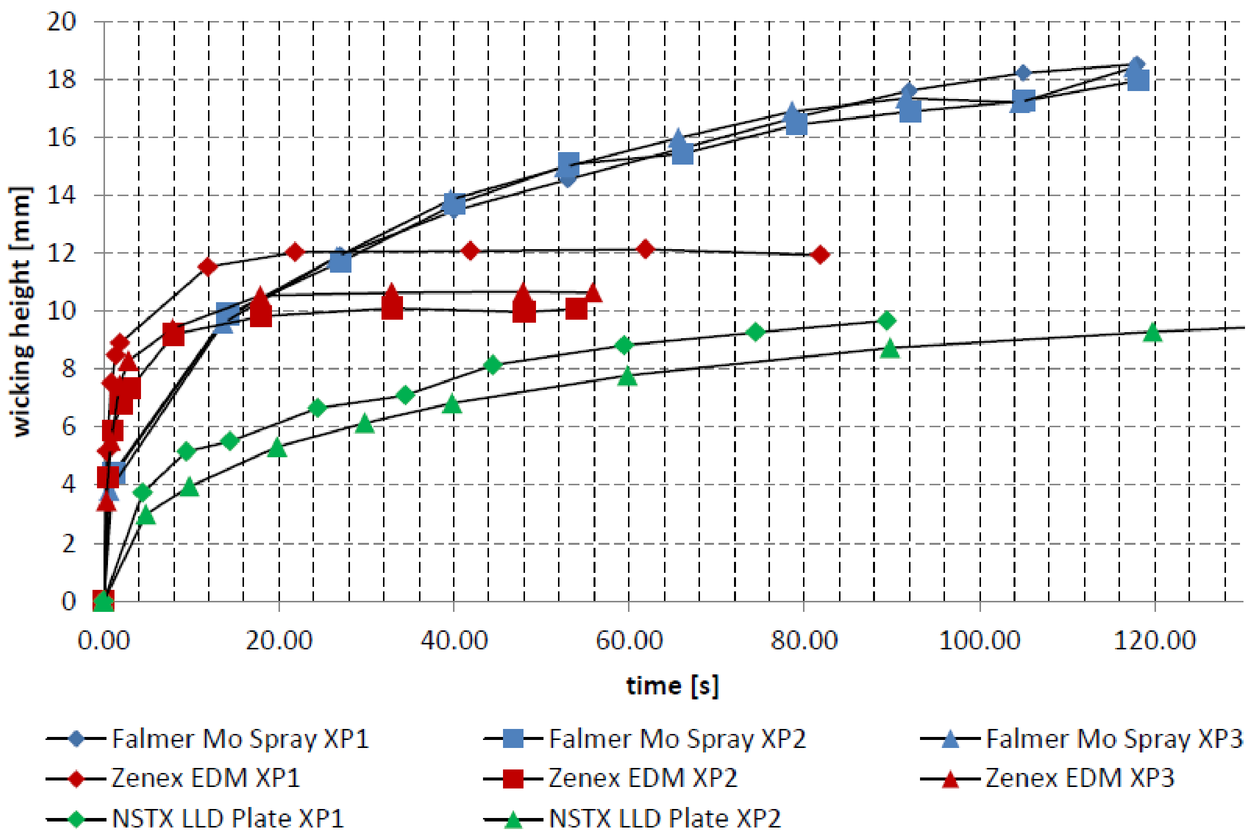






Multiple surface treatments tested for enhancement of wicking and flow (2)

- 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)



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