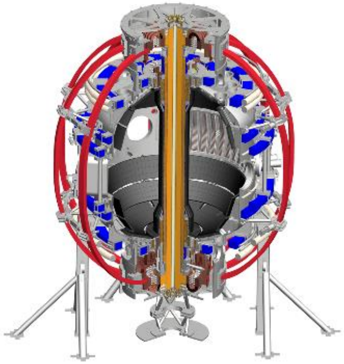
Overview of NSTX-U plans for high-Z and liquid lithium plasma-facing components

MA Jaworski[1], M.L. Reinke[2], V. Soukhanovskii[3], A. Brooks[1], R. Kaita[1], R. Maingi[1], J. Menard[1], M. Ono[1], C. Skinner[1], K. Tresemer[1], and the NSTX-U Team

[1]Princeton Plasma Physics Laboratory
[2]Oak Ridge National Laboratory
[3]Lawrence Livermore National Laboratory

37th NSTX-U Program Advisory Committee Meeting
Princeton Plasma Physics Laboratory
26-28th, January 2016



Outline

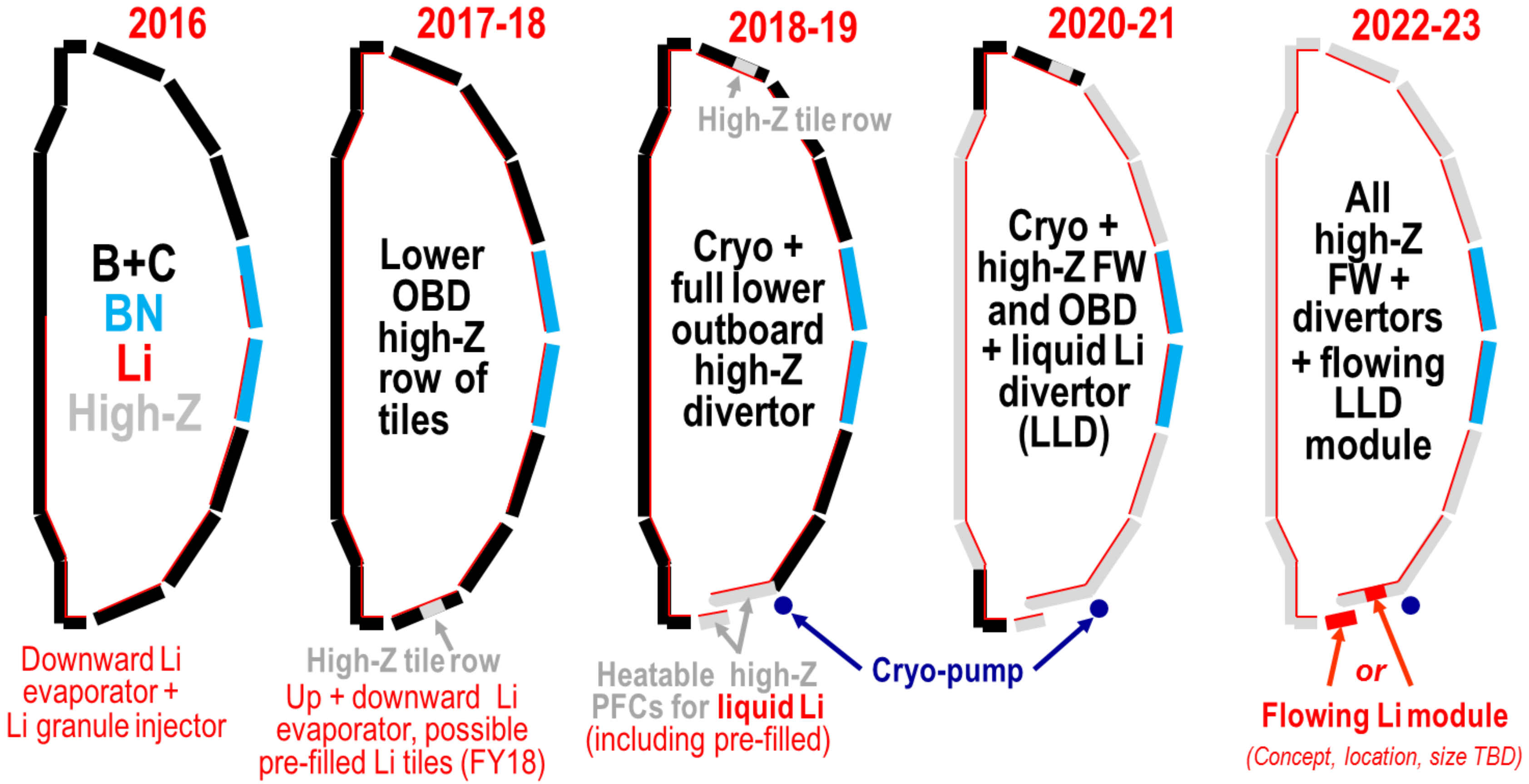
- Why must NSTX-U change its PFCs?
- How will the PFC modification be conducted while maintaining scientific productivity?
- Are we technically ready to move toward liquid lithium PFCs?
- Are we prepared to address the scientific challenges associated with the PFC changes?
- What strategies are being developed to mitigate risk?

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

- Serious attention to potential weaknesses of Li approach demands serious answers on whether liquid Li will deliver on promises
- Studies in NSTX and LTX have revealed complex chemistry in general as well as substrate dependence (i.e. C vs. metal)
- Evaporated films on graphite are not reactor relevant
- Importance of integrated scenarios *including the wall materials* recently demonstrated (i.e. JET-ILW)

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)



2016

B+C
BN
Li
High-Z

Downward Li evaporator + Li granule injector

2017-18

Lower OBD high-Z row of tiles

High-Z tile row

Up + downward Li evaporator, possible pre-filled Li tiles (FY18)

2018-19

High-Z tile row

Cryo + full lower outboard high-Z divertor

Heatable high-Z PFCs for **liquid Li** (including pre-filled)

Cryo-pump

2020-21

Cryo + high-Z FW and OBD + liquid Li divertor (LLD)

2022-23

All high-Z FW + divertors + flowing LLD module

or

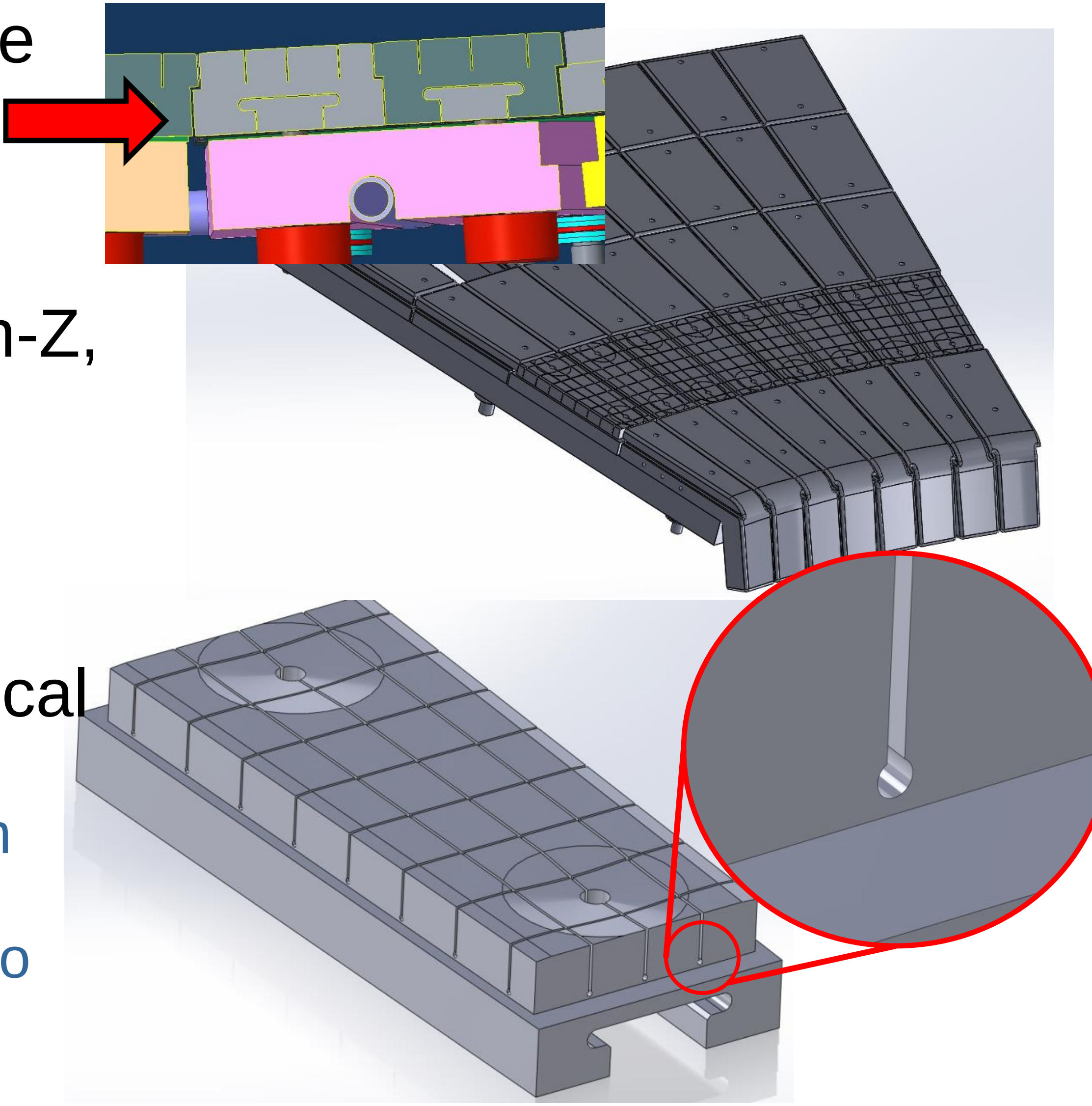
Flowing Li module

(Concept, location, size TBD)

High-Z tile row will provide design and engineering assessments

- Replace continuous row of graphite tiles with high-Z
  - Avoid Li substrate diffusion 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 deployments of metallic PFCs
- Continue experiments on evaporated Li films on high-Z substrate in diverted configuration

Rapid experiments facilitated by direct replacement of graphite tiles



- Machine installation time minimized with 1-for-1 replacement
- TZM-alloy provides high-Z, Li-compatible substrate and machinability
- Surface castellations relieve thermo-mechanical stresses
  - Separate peak stress from peak temperature
  - Several design iterations to optimize for NSTX-U tile shape

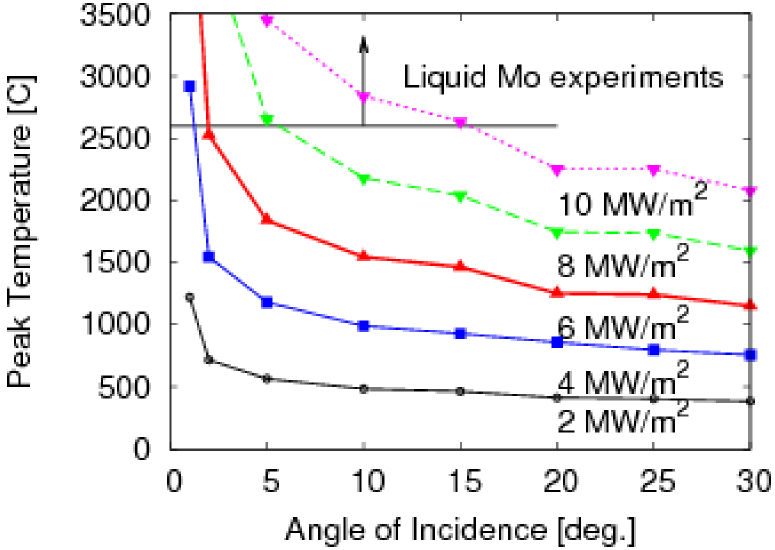
High-Z design will enable broad temperature range and power handling capabilities for experiments

- Engineering design improves over graphite

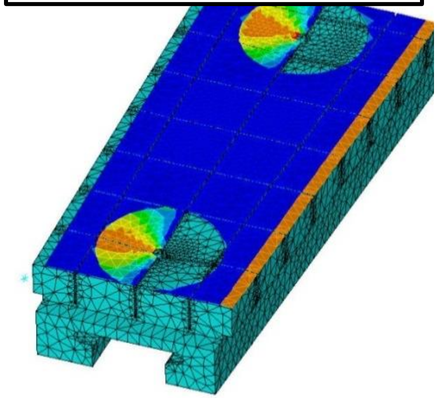
- Geometric envelope lead to optimized, but stress-limited design -> good engineering tests

- Nominal heat-flux impact factor of 10 MJ/(m^2 $s^{1/2}$) capabilities
  - Leading edges mitigated with chamfering
  - Requires careful alignment

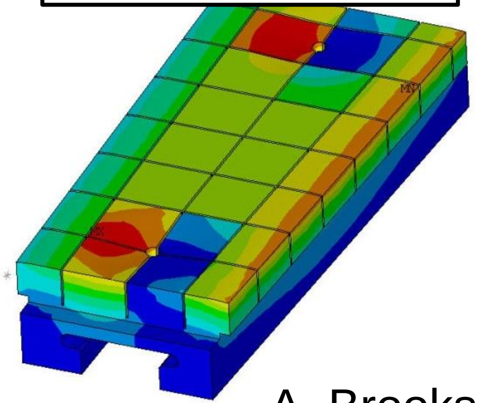
Graphite Geometry



Surface heat flux



Temperature



A. Brooks

Two options leading for low-heat flux PFCs

- Previous machines utilized coated graphite (e.g. AUG)
- **LTX** studies show improvement with very-low water partial pressures (~10^{-10} Torr)
- Coated graphite may retain H_2O reservoir while a high-Z coated metal will not
  - LLD-like construction feasible with copper base tile with bonded steel and high-Z coating
  - Alternative base metals (e.g. stainless steel) with coating or bulk high-Z also options

Near-term program milestones are emphasizing high-Z tile capability

- R(17-2): Assess high-Z divertor PFC performance and impact on operating scenarios
  - Operations, heat-flux mitigation, erosion, migration and impact on core performance to be assessed
  - XP time dedicated in FY16 (XP1526) to establish baseline performance with boronized and lithiated graphite

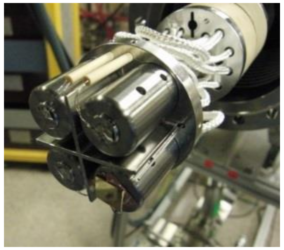
- IR(18-1) (incremental): Investigation of power and momentum balance for high-density and impurity fraction divertor operation
  - Establishes baseline assessment of dissipative divertor operation in the NSTX-U
  - Critical for establishing vapor-shielding identification and physics studies

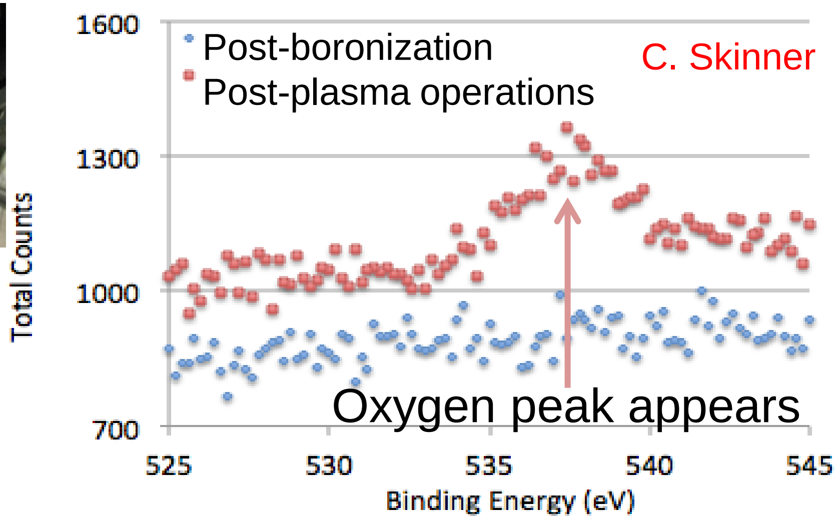
Multi-institution effort underway to deploy diagnostics and modeling

- Plasma-material interaction science, material migration and surface science studies
- Divertor and edge transport studies
- Core transport studies

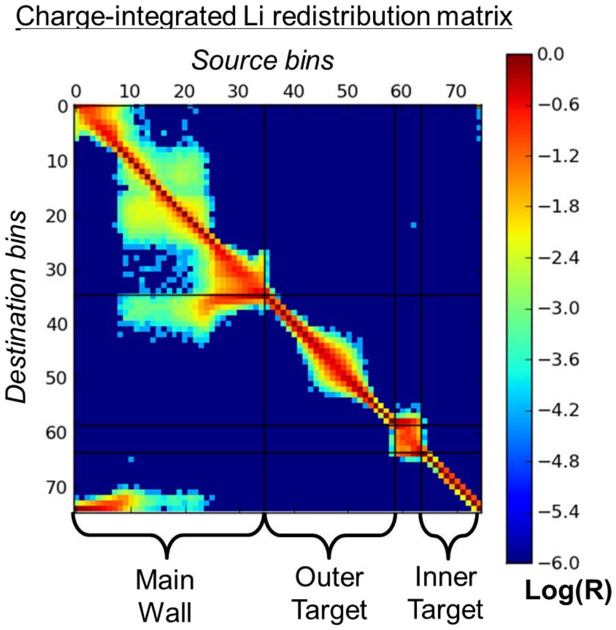
High-Z progression highlights mixed-material PMI and coordinated lab studies

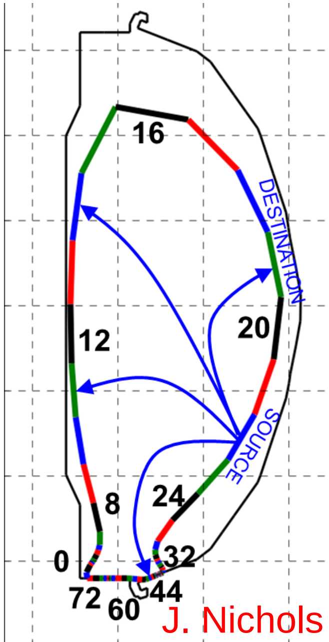
- Material Analysis and Particle Probe enables compositional analysis
  - Measurements of C, Li, Mo, B, O via XPS
  - D retention via TPD





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

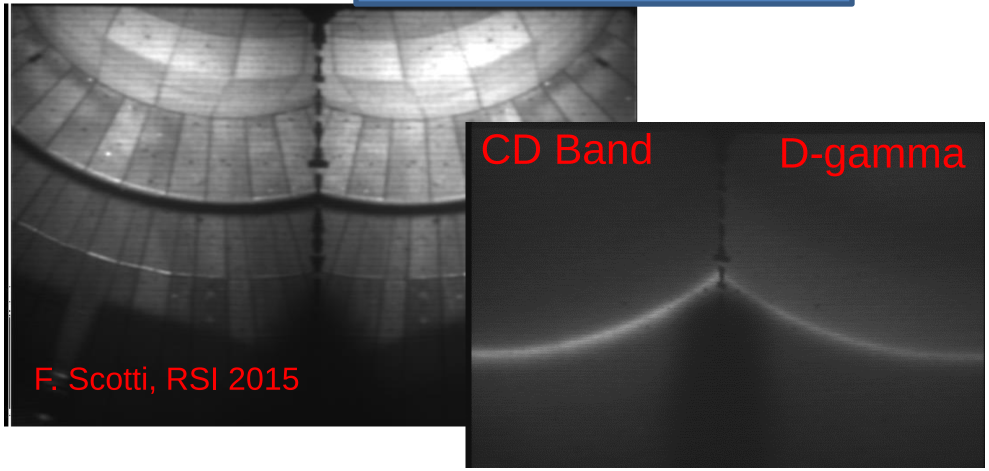




J. Nichols

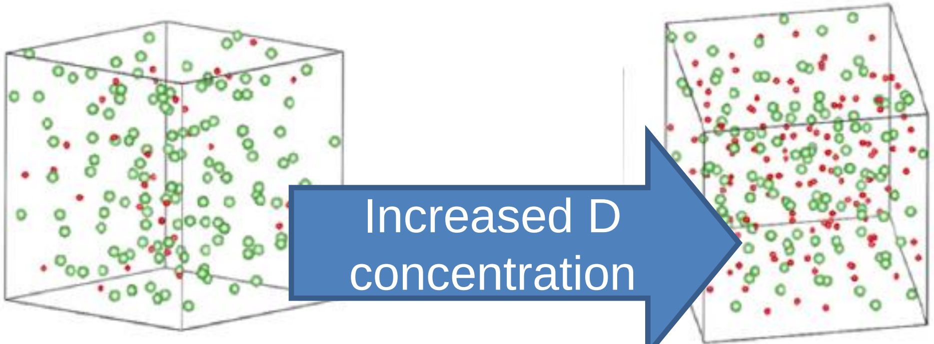
High-Z, mixed-material erosion examined in experiment and with quantum modeling

- Extensive diagnosis of PFCs via plasma
  - Multiple imaging systems, spectrometers
  - Langmuir probes
  - Infrared thermography
- Atomic scale quantum modeling of lithium mixed-material (Li+D on TZM)
  - Examined LiD “rock-salt” formation in liquid lithium
  - Results coupled into analysis of Magnum-PSI experiment on TZM(Abrams, NF 2016)



2-color simultaneous imaging

F. Scotti, RSI 2015



Increased D concentration

(e)
β=0.25, T=570 K

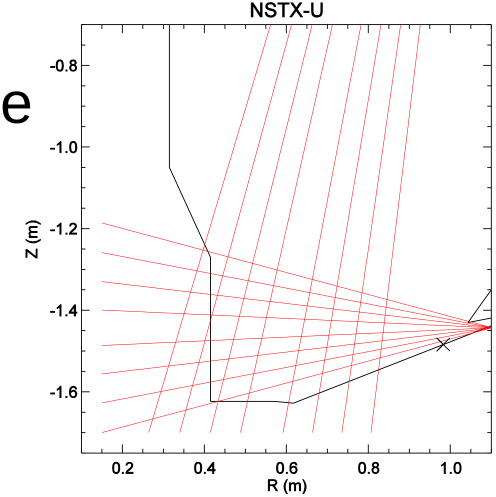
(h)
β=1.00, T=943 K

$\beta = N_D/N_{Li}$

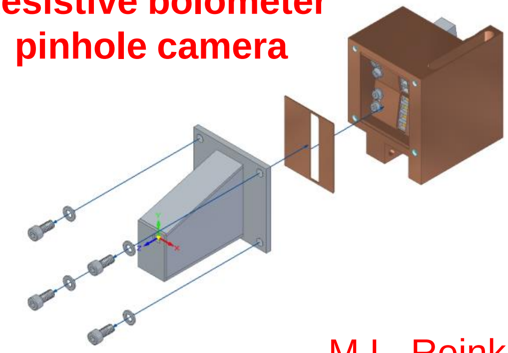
Chen, NF 2016

Impact of low-Z and high-Z operations on divertor assessed via spectroscopy and bolometry

- Near-surface prompt redeposition modifies effective material yield into plasma
  - Auburn U. group providing ADAS simulation & support
  - LLNL measurement via 2-color intensified imaging

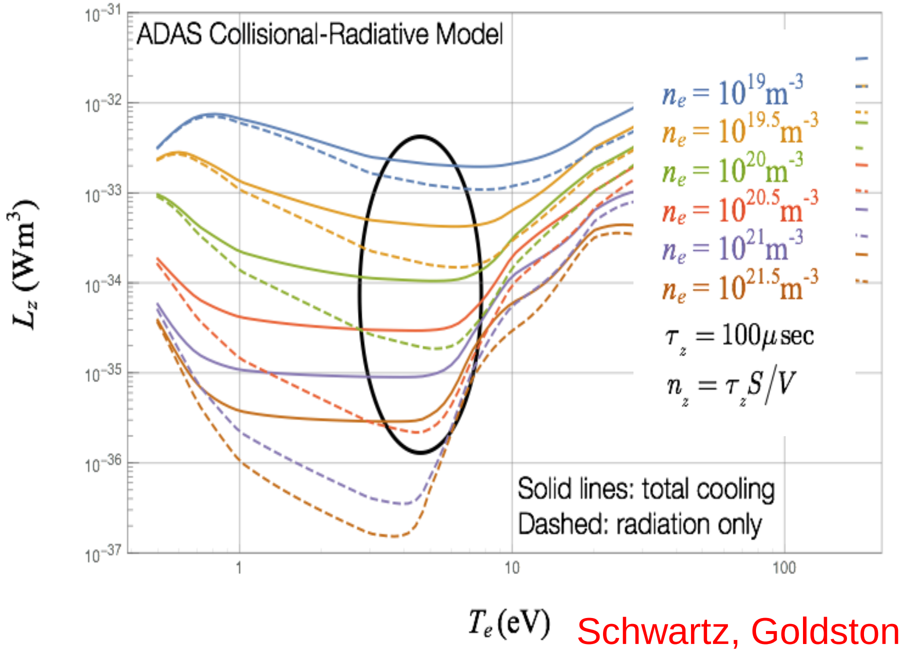


Resistive bolometer pinhole camera



M.L. Reinke

- Radiative power measurements critical to science goals
  - New bolometric measurements via video and resistive foil bolometers (ORNL+PPPL+DIFFER+NIFS)
  - Visible imaging and spectroscopy provide species identification and localization
  - Comparison with numerous codes in NSTX-U Team (UEDGE, SOLPS, OEDGE) and ADAS coll-rad models

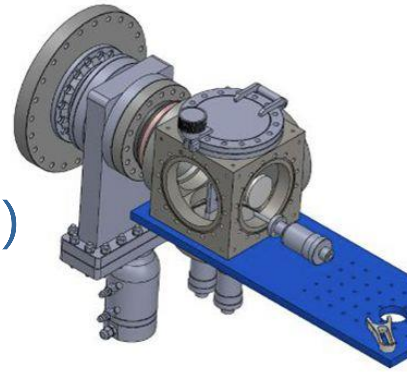


Schwartz, Goldston

Core transport toolset of diagnostics and actuators in development

- VUV/SXR spectroscopy to track core high-Z contamination
  - MONA-LISA, XEUS, LoWEUS (demonstrated w/ Mo in C-Mod)
  - X-ray crystal spectrometer(future)
- New full-midplane core resistive bolometer system
- Actuators enable physics and control experiments
  - **Investigate neoclassical + turbulent + MHD driven transport in low-A device**
  - LBO and high-Z noble gas injection provide controlled sources
  - Core/edge control from ELMs (LGI, 3D fields) and on-axis RF

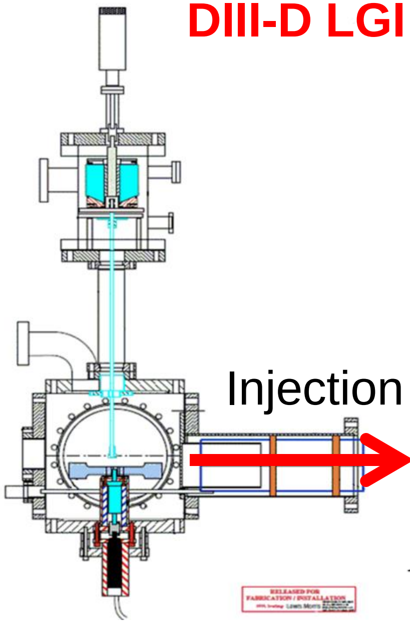
Laser Blow-Off target chamber

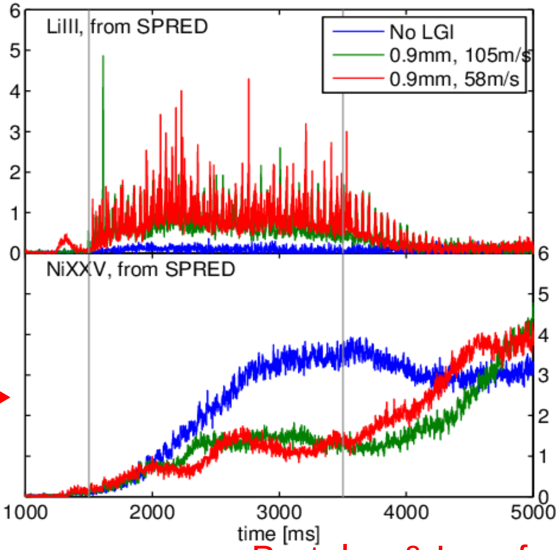


LLNL Core Spectroscopy

M. Weller

DIII-D LGI experiments





Bortolon & Lunsford

Preparation for all high-Z PFC operation will enable future liquid Li comparison experiments

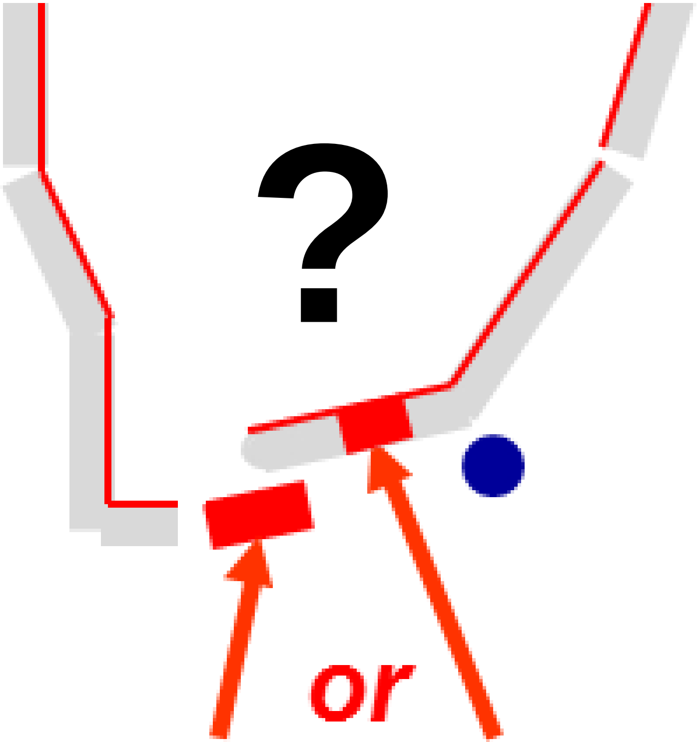
- Numerous examples from world program demonstrate importance of scenario impact with high-Z PFCs
  - Constrained operating windows
  - Modified performance (e.g. confinement)

- Power exhaust solutions in development
  - Advanced divertor configurations (e.g. snowflake, X-div)
  - Extrinsic impurity seeding for radiative divertor

- Wall conditioning techniques (i.e. B & Li coatings) mitigate risk to broader science program

- Experience of operating with high-Z will feed back into world machine knowledge base

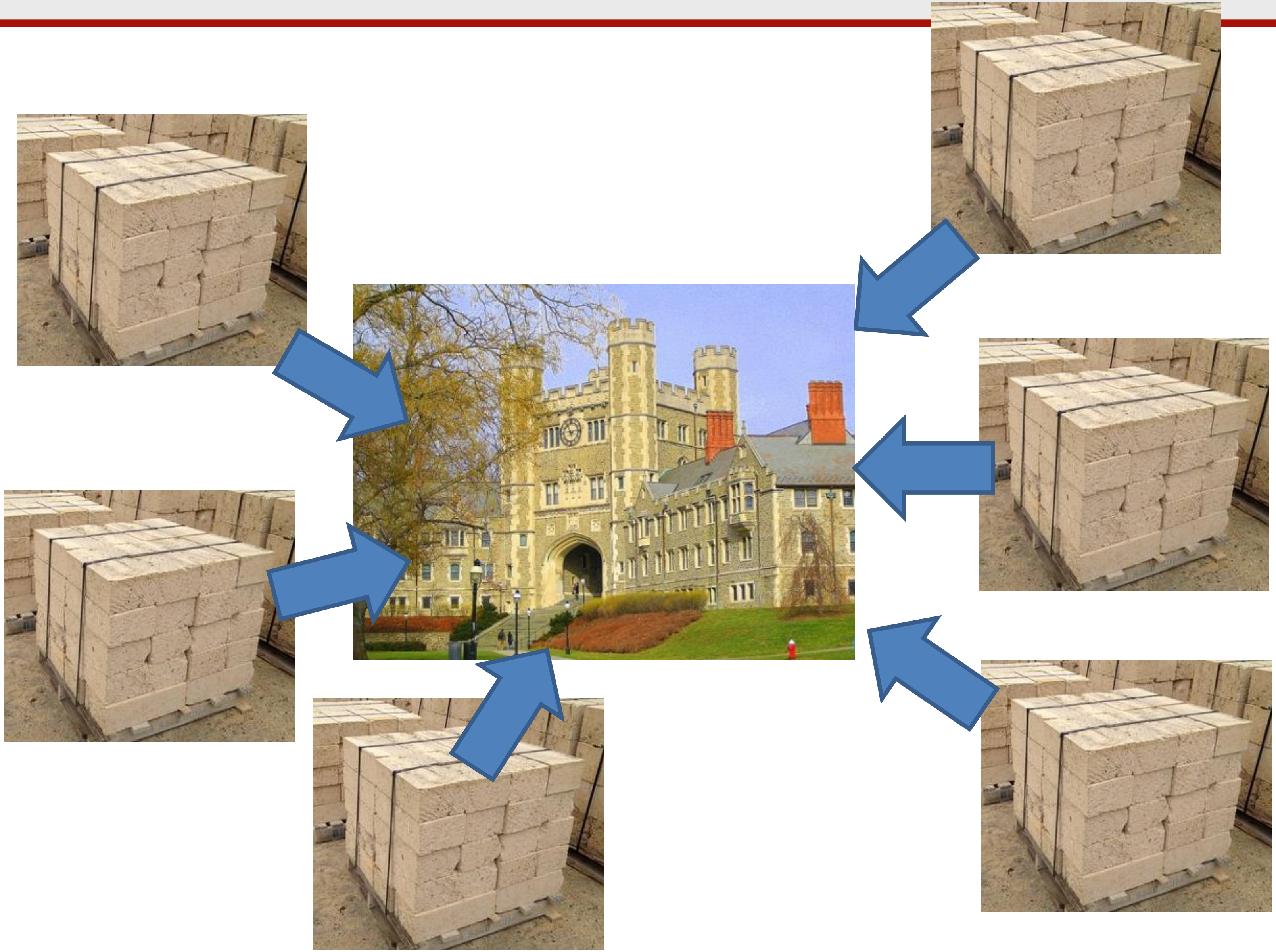
Research and development for flowing liquid lithium modules



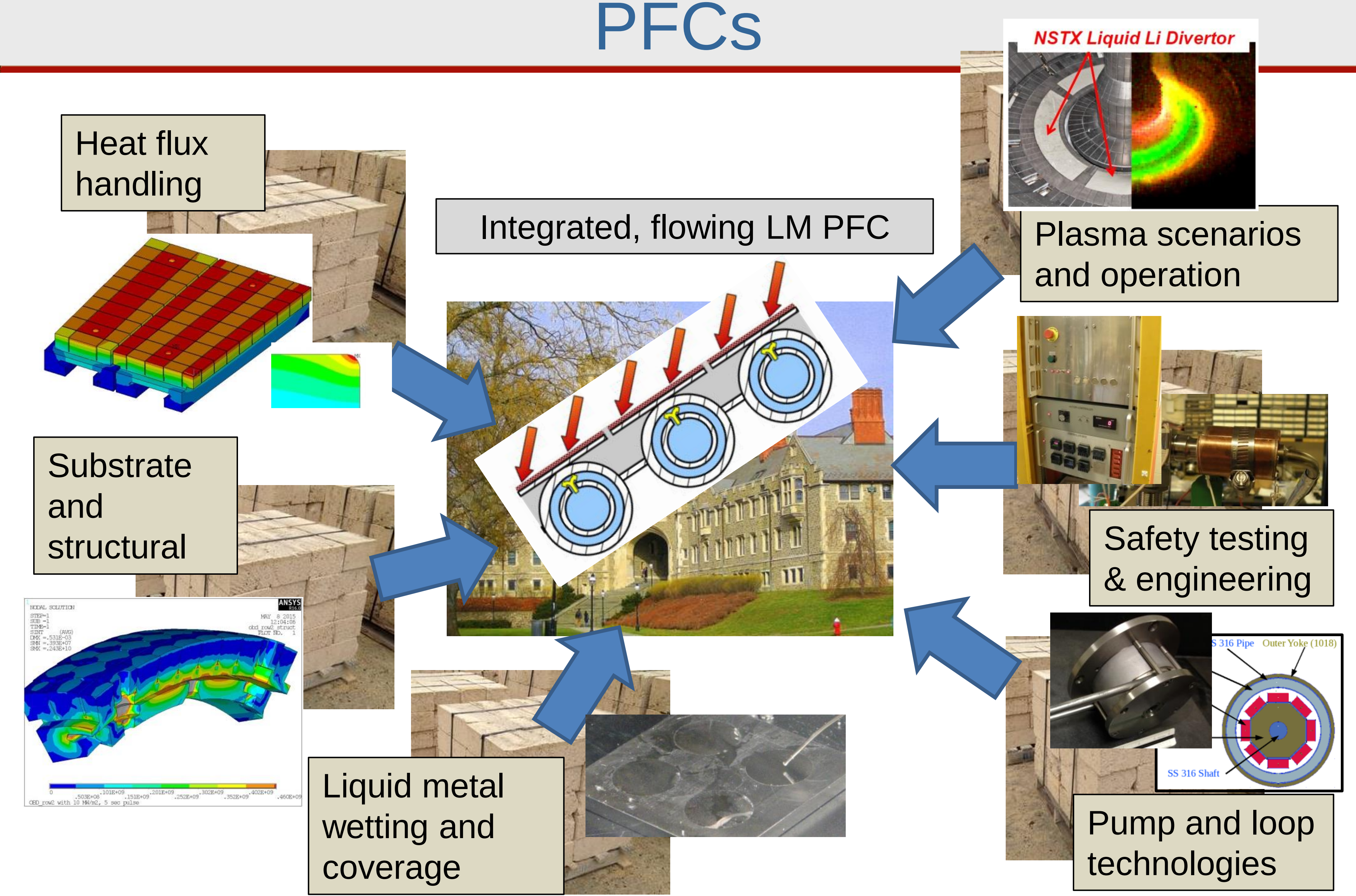
Flowing Li module

(Concept, location, size TBD)

Multiple required elements complex projects



Required elements for flowing, liquid metal PFCs



Heat flux handling

Integrated, flowing LM PFC

Plasma scenarios and operation

Substrate and structural

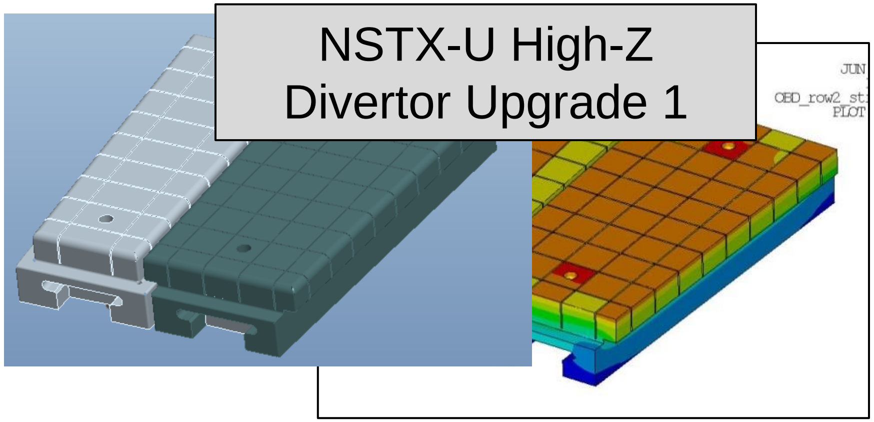
Safety testing & engineering

Liquid metal wetting and coverage

Pump and loop technologies

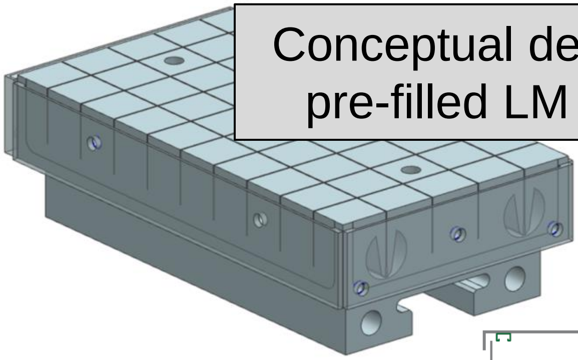
A three-step progression can accelerate tests of flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER



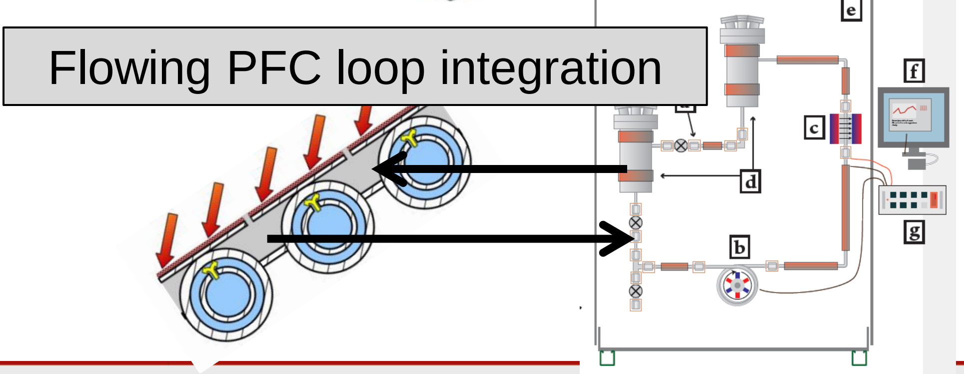
NSTX-U High-Z Divertor Upgrade 1

2. Pre-filled liquid-metal target



Conceptual design for pre-filled LM target

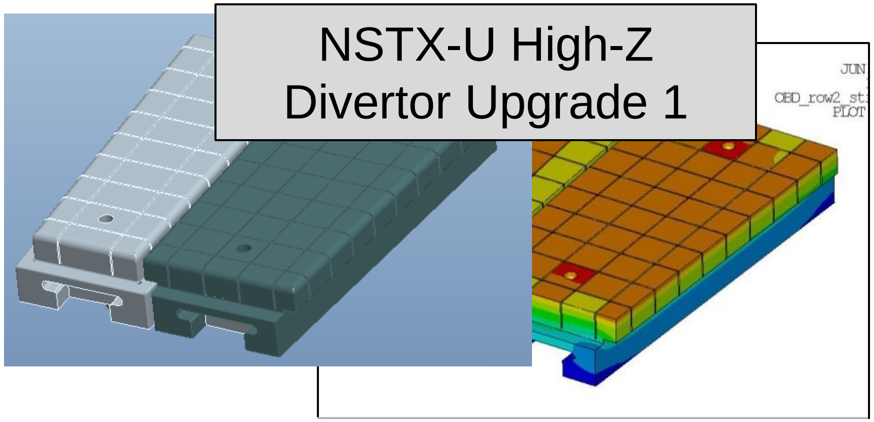
3. Flowing LM PFC



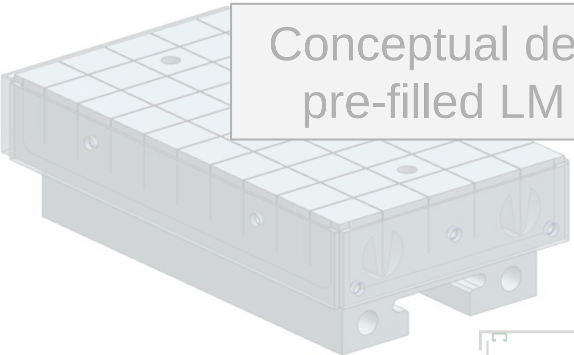
Flowing PFC loop integration

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

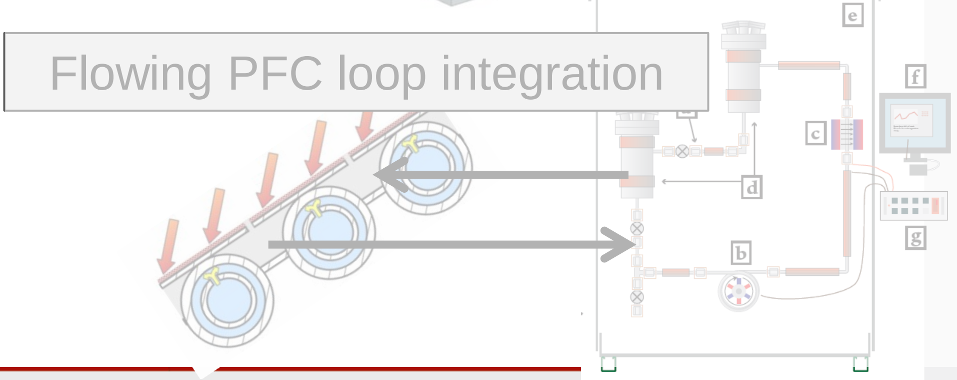
1. High-Z divertor tiles + LITER
   - Technical goals:
     - Establish non-intercalating substrate for evaporated Li
     - Provide high-heat flux substrate for Li experiments
   - Scientific goals:
     - Quantify maintenance of Li on high-temperature substrate and protection of substrate
     - Re-examine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



NSTX-U High-Z Divertor Upgrade 1



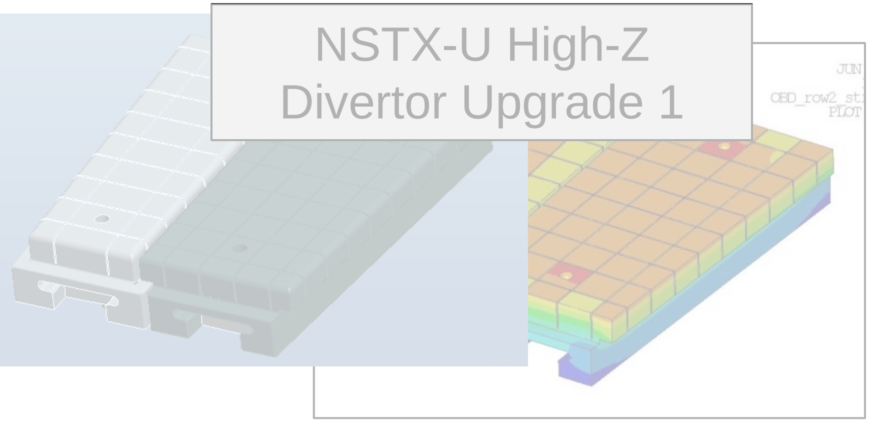
Conceptual design for pre-filled LM target

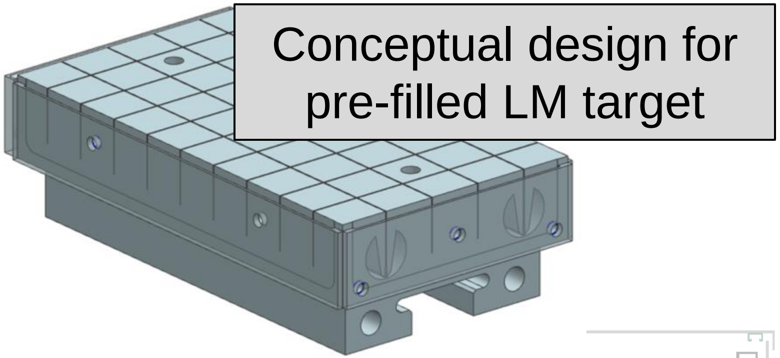


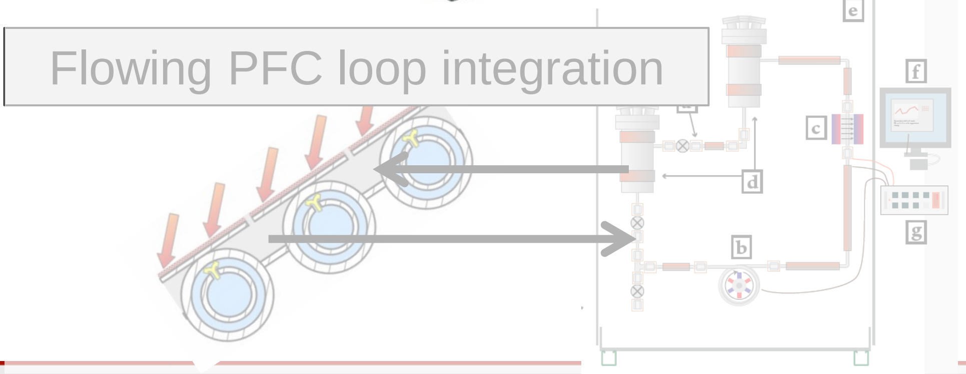
Flowing PFC loop integration

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 high-temp. target with **larger** inventory of Li


NSTX-U High-Z Divertor Upgrade 1

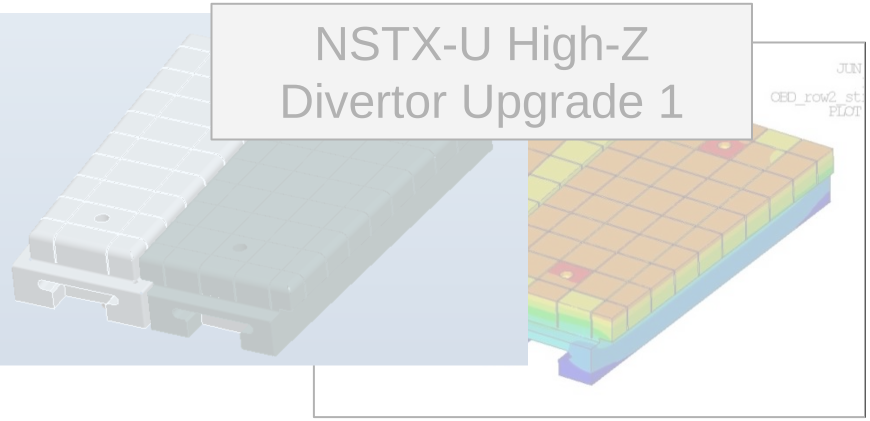

Conceptual design for pre-filled LM target


Flowing PFC loop integration

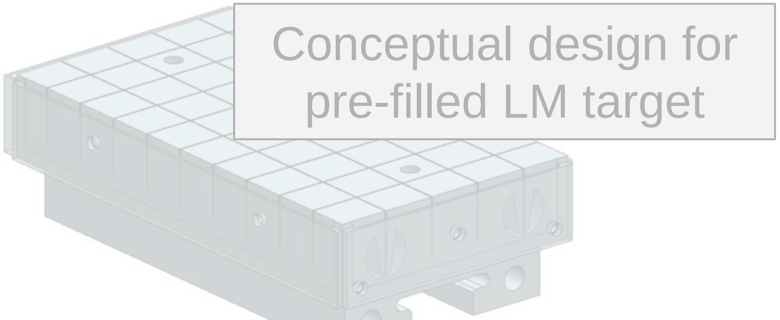
Final integration demonstrates LM introduction/extraction and inventory control

3. Flowing LM PFC

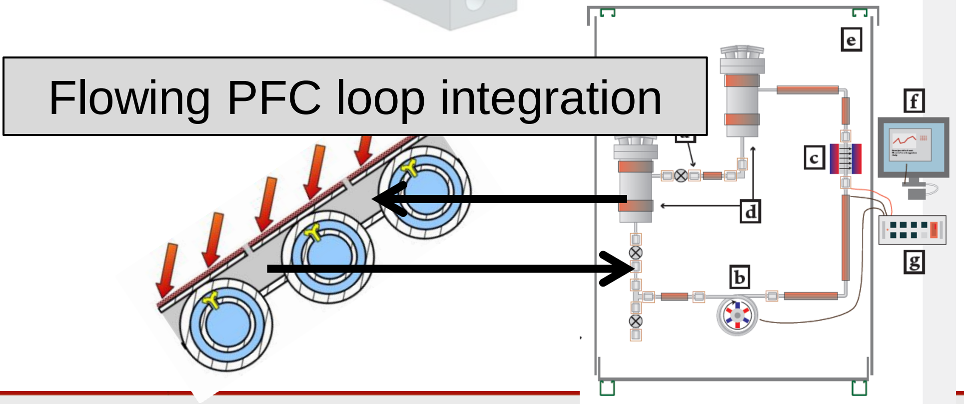
- Technical goals:
  - Integrate parallel effort on loop technology with confinement experiment
  - Achieve active introduction and extraction from exp.
- Scientific goals:
  - Assess material inventory control from LM target
  - Understand performance of passive + active replenishment techniques
  - Understand impact and core-edge compatibility of <u>high-temp. target</u>



NSTX-U High-Z Divertor Upgrade 1



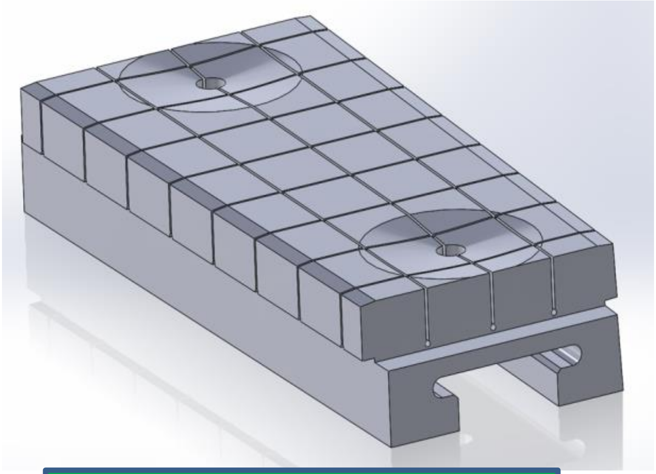
Conceptual design for pre-filled LM target



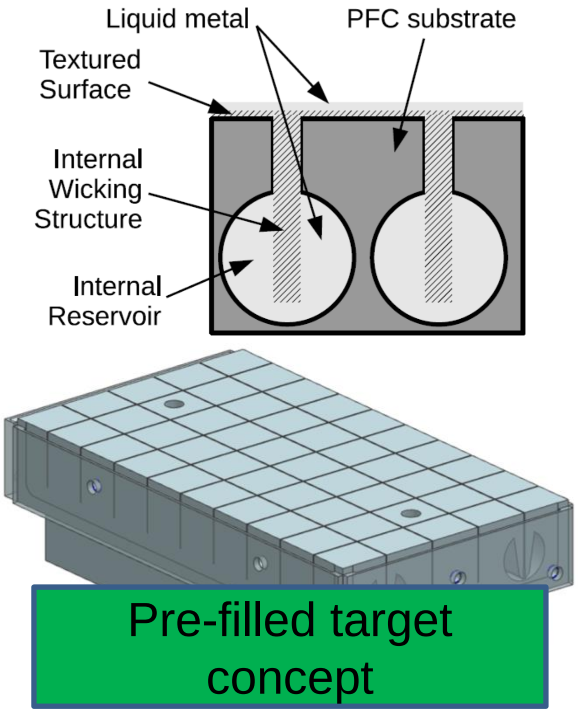
Flowing PFC loop integration

Most mature technologies emphasized for current development path

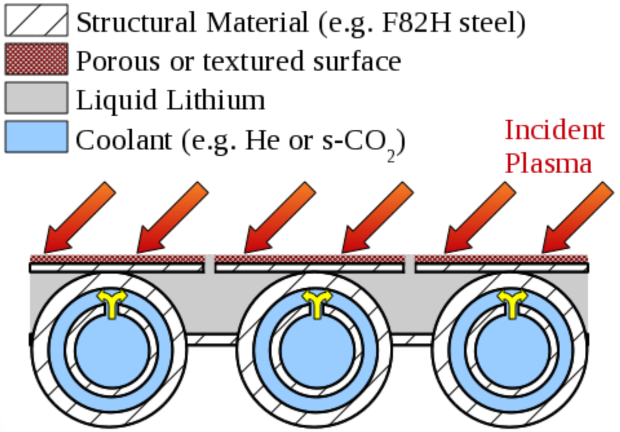
- Capillary-restrained PFCs demonstrated in numerous machines – nearest technology
- Pre-filled targets build on high-Z substrate design (see backup)
- External Li feed into reservoir region with inertial cooling provides nearest target technology for NSTX-U



High-Z PFC design



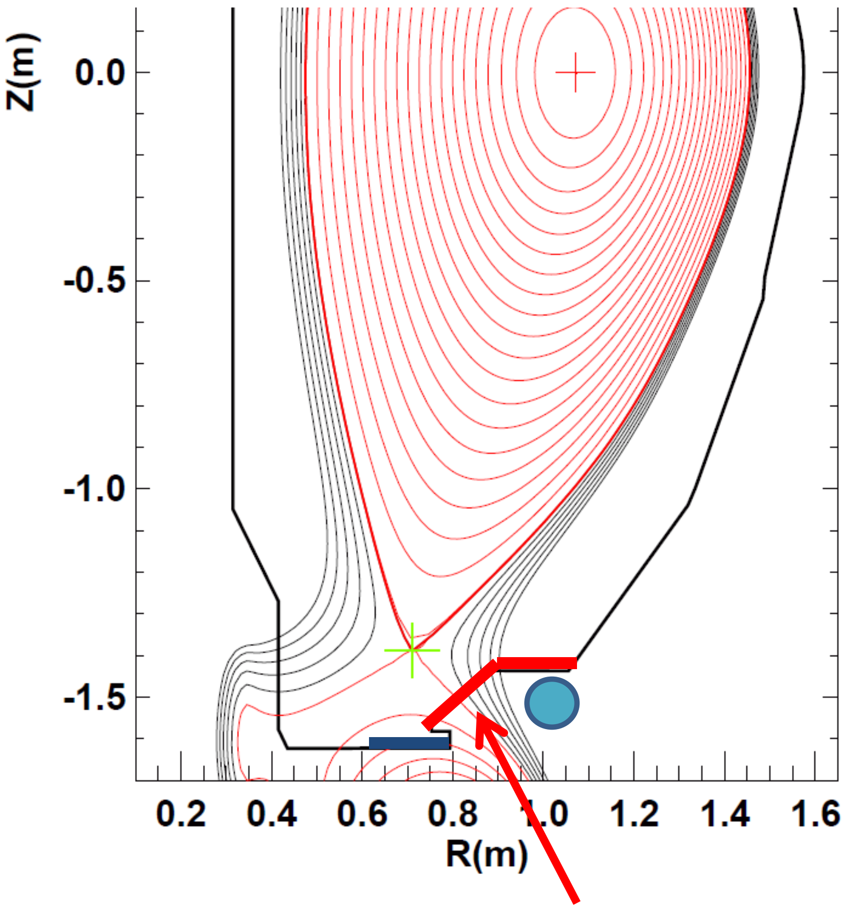
Pre-filled target concept



DEMO-relevant PFC concept

Cryo-pump design requirements being refined to accommodate liquid-metal PFCs

- Design requirements for cryo-pump PFCs and divertor currently being developed
- Current plan is for significant usage of high-Z material for PFCs
  - Upper bullnose and plenum currently specified as high-Z
  - Lower bullnose material TBD
- Heating of PFCs to 350C during operations will enable liquid metal flow between discharges



Heatable cryo-pump PFCs to 350C ***during operations***

Summary

- Completion of NSTX-U mission element for comparative assessment of high-Z and low-Z liquid PFCs requires high-Z and liquid metal PFC development

- Scientific productivity will be maintained by gradual and targeted change-over of PFCs

- Staged approach addresses technical readiness by providing incremental R&D path and decision points for push to near-term liquid metal target PFCs

- Scientific questions will be addressed with mix of diagnostic, modeling and control tools ranging from PFC to core

- Strategy in place to mitigate operations risks associated with PFC upgrades
  - High-Z risks mitigated by cognizance of worldwide experience with high-Z and continued wall conditioning program

  - Liquid Li PFC risks assessed by broad off-line research and development program including off-line experiments, surface science experiments and linear plasma device testing

Thank you for your attention!

Questions?

Backup slides content overview

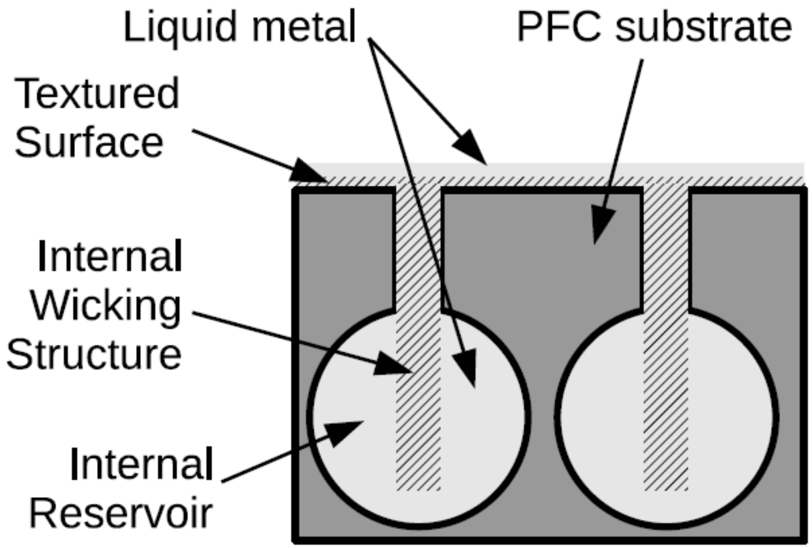
- Slide 28: Technical aspects of pre-filled liquid metal target R&D
- Slide 39: Liquid metal PFC potential benefits
- Slide 47: Recent research results and surface science aspects of liquid metal PMI
- Slide 58: Further technical aspects of high-Z divertor target upgrade development
- Slide 73: Additional LLNL & ORNL diagnostic details

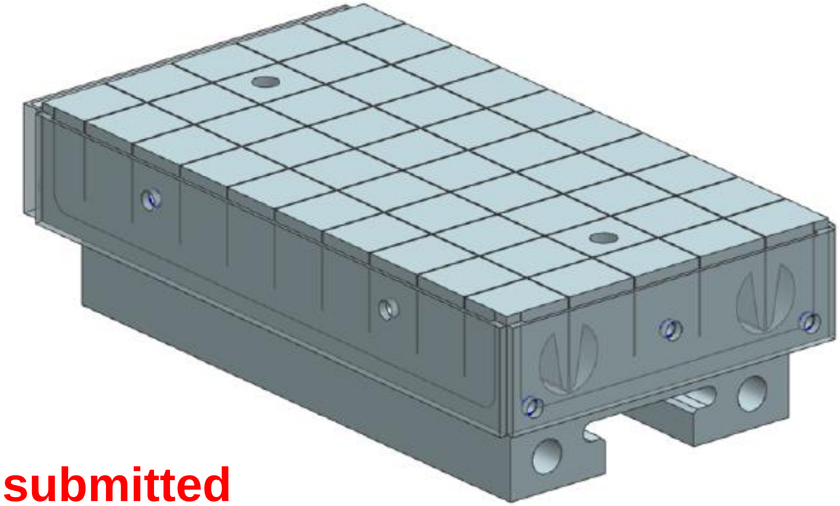
Technical aspects of pre-filled liquid metal targets R&D

- Concept overview
- Prototype testing and initial surface testing and evaluation
- Porous-MHD equations
- R&D plan including summer collaboration experiments

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

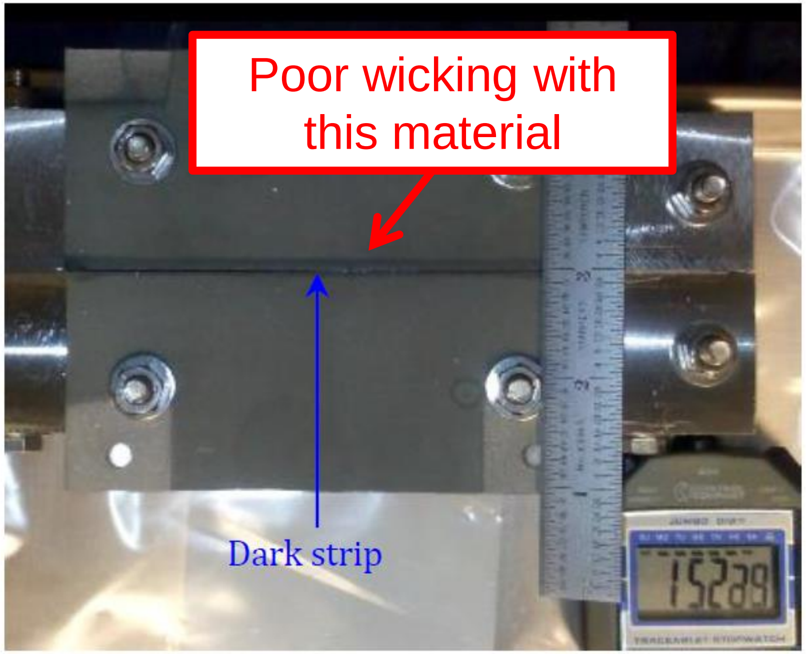




P. Rindt, TU/Eindhoven Thesis, Jaworski FED submitted

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

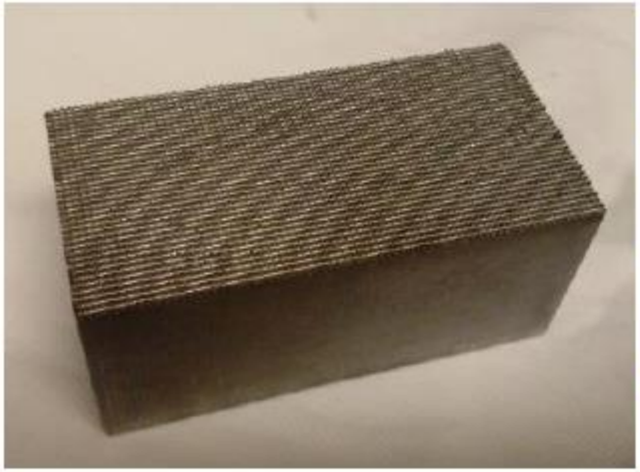
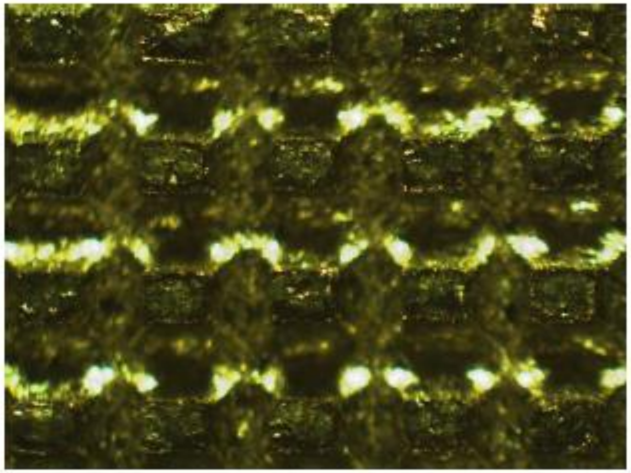
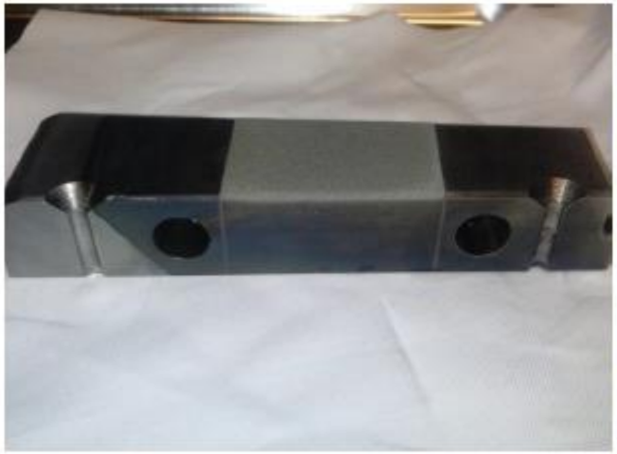
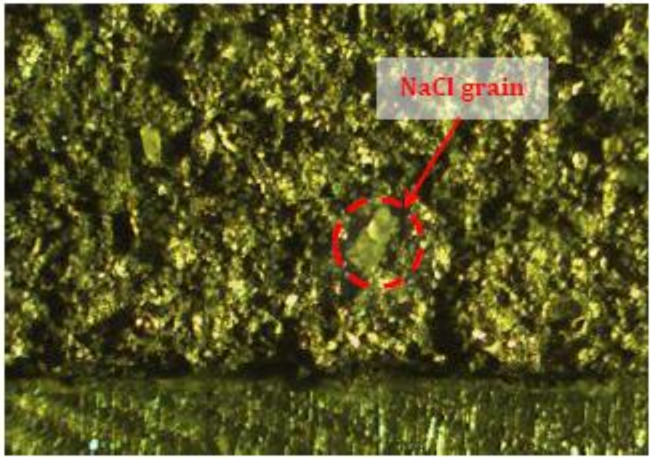


Poor wicking with this material

Improved wicking with better material

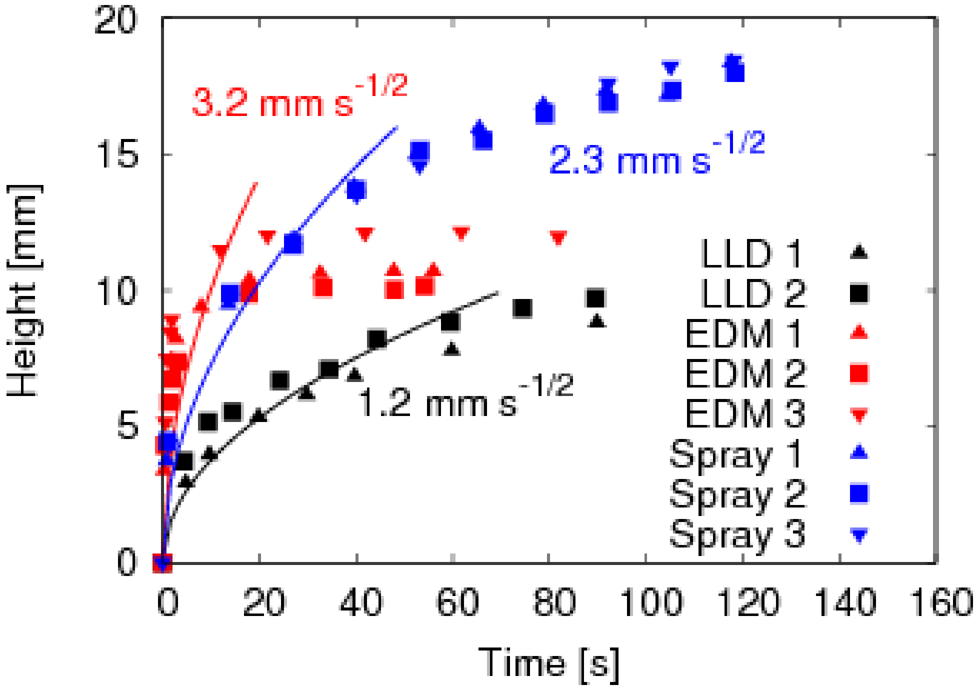
Multiple surface treatments tested for enhancement of wicking and flow (1)

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

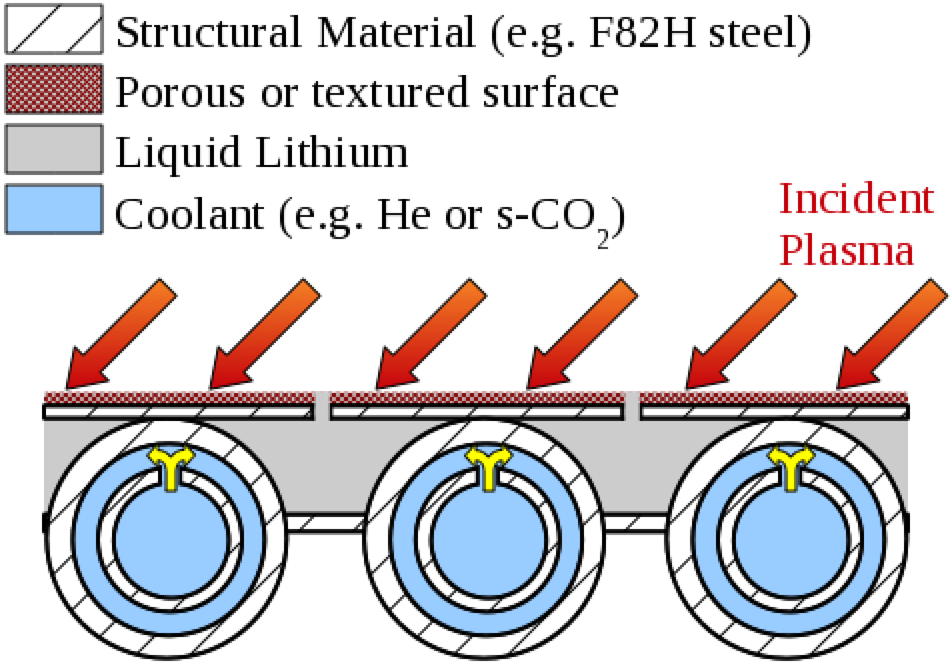
Multiple surface treatments tested for enhancement of wicking and flow (2)

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



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

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



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

Jaworski, PPCF 2013

Pre-filled target research and development plan snap-shot

- Multi-institution collaboration to address practical and scientific questions
  - US partners: JP Allain, DN Ruzic (UIUC)
  - International: P Rindt, N Lopes-Cardozo (TU/Eindhoven), TW Morgan (FOM-DIFFER)

- Wetting and handling tests to be conducted on candidate surface materials in the Netherlands, Illinois and PPPL

- Heat flux testing of pre-filled targets proposed as part of thesis work at Magnum-PSI (P. Rindt, Fall 2016 restart of device)

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

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

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

Overview of proposed experimental studies at UIUC

- Development and testing viability of nanoscale, removable films (leverage low-temperature, controlled plasma processing equipment)
- ELM-like heat pulse survival and recovery (leverage DEVEX device)
- Characterization of Kelvin effect in porous liquid metal system, multiple substrates
- Evaluation of liquid layer thickness and coverage from passively replenished systems
- Calibration of UIUC calorimeter probes

Liquid metal PFC potential benefits

How do we assess 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

Liquid metals offer potential advantages over solid plasma-facing components (PFCs)

- Liquid metals provide a self-healing 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

JET

Arnoux, PFMC-14, Juelich

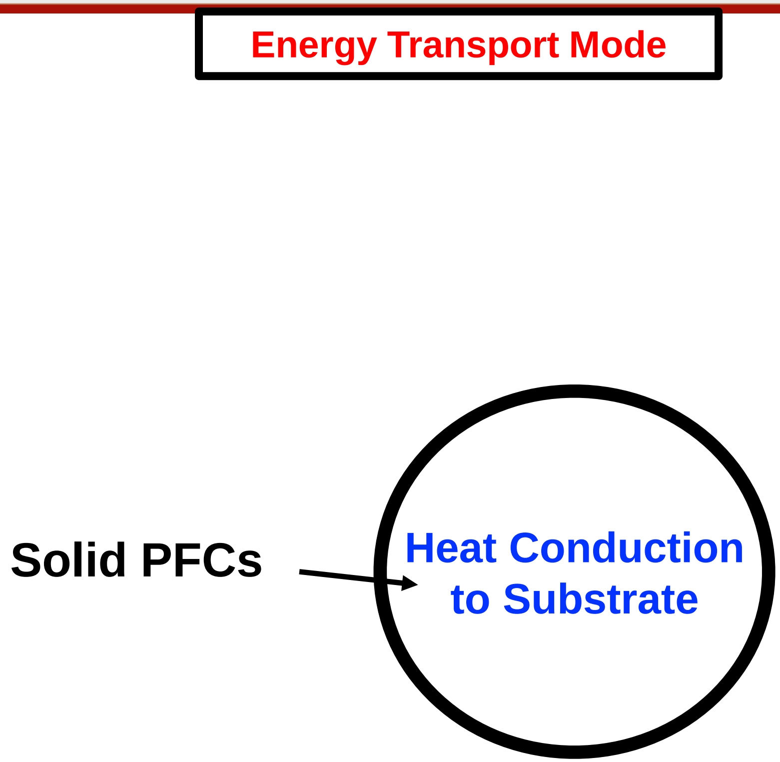
CMOD

Coenen, et al., JNM 2013

Can enhanced heat exhaust be added to this list?

NSTX-U Jaworski – Prospects for liquid lithium divertors – 26th SOFE – Austin, TX – June 1st, 2015 4

Liquid metal PFCs provide additional pathways for energy transport



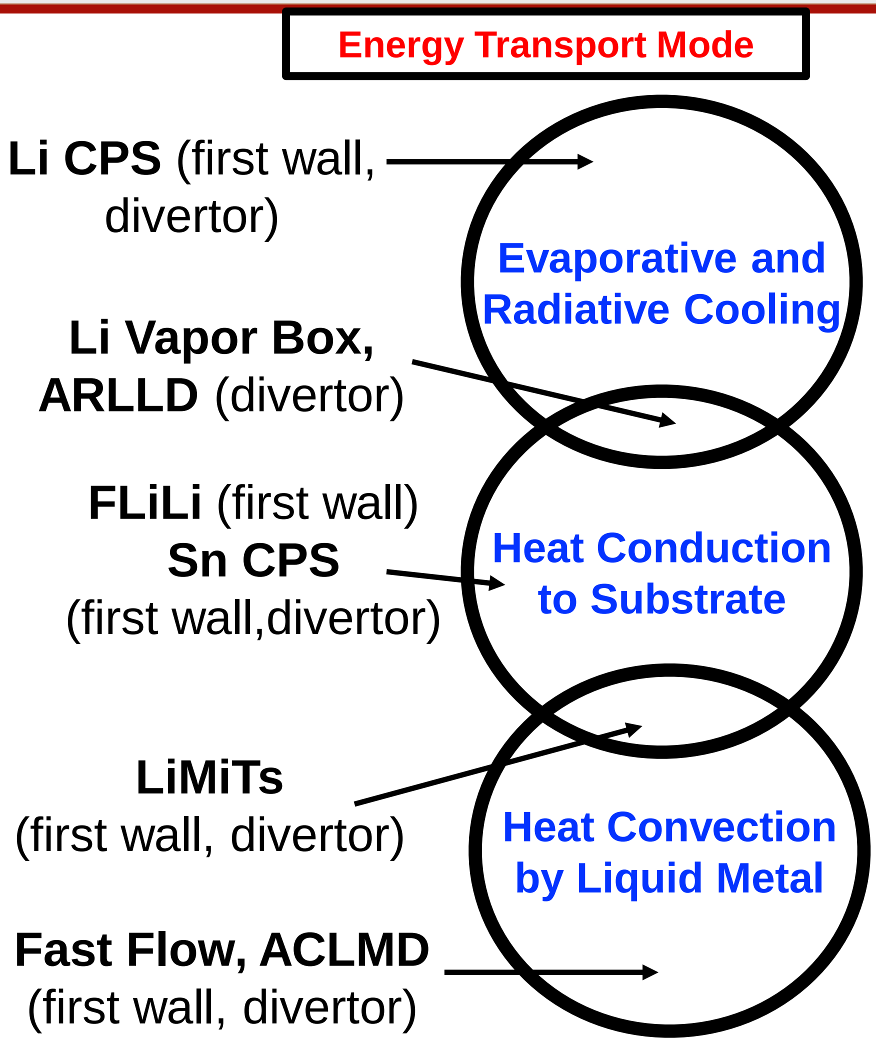
Energy Transport Mode

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)

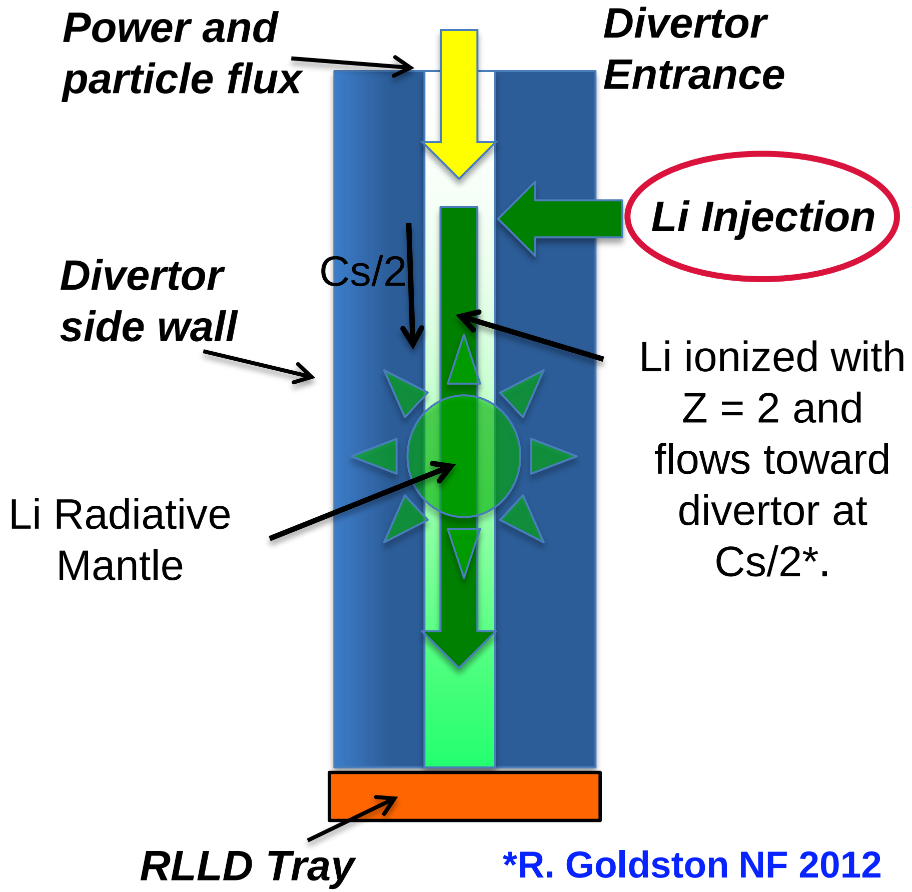
Evaporative and Radiative Cooling

Heat Conduction to Substrate

Heat Convection by Liquid Metal

- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- 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

Active Injection of LL as First Line of Defense
Li injection as needed via feed-back control



Power and particle flux

Divertor Entrance

Li Injection

Divertor side wall

Cs/2

Li ionized with Z = 2 and flows toward divertor at Cs/2*.

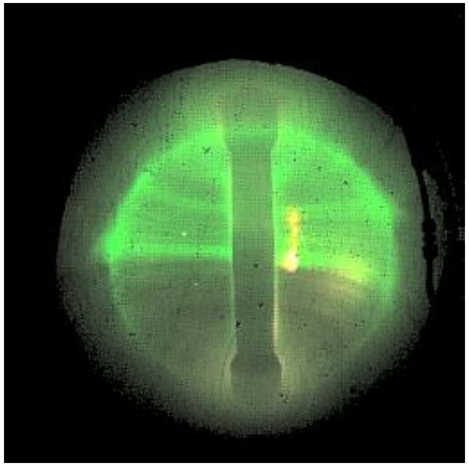
Li Radiative Mantle

RLLD Tray

***R. Goldston NF 2012**

Li granular injector on NSTX-U will provide important data on ARLLD.

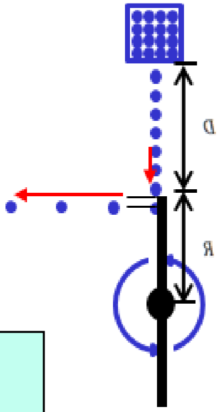
Li Aerosol in NSTX

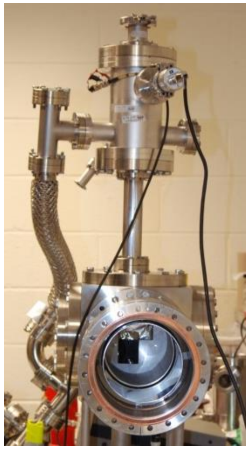


Lithium aerosol is introduced by a “droper” at the plasma edge and the ionized lithium tends to flow toward the divertor plate along the field line.

D. Mansfield FE&D 2010

Li granular injector for NSTX-U

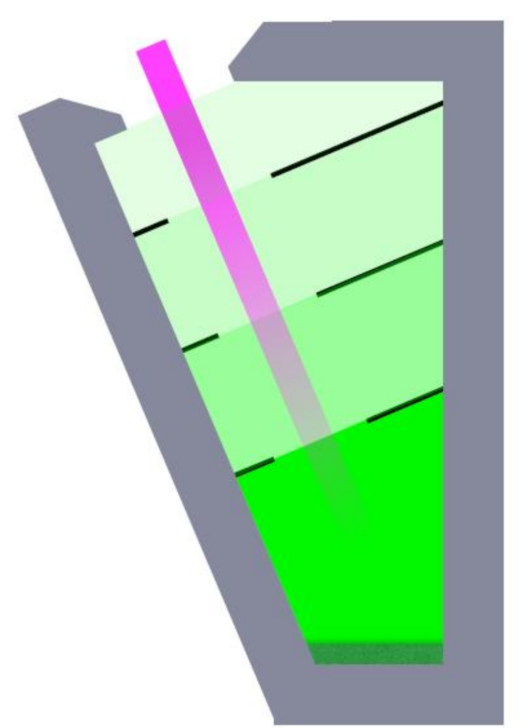


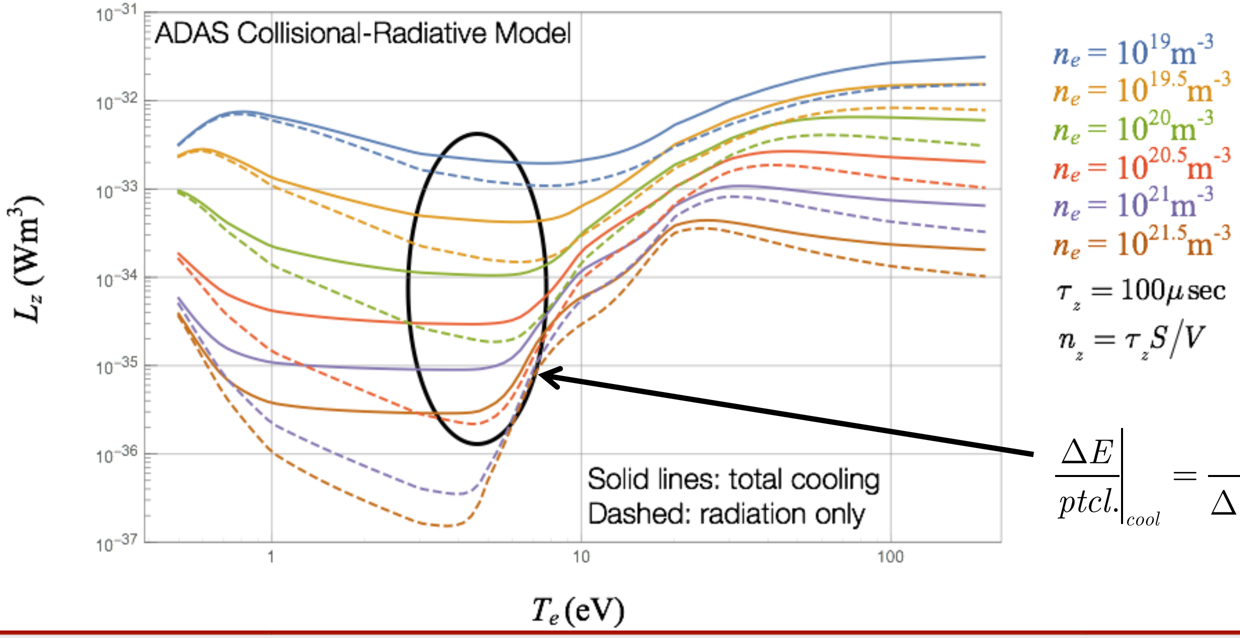


M. Ono ISLA-4 2015

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





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

Goldston, ISLA 2015

Simple Model Provides Estimate of Bottom Box Operating Point

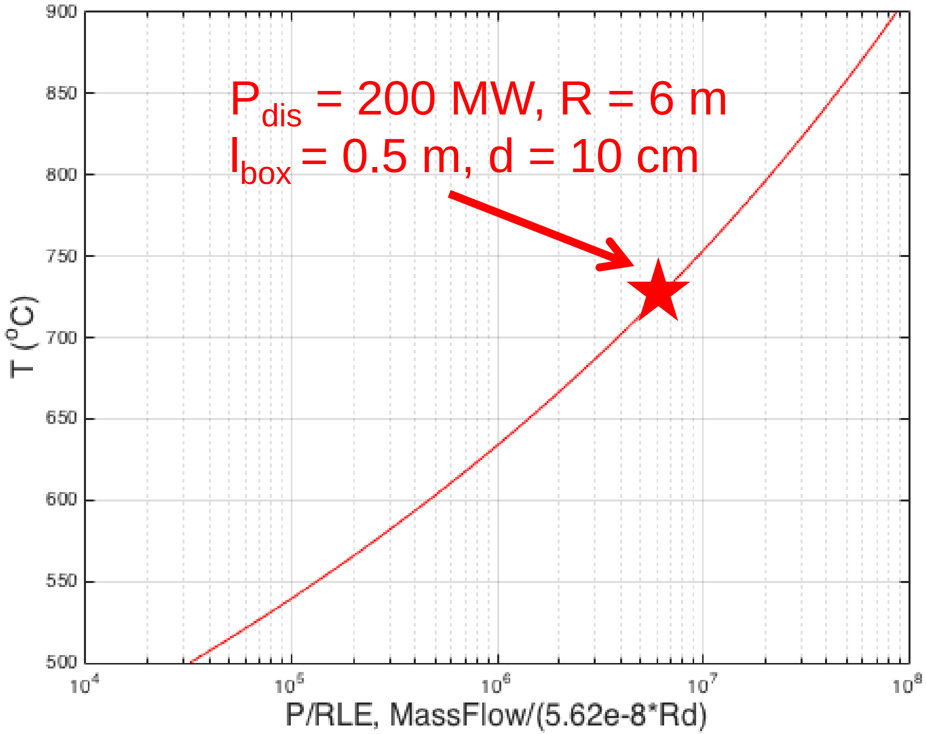
- Dissipated power estimated from
  - Langmuir flux of vapor atoms into plasma
  - Conservative E_{dis} = 10 eV energy loss per atom

- Mass efflux calculated assuming choked flow

- Reactor design point indicates only 230g/s exiting bottom box
  - Expect < 1 g/sec to reach main chamber

$$P_{\mathrm{dis}} = 4\pi R \ell_{box} E_{\mathrm{dis}} n_{\mathrm{vap}} \sqrt{T_{\mathrm{vap}} / (2\pi m)}$$

$$\frac{\dot{M}}{2\pi R d} = 0.6228 \cdot n_{\mathrm{vap}} \sqrt{T_{\mathrm{vap}} m}$$

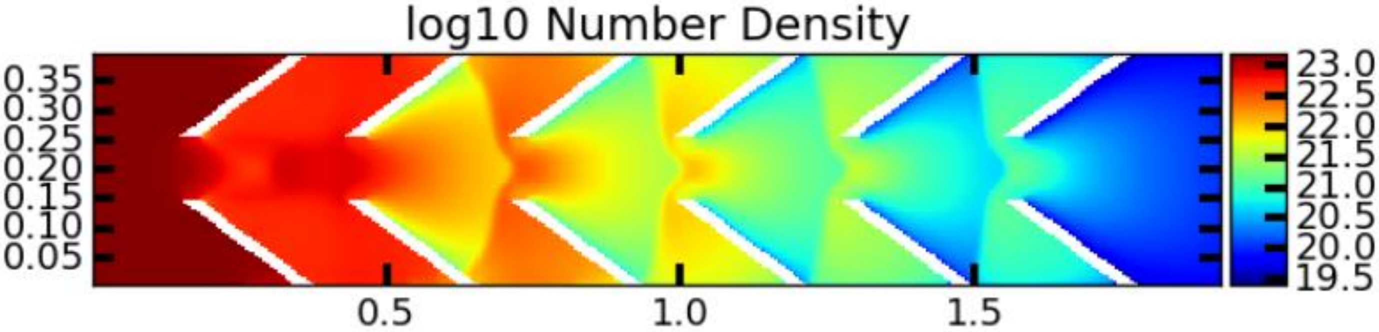


P_{dis} = 200 MW, R = 6 m
l_{box} = 0.5 m, d = 10 cm

R. Goldston

Initial 2-D Navier-Stokes calculations are similar to initial 0-D calculations

2-D



0-D

T (wall) (C)	950	787.5	625	462.5	300
T (vapor) (C)	2443.9	1756.5	1533.9	1499.1	1498.6
n (vapor) (m^{-3})	1.15E+23	1.80E+22	1.74E+21	1.23E+20	8.21E+18
Radiated Power (W)		5.36E+08	4.89E+07	3.42E+06	2.29E+05
Mass flow (kg/s)	5.3605	0.7124	0.0643	0.0045	0.00037
Latent heat flow (W)	1.05E+08	1.40E+07	1.26E+06	8.81E+04	5.89E+03
Enthalpy flow (W)	3.92E+07	3.75E+06	2.95E+05	2.02E+04	1.35E+03

(NSTX “thrives” on 220 mg/s from dropper)

- Initial 0-D calculations assumed choked flow and equilibration in each chamber. Also showed pressure balance with lithium unnecessary.

- 2-D fluid calculations by Hakim and Hammett result in similar behavior (factor of ~2 difference), require reflecting boundaries (white)

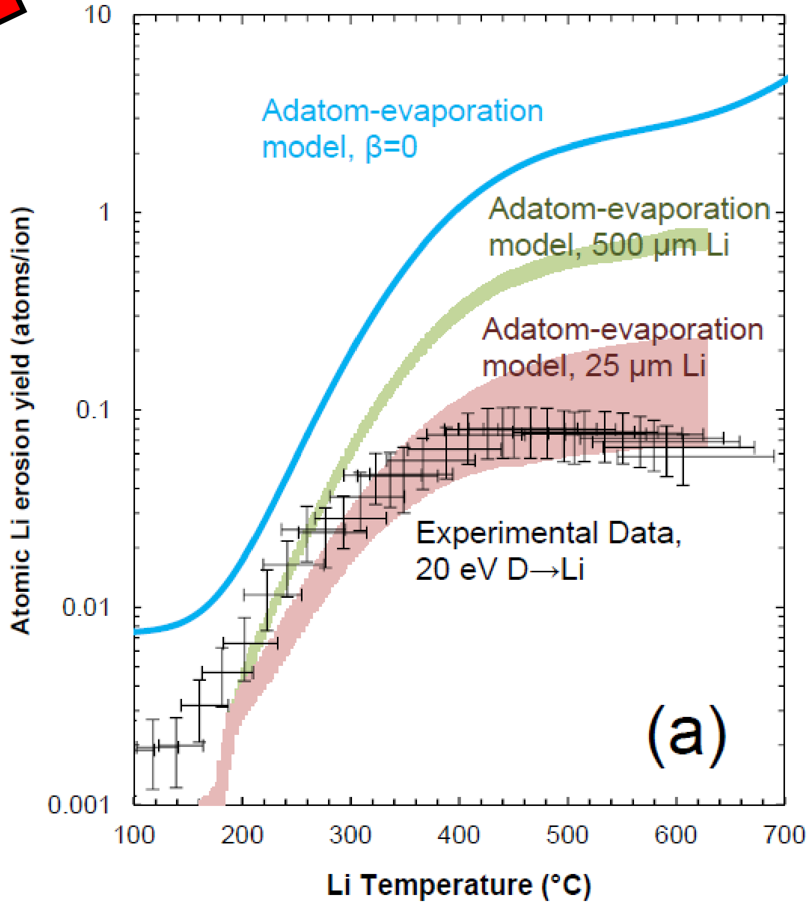
- Similarity experiment being designed at PPPL to validate simulations

Recent research results and surface science aspects of liquid metal PMI

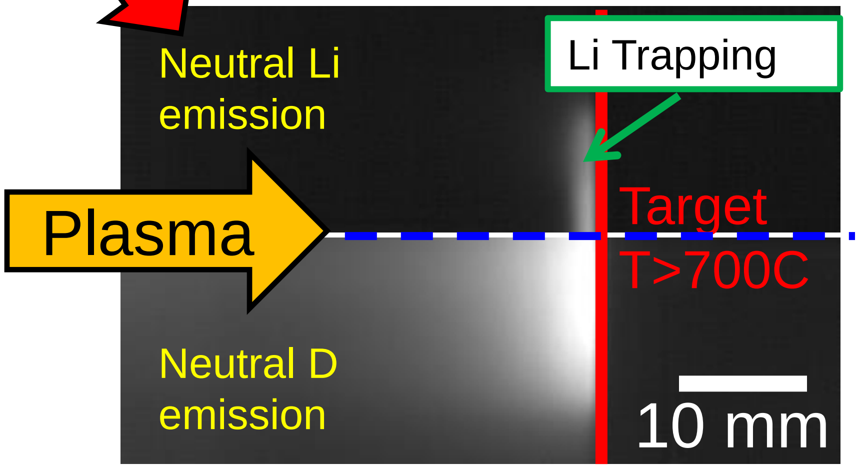
Suppressed erosion and trapping at target observed in linear plasma device

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

T. Abrams 2014 PhD Princeton U.,
T. Abrams 2016 Nucl. Fusion,
M. Chen 2016 Nucl. Fusion.



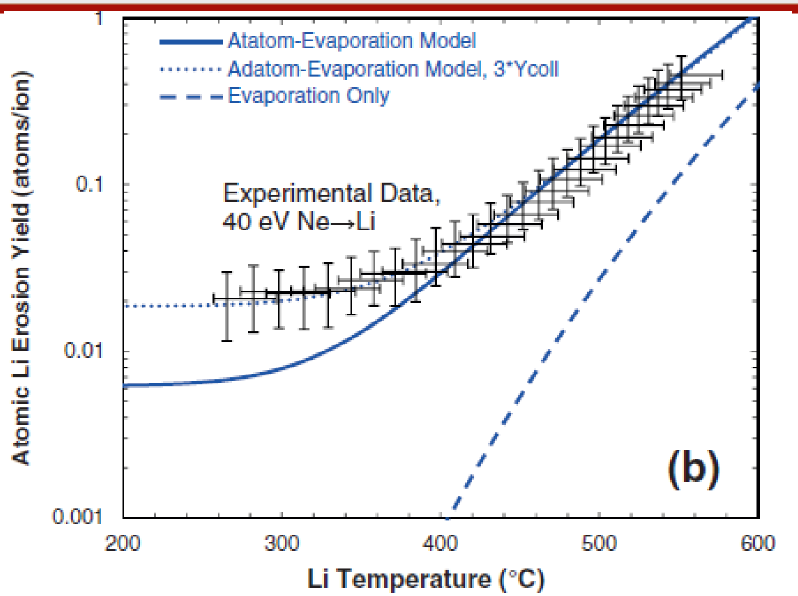
Li-I emission, t=2.5s

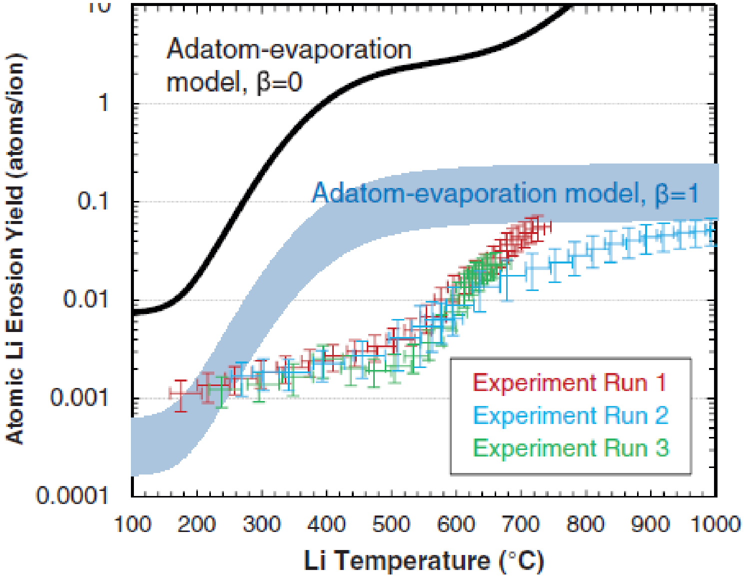


Jaworski, 3rd ISLA, 2013

Suppressed Li erosion observed under high flux deuterium bombardment

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

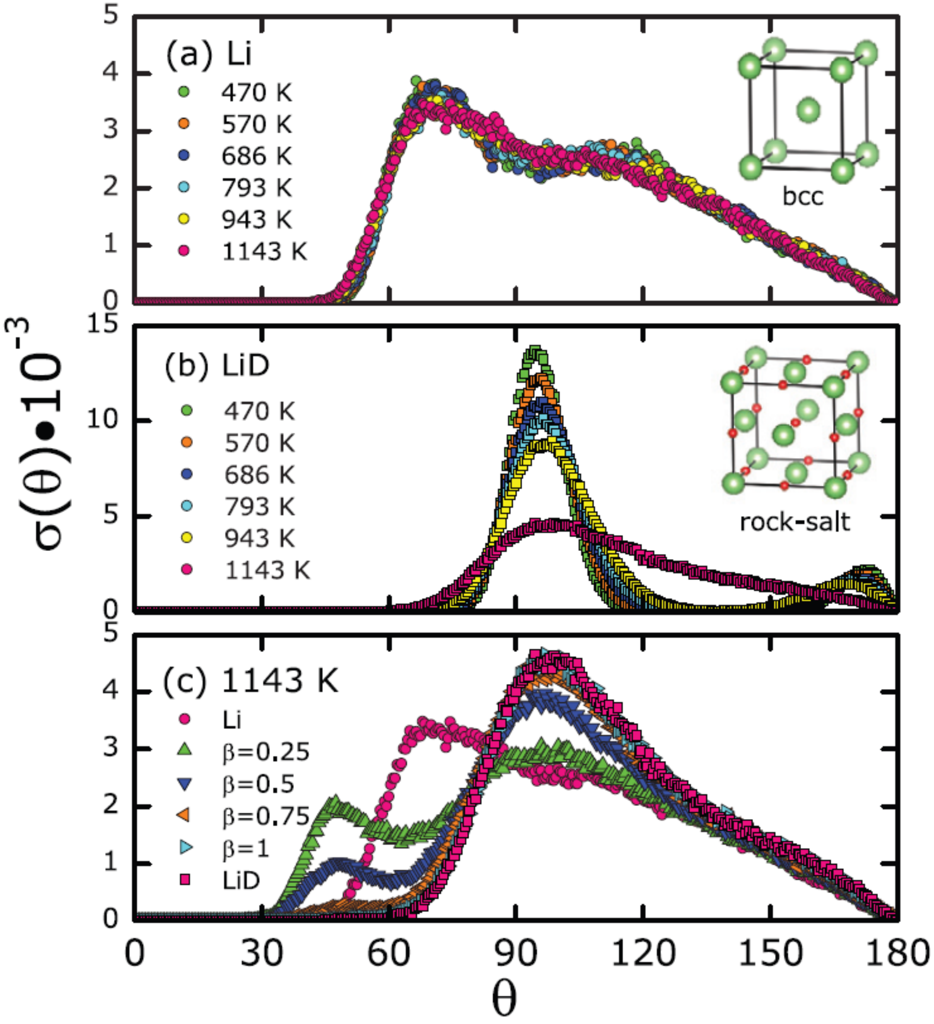




Abrams, 2016 Nucl. Fusion

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

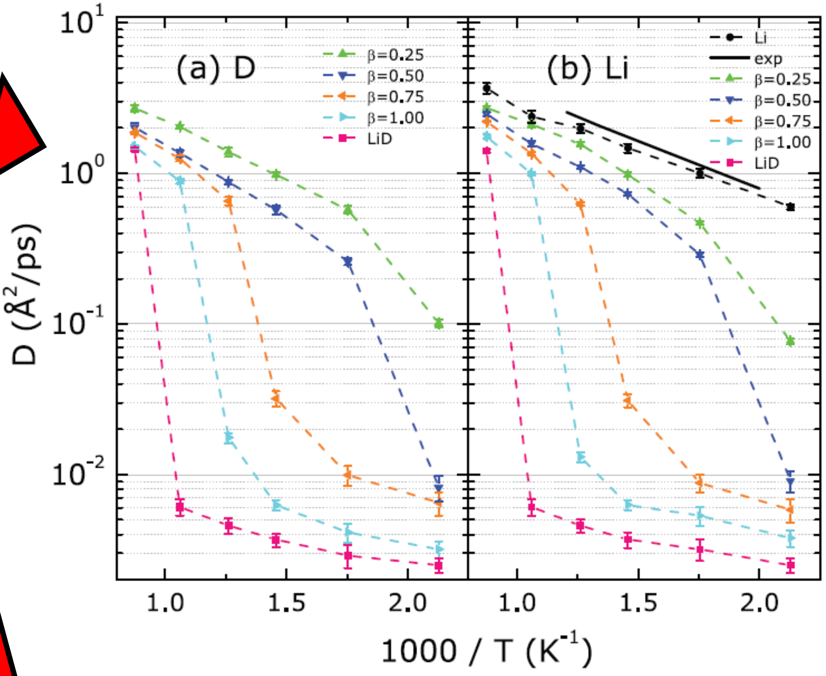
- First-principles density-function-theory applied to Li-D mixed problem
  - DFT simulations calculate interatomic potentials as opposed to classical MD
  - Limited to 100s of atoms and 10-20ps simulation times
- Bond angle distribution provides "finger-print" compounds in simulation
  - Shows rapid formation of LiD compounds



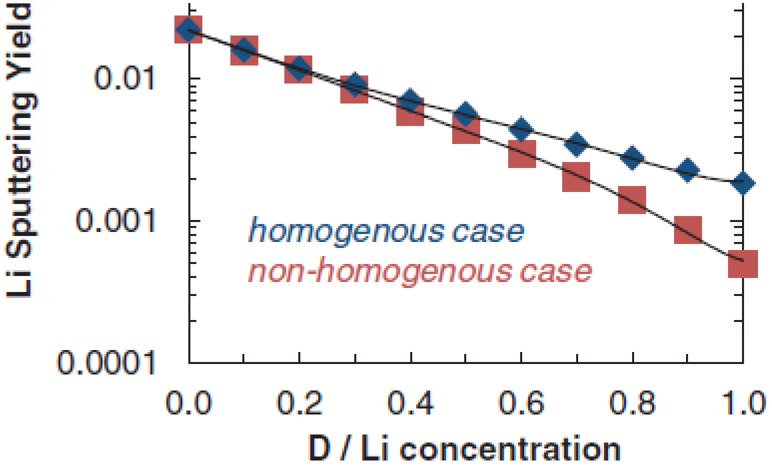
Chen, 2016 Nucl. Fusion

Three effects of LiD formation impacting Li erosion from sample and included in Abrams model

- Reduced D diffusivity in LiD predicted from DFT modeling
  - D “piling up” at surface at high flux



- Preferential D-D sputtering



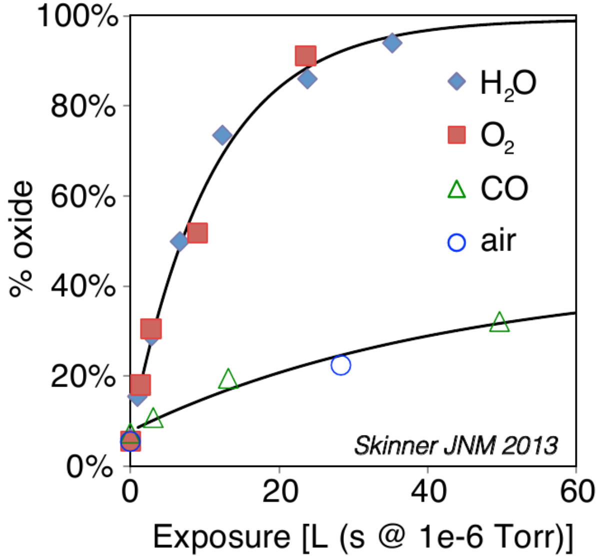
- Reduced Li vapor pressure over LiD vs. pure Li

Chen, 2016 NF; Abrams, 2016 NF

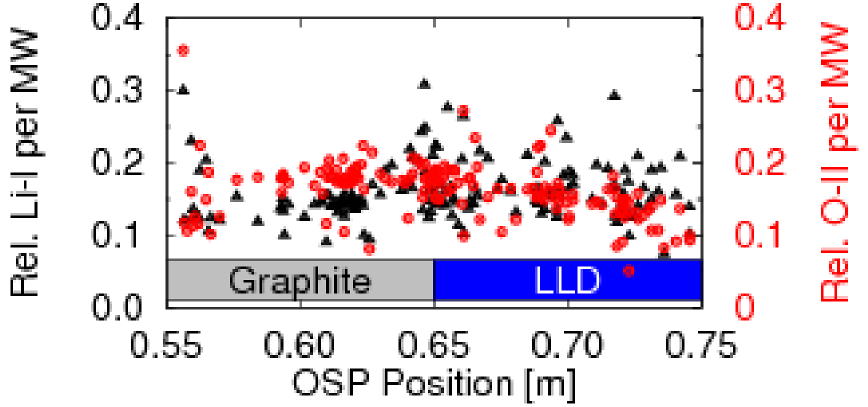
Lithium reactivity leads to mixed-material surfaces

- Oxygen uptake by lithium films quantified in laboratory experiments (Skinner, 2013 JNM)
  - Oxide layer formation in ~200s in NSTX (~600s inter-shot time)
  - NSTX-U inter-shot time even longer during full-power discharges

- NSTX whole-divertor impurity emission indicates little change (Jaworski, 2013 NF)
  - Graphite and liquid-lithium divertor (LLD) surfaces have similar emission properties
  - Little impact over entire run from 60g to nearly 1kg injected Li



Oxygen uptake by Li on Mo

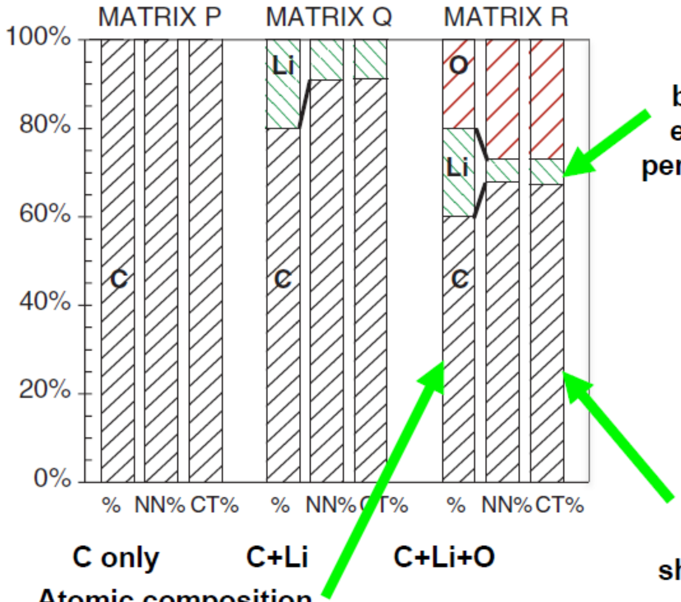


NSTX whole-divertor impurity emission

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

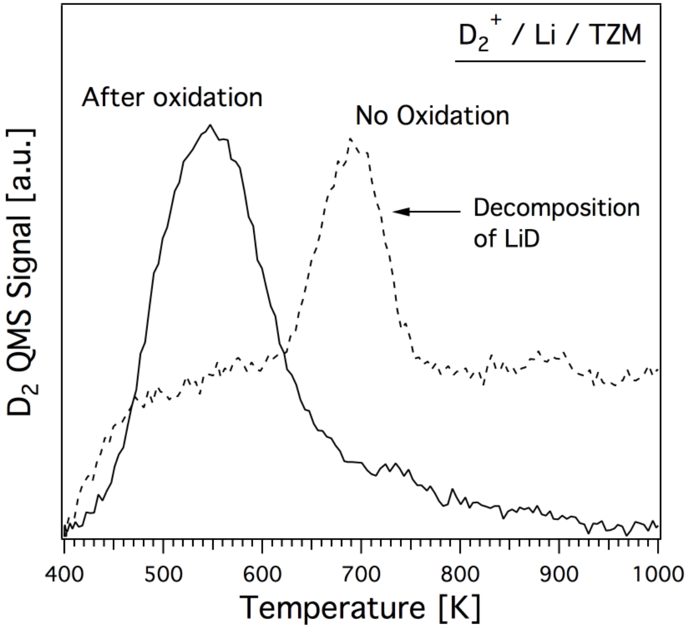


Amount of D bound by Li is even less than percentage of Li in PFC matrix

Atomic composition of matrix

Fraction of D sharing charges with matrix constituents

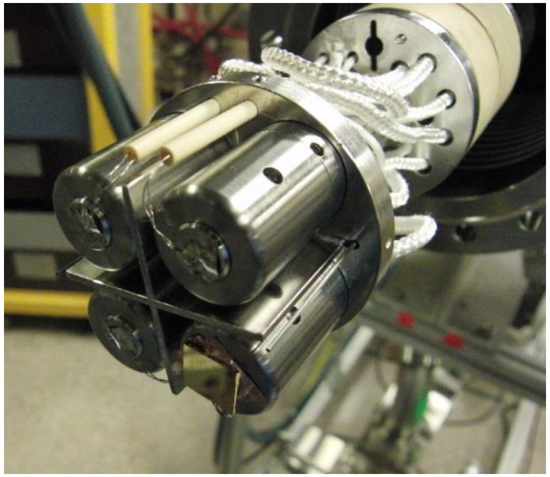
Krstic, 2013 PRL

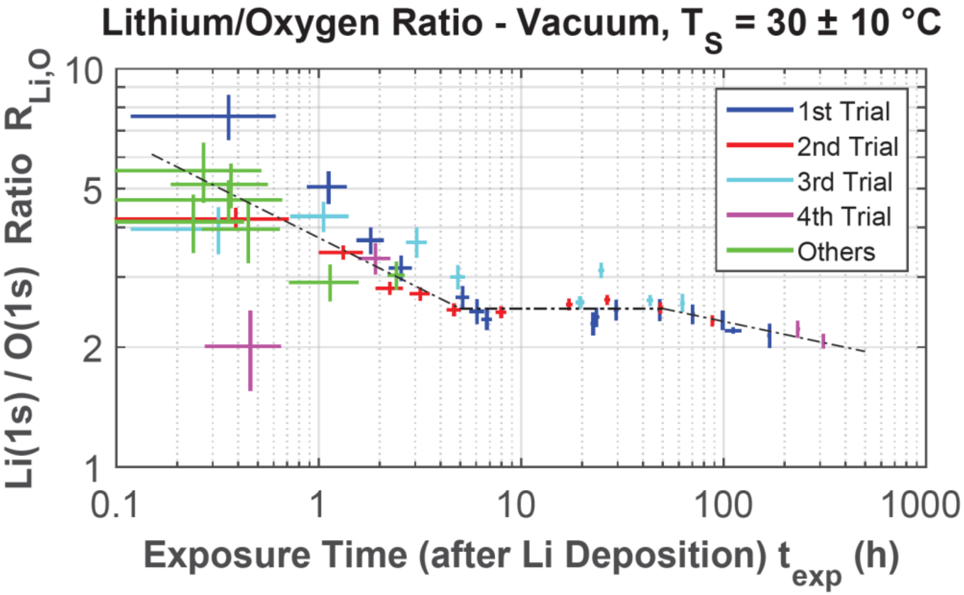


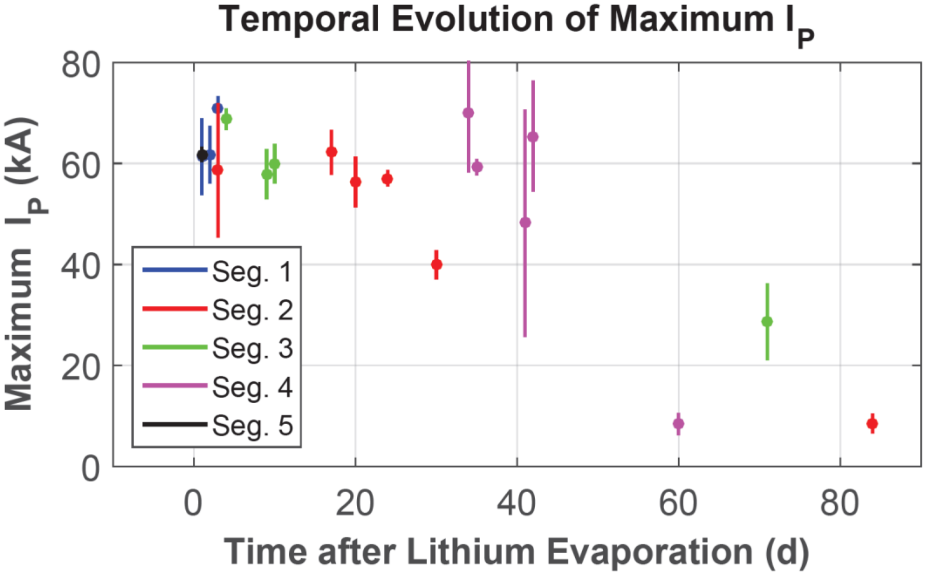
Capece, 2015 JNM

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

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





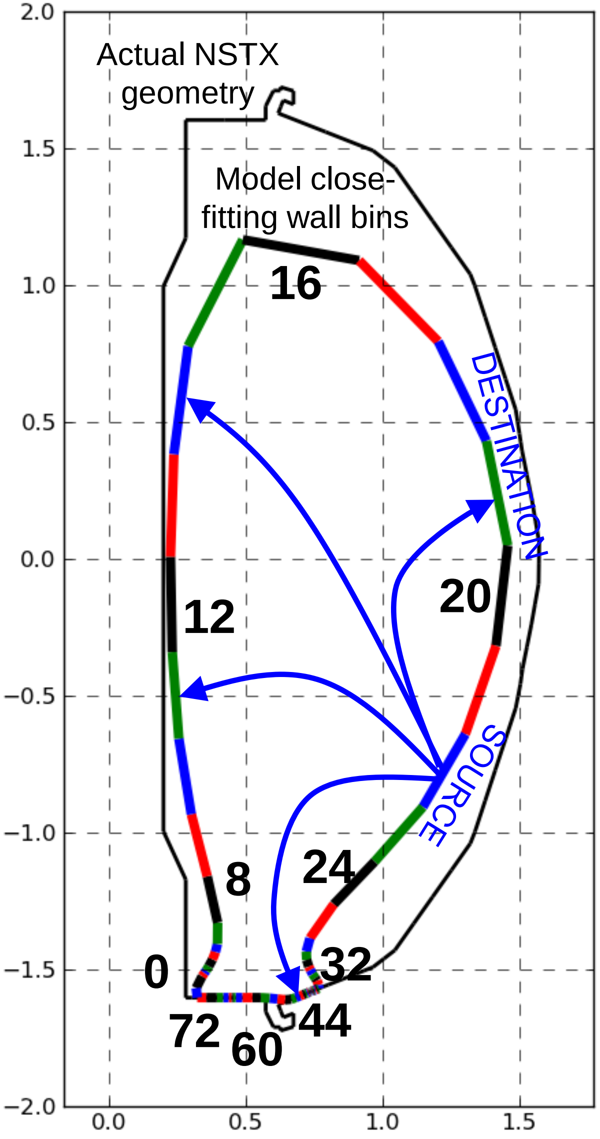


Lucia, PhD thesis, Princeton Univ. (2015), Kaita, ISLA 2015

Understanding material mixing and migration major thrust in NSTX-U

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

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



Nichols, 2015 APS

Many remaining issues facing liquid metal PFCs

- If temperature limit determined to be a low temperature despite divertor trapping (e.g. LVB) then this would shift technological development for Li to fast flow (see Majeski talk next)

- Slow-flow/oozing systems can also utilize tin as alternative metal (strong push in EU)

- Significant engineering still required to qualify components and optimize designs

- Lithium-based fuel control still would benefit from overall fuel-cycle demonstration (also see Majeski talk)

Steady progress being made to demonstrate and understand liquid metal PFCs and PMI

- Compatible temperature limit of liquid lithium PFCs should be experimentally demonstrated and greatly affects heat exhaust potential and concept viability e.g. vapor box or active lithium injection (Ono NF 2013)
  - Strong mixed-material effects lead to reduced lithium production
  - High redeposition fraction also observed in these experiments

- NSTX-U upgrade program aims to experimentally compare high-Z and low-Z approaches in single device with three-step upgrade scheme

- Understanding lithium PMI requires attention to mixed material effects
  - Impure lithium films observed in most (all?) major devices
  - Extrapolation to “pure” lithium flows represents major question in evaluating reactor performance

- Near-term science and technologies for realizing pre-filled targets nearly in hand and being considered for FY2018 run campaign

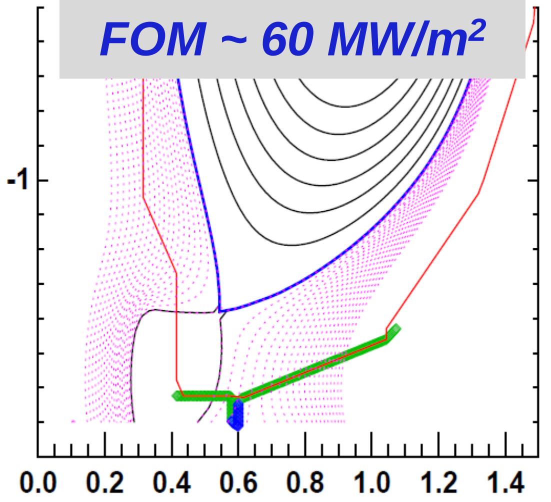
- Flowing PFCs can build upon operational experience gained with pre-filled targets and parallel efforts in safety and LM handling systems

Further high-Z divertor target engineering details

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

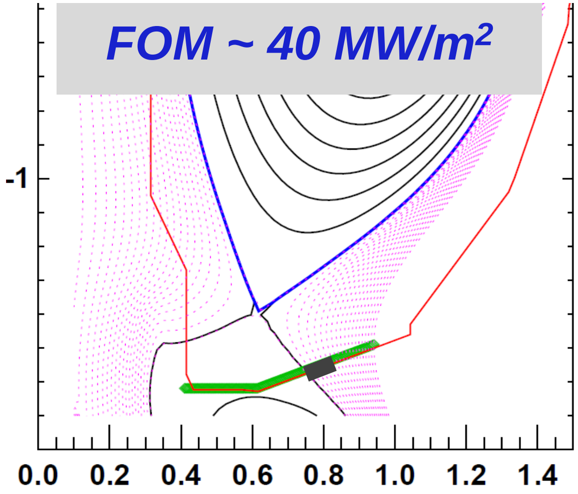
- Shape developed to perform dedicated tests on outboard PFCs
  - – ISOLVER free-boundary solver utilized with specified β_N
  - – 0D-analysis obtains heating power for some assumed confinement (ITERH98)

High-performance discharge



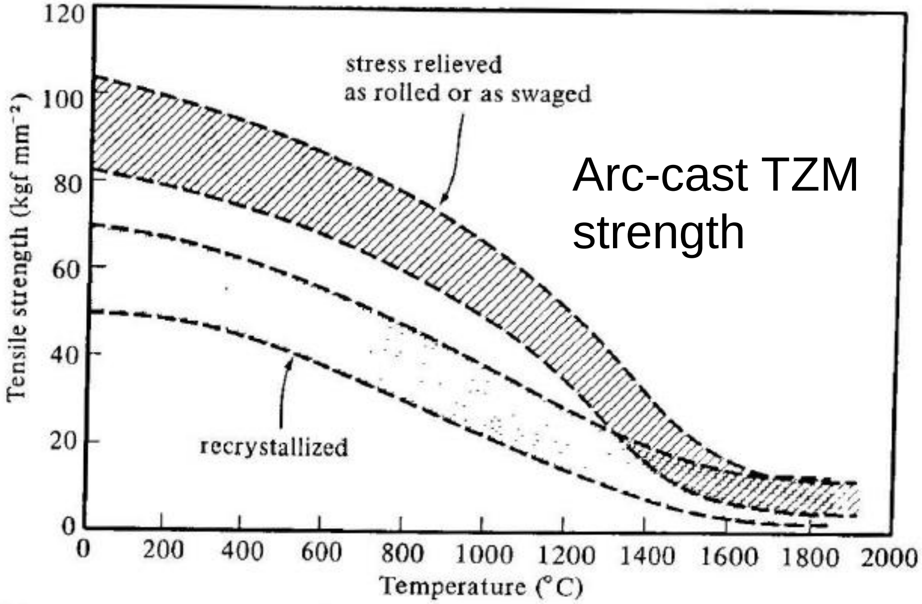
- Zero-radiation power exhaust provides heat flux figure-of-merit (FOM)
  - – FOM calculates incident power accounting for magnetic shaping only
  - – High-Z shape FOM is 66% of full-power, high-triangularity scenario

High-Z reference discharge



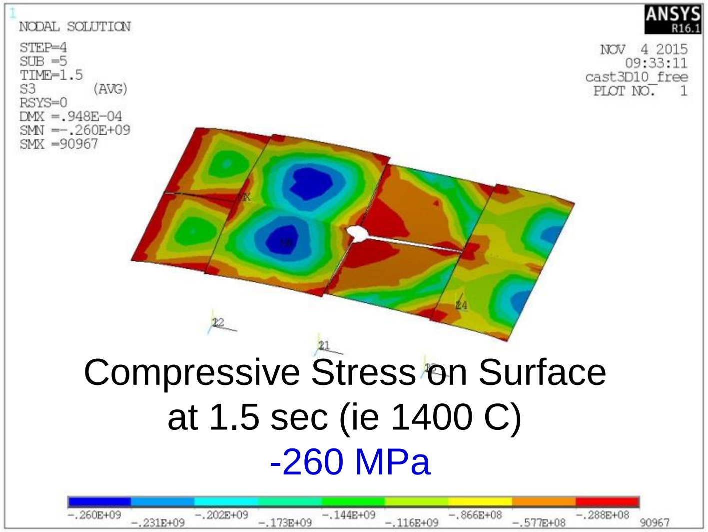
Castellations separate peak stress from peak temperature

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

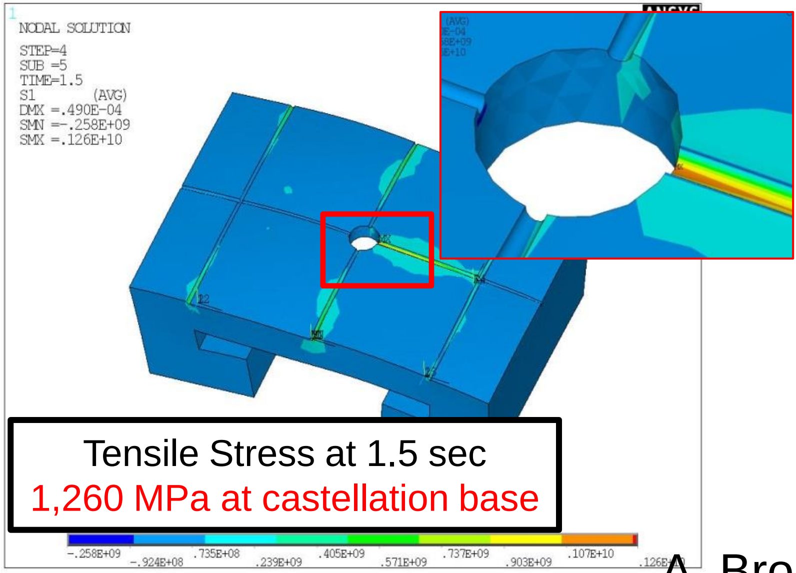


Arc-cast TZM strength

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



Compressive Stress on Surface
at 1.5 sec (ie 1400 C)
-260 MPa



Tensile Stress at 1.5 sec
1,260 MPa at castellation base

A. Brooks

Tile Design Basics

- 7 “Special” Tiles, 5 Diagnostic and 2 XP

Tile sub-type	Number required	Material
Diagnostic: OLPA	2 (over and under styles)	TZM
Diagnostic: RF Langmuir probe	1	TZM
Diagnostic: magnetic sensor	1	TZM
Diagnostic: embedded TC	1	TZM
Experimental: leading edge	1	TZM
Experimental: W+$T_{recryst}$ effect	1	W (or W-alloy)
Total	9	

- Most tiles (not Mirnov) are modifications of the base tile type.
  - The tile which contains a Mirnov sensor has shallower castellations so as not to clash with diagnostic pocket.
- These modified base tiles are not under review at this time
  - Analysis is planned to qualify mods
  - If we find they are unable to meet the SRD requirements…
    - If they fail XP loads, modify the XP conditions
    - If they fail Normal loads, propose to eliminate the tile causing the problems.

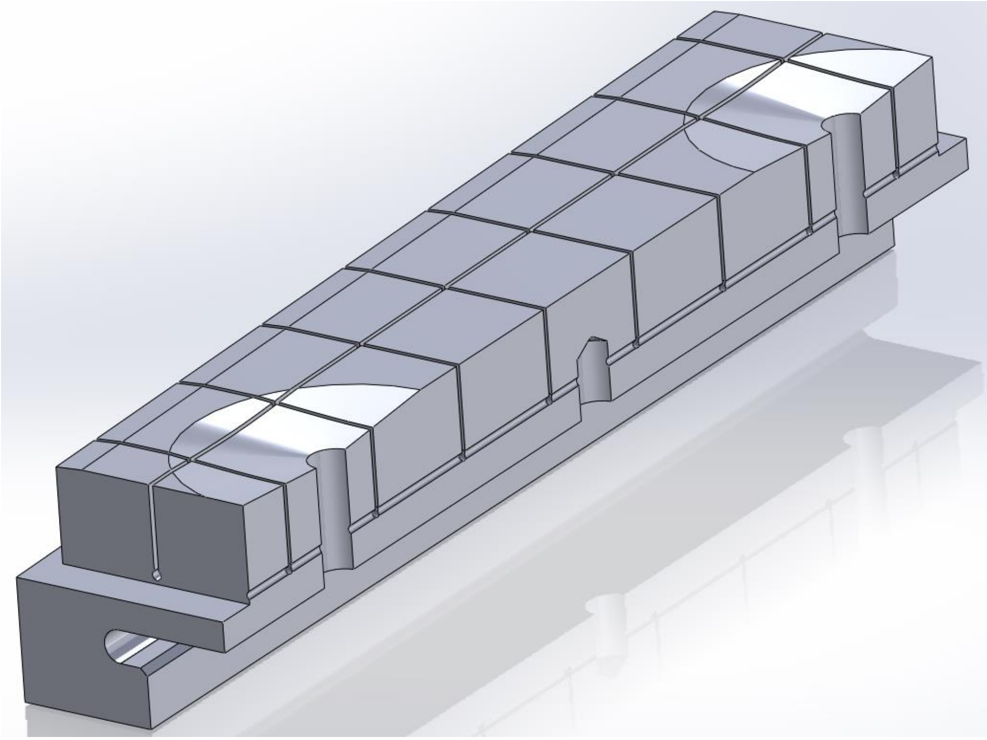
Results for “Normal”, 2 MW/m2 Nominal for 5 sec

	Configuration		Time, s	Temp, C	Tension, Mpa		Compression, Mpa		Limits	
Location	Castellation Radius	Bolt Head Recess			Free	Clamped	Free	Clamped	Static Thermal	Fatigue 6000 cycles
Tile Surface			5	482	0.5	0.5	-43	-44	520	<500(?)
Base of Castellation	Nominal .010"	Yes	5	160	595	487	-609	-824	1300	500
Base of Castellation	Nominal .010"	No	5	160	497	398	-443	-619	1300	500
Base of Castellation	Enlarged .020"	No	5	160	388	304	-342	-478	1300	500

- Clear winner: no counterbore, larger castellation base
  - Just from this analysis, we could conclude that increasing the clamping strength would be a good idea, however when we take a look at the results from the same analysis, but for the “XP” operating parameters of 10MW/m2 for 1.5 sec…

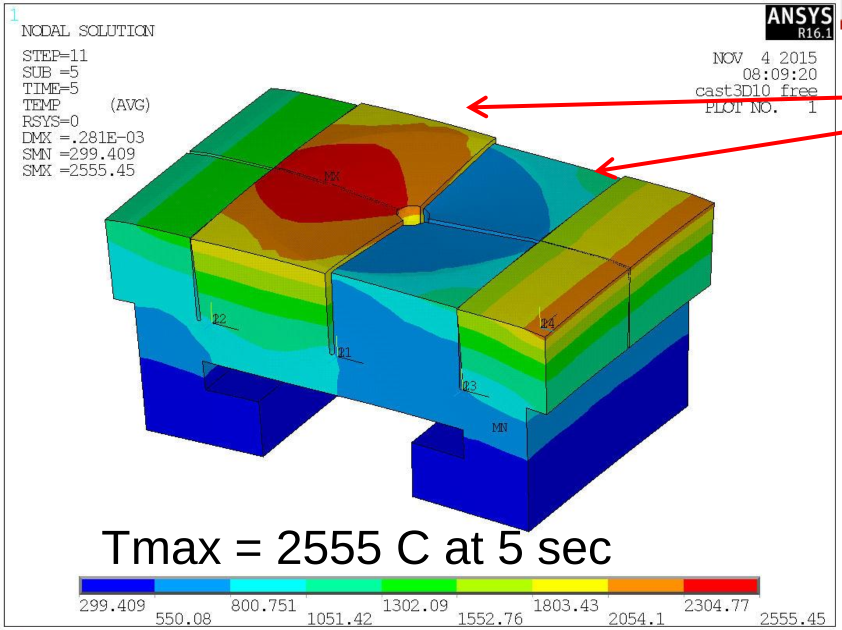
Static Analysis Summary

- Results show that, for both operating conditions
  - Castellated tiles, with no bolt counterbores, and with increased radii at the castellation bases are adequate designs to avoid yielding.



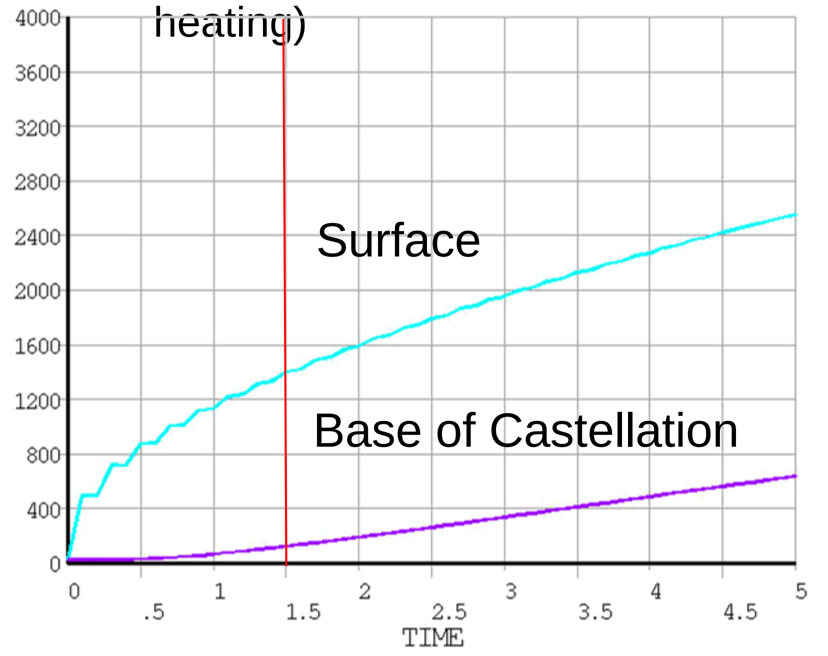
However, what about Cyclic Fatigue?

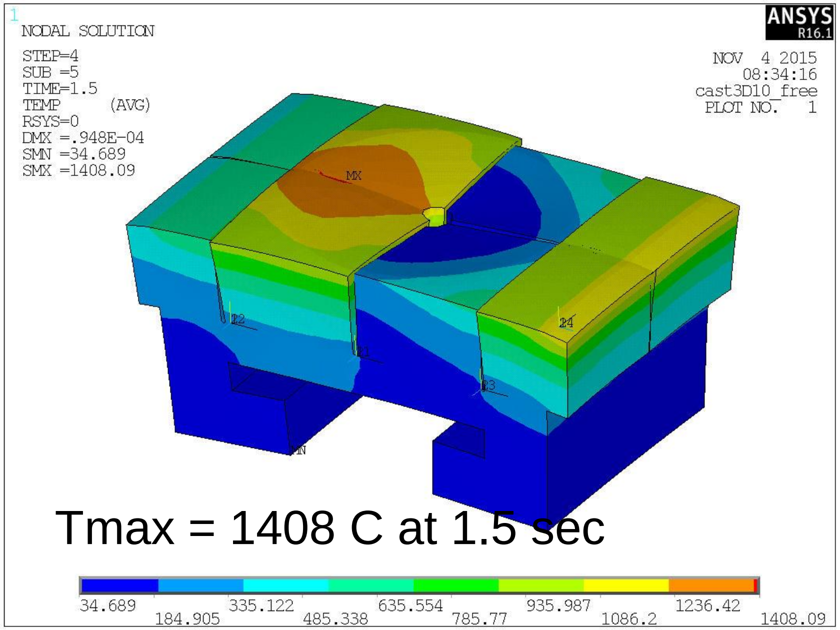
Surface Temperature Reaches 1400 C after 1.5s



Tmax = 2555 C at 5 sec

Large Temperature Differences on shaded segments between shaded and unshaded (ie enhanced heating)





Tmax = 1408 C at 1.5 sec

Heat Flux Distribution

Results summary table

“Normal” 2 MW/m2 and 5 sec pulse

	Configuration		Time, s	Temp, C	Tension, Mpa		Compression, Mpa		Limits	
Location	Castellation Radius	Bolt Head Recess			Free	Clamped	Free	Clamped	Static Thermal	Fatigue 6000 cycles
Tile Surface	Enlarged .020"	No	5	479	17	15	-43	-44	1300	<500(?)
Base of Castellation			5	277	388	304	-342	-478	1300	500

“XP” 10 MW/m2 and 1.0 sec pulse

	Configuration		Time, s	Temp, C	Tension, Mpa		Compression, Mpa		Limits	
Location	Castellation Radius	Bolt Head Recess			Free	Clamped	Free	Clamped	Static Thermal	Fatigue 6000 cycles
Tile Surface	Enlarged .020"		1.5	~1200	70	72	-256	-255	520	<500(?)
Base of Castellation		No	1.5	~100	**495**				1300	500

**at sharp corner where fillet is needed & and stress excluding corner*

10MW/m2, 1.0 sec

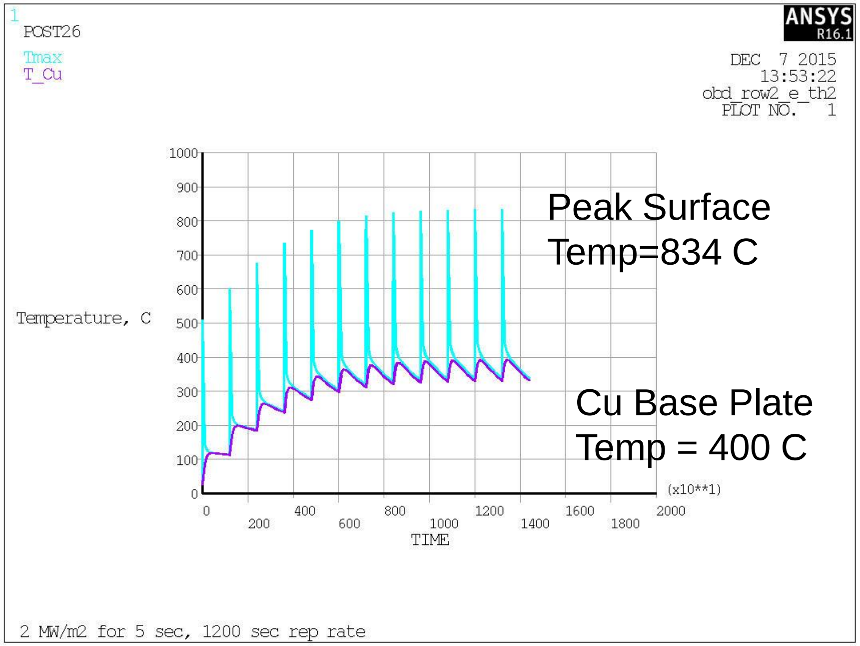
- Reduce duration of XP shots
  - By lowering the duration from 1.5 to 1, we effectively lower the peak stresses at the castellation base, gaining thousands of cycles.
  - The q√t of this parameter is 10, which is the same as in the "normal" operation conditions
    - Appears to be a healthy limit for this system.

- Racheting concerns?
  - The overall effect of racheting, for a q√t value of 10, is an increase of about 330C.
    - Assumes emissivity of 0.3
  - For the area of interest, the castellation base, this means at the end of 12 cycles, the castellation temperature reaches ~450C and the yield strength remains essentially unaffected.
  - This also means that, with racheting, even at the reduced duration of 1 sec, we have a wider range of surface temps with which to experiment.
    - 1200 - 1500C

Thermal Ratcheting

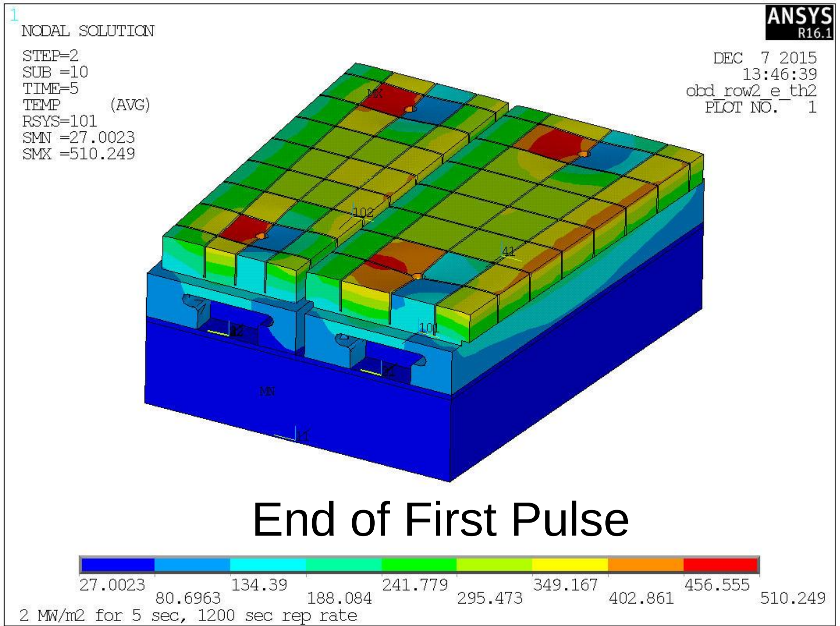
2 MW/m2 Nominal for 5 sec
1200 sec Rep Rate

Radiation Cooling Only from Tile Surface and Copper Back Plate
Assumes emissivity of 0.3

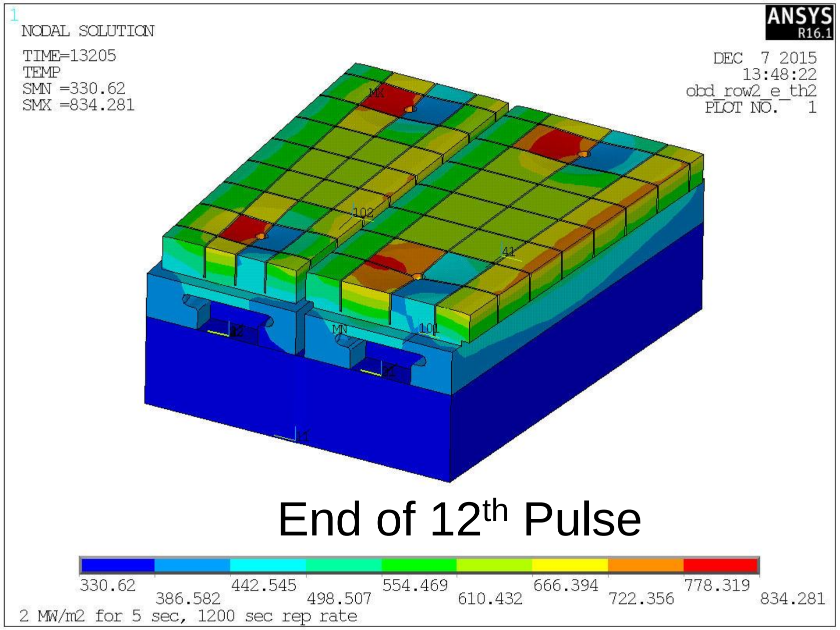


Peak Surface Temp=834 C

Cu Base Plate Temp = 400 C



End of First Pulse



End of 12th Pulse

Analysis Summary

- Recap
  - Tiles in free expansion, with no counterbores, and have castellations with enlarged bases are adequate to withstand both “normal” and “XP” operational conditions.
    - Neither conditions cause yield
    - Both conditions can survive 10^3 cycles
  - Racheting will have little to no effect on tile performance
    - May actually benefit experiments

Design Summary

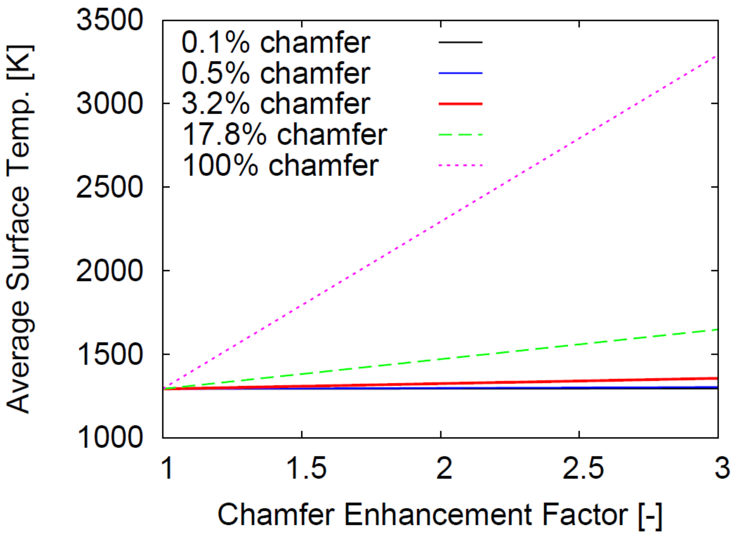
- The basic tile design is complete.
  - Confident in performance for 2 years of operations and experiments
- A few remaining tasks…
  - Would like to optimize chamfers to help minimize internal stresses
  - Need a few more analysis runs to help create more detailed heat flux/duration limits for operational control. (Project deliverable)
  - Begin analysis on special tiles, to confirm/deny compliance with requirements.

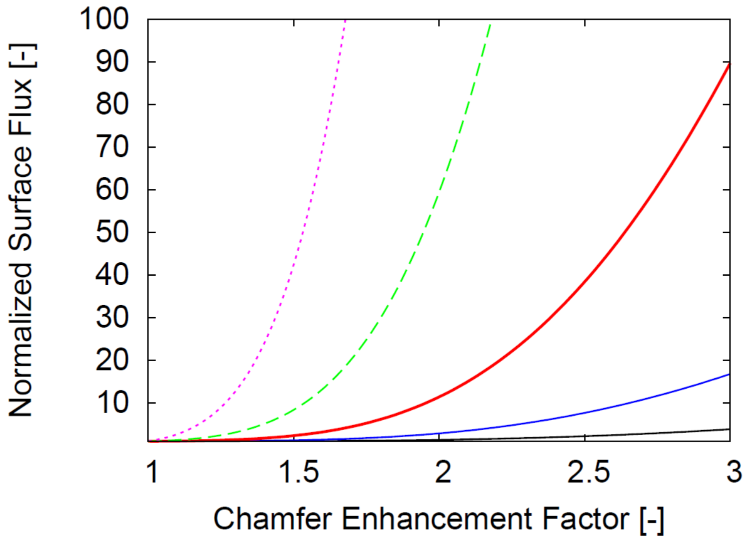
Schedule

- Priority on machining procurement
  - Once FDR is complete, chits are put to bed
    - Finish analyses, finalize basic tile design
    - Begin procurement package on basic tile design, start special tile analyses (simple thermo-mechanical to check thermal stresses)
      - Finish package by 1st week in Jan, submit to procurement
      - If special tiles need review, hold it 2nd week in Jan
    - Special tile procurement to follow close behind normal tiles, asking for partial deliveries & priority on special tiles (to allow for ample time to pot diagnostics)
    - Other procurement items (new Bellevilles, grafoil, shim stock, bolts…) follow tile procurement.
      - Complete by end of Jan
    - Concurrent with these tasks, begin writing installation procedure with whomever will take over this job.

Inhomogeneous surface temperatures result in larger total particle flux

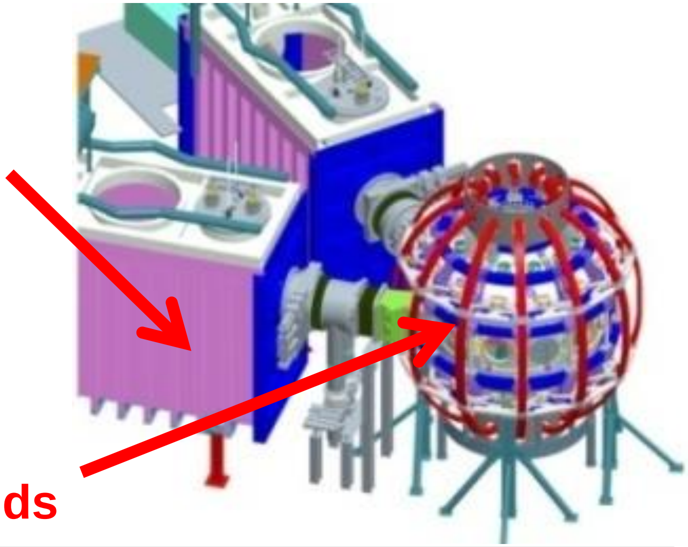
- Leading edges result in larger average temperature
  - Chamfers localize heating
  - Fish-scaling increases average heating
- Exponential vapor pressure produces strong increase in particle flux
- Lithium likely to erode fastest from areas of enhanced heating





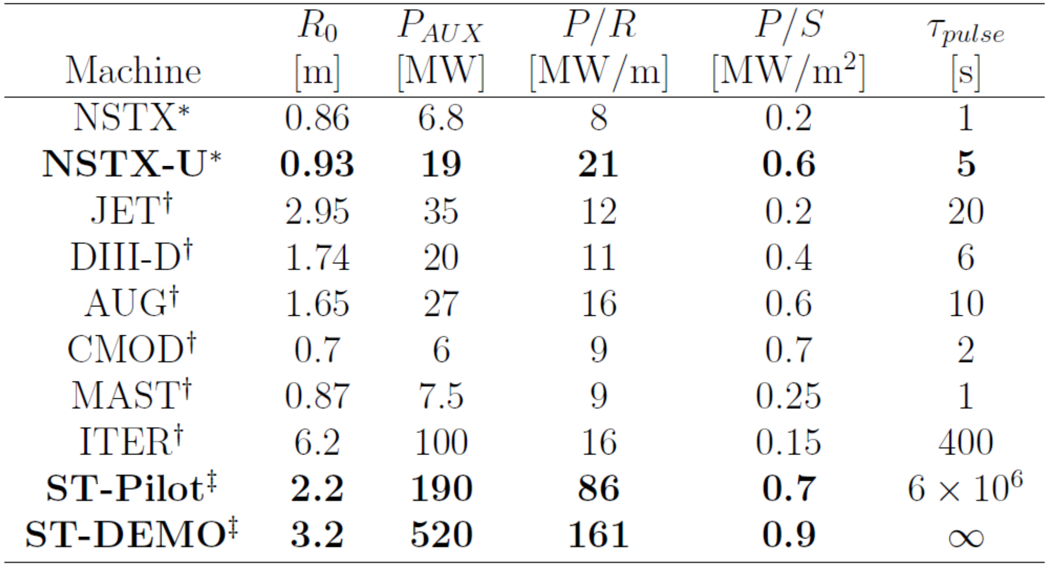
NSTX-U plasma-facing components (PFCs) will be subjected to significant heat and particle fluxes

- 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



2nd NBI system

Upgraded OH and toroidal fields

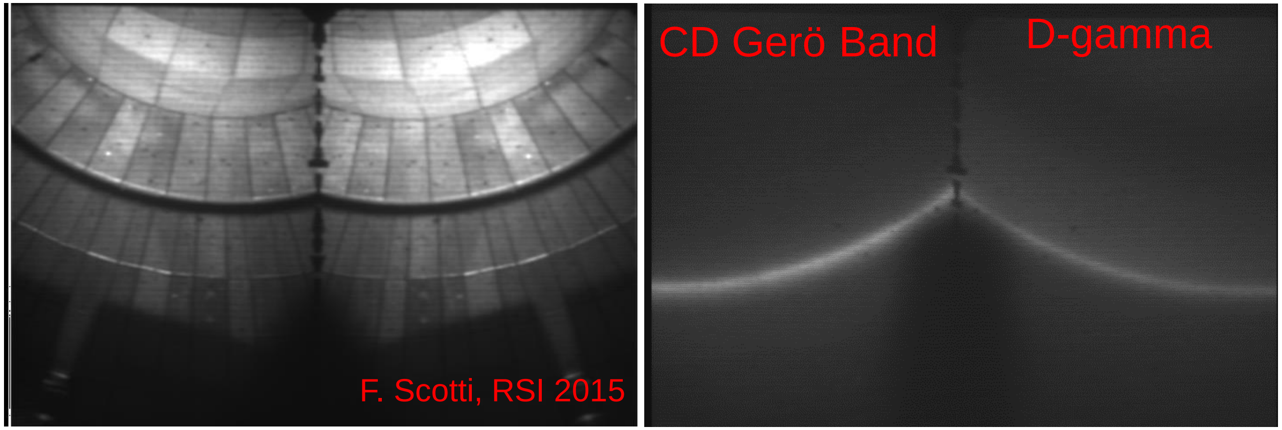


Machine	R_0 [m]	P_{AUX} [MW]	P/R [MW/m]	P/S [MW/m^2]	τ_{pulse} [s]
NSTX*	0.86	6.8	8	0.2	1
NSTX-U*	**0.93**	**19**	**21**	**0.6**	**5**
JET†	2.95	35	12	0.2	20
DIII-D†	1.74	20	11	0.4	6
AUG†	1.65	27	16	0.6	10
CMOD†	0.7	6	9	0.7	2
MAST†	0.87	7.5	9	0.25	1
ITER†	6.2	100	16	0.15	400
ST-Pilot‡	**2.2**	**190**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

Further LLNL and ORNL diagnostic details

New LLNL diagnostics for high-Z sources and transport studies

- Two new radiation-hardened, intensified CID cameras equipped with custom two-color optics (TWICE-1,-2) (Mo I)
- UV-VIS-NIR divertor spectrometer (DIMS) for high resolution multi-chordal spectroscopy (Mo I)
- Divertor SPRED VUV spectrometer (Mo III – Mo VIII)
- Divertor radiometer based on AXUV diode array (LADA)
- Complements diagnostic suite for low Z impurity emission

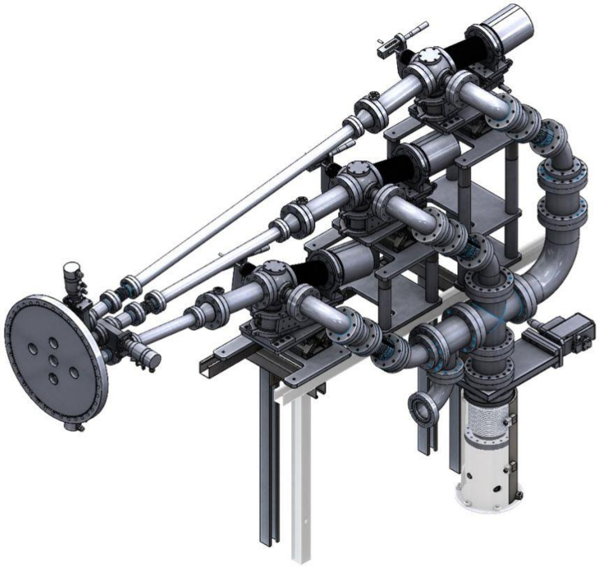


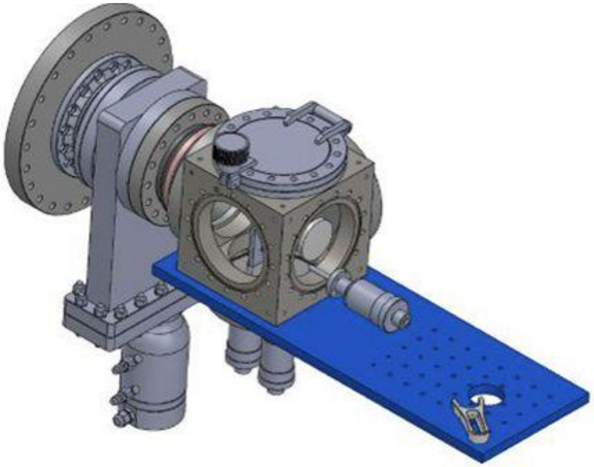
F. Scotti, RSI 2015

TWICE-2 views and NSTX-U measurements

New LLNL diagnostics and tools for high-Z core impurity transport studies

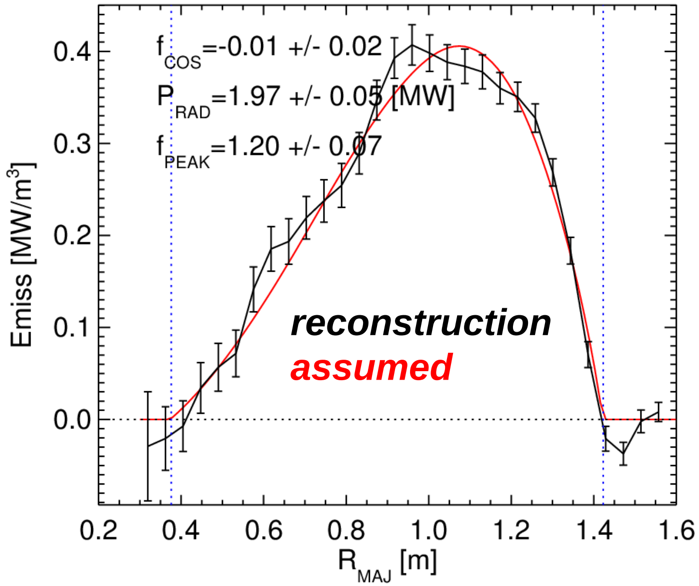
- Unique suite of three EUV spectrometers (XEUS, LoWEUS, MonaLisa)
  - Continuous spectral coverage 10-450 Å for low and high-Z line emission measurements with ~30 ms time resolution
- Laser Blow-Off (LBO) system
  - Determination of impurity confinement times, penetration efficiencies
  - Determination of impurity radial transport coefficients
  - Funded by LLNL internal funding
- Mo, W spectroscopy and atomic physics

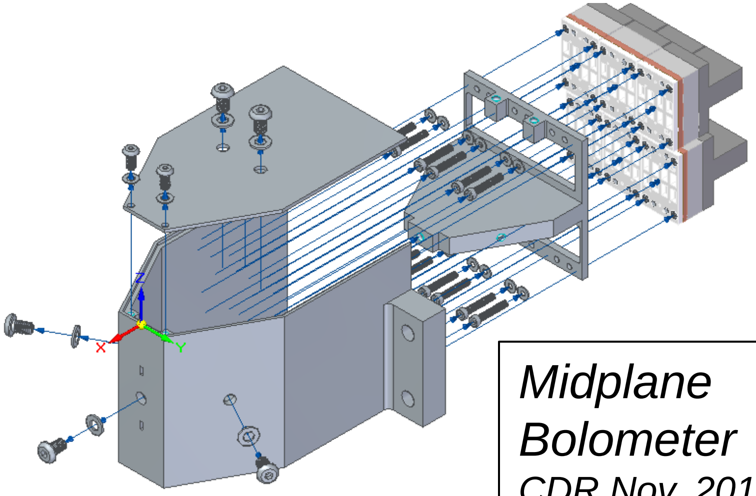




NSTX-U Developing Tools for Measuring Core and Boundary Radiation

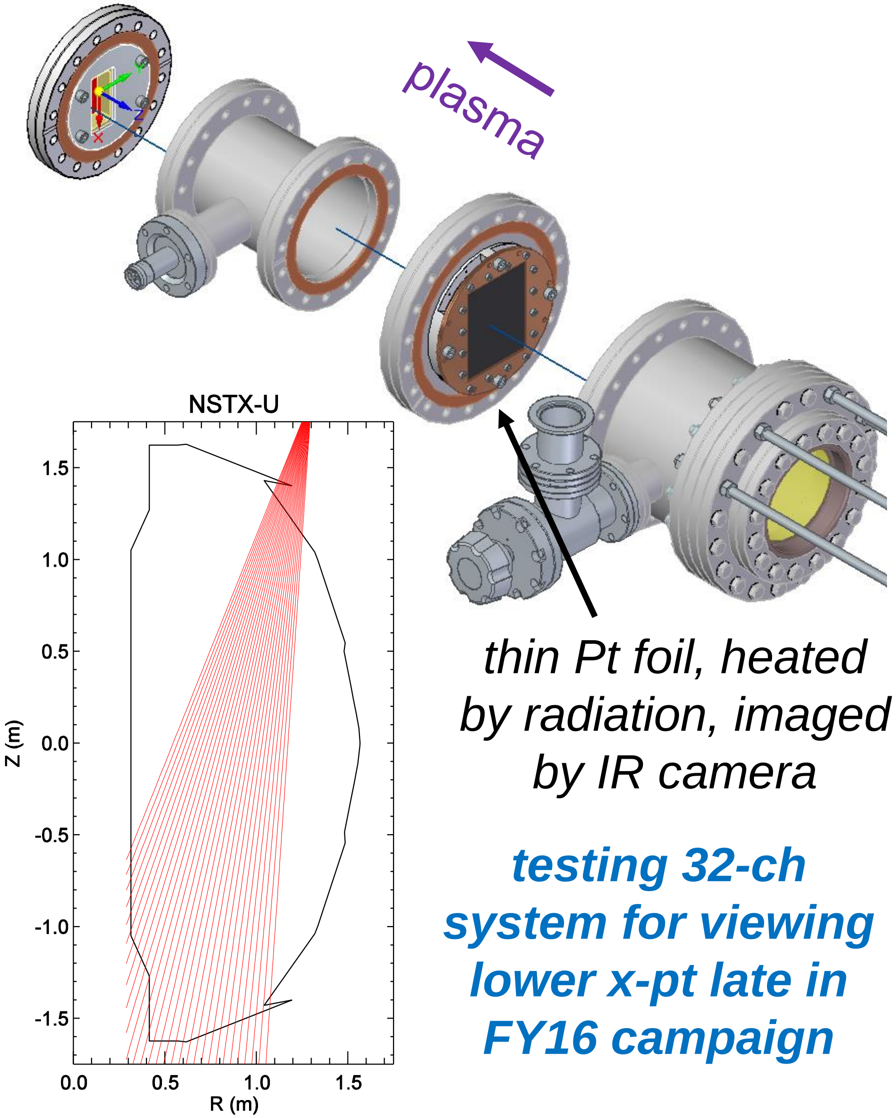
- failures during bake prevented utilization of resistive bolometer sensors for P_{RAD} on NSTX
- present efforts to redesign and expand bolometer diagnostics to support FY17 operations
  - 16 ch of lower divertor viewing for boundary radiation
  - 24 ch tangential midplane core radiation (simulated results shown)
- resistive bolometers complemented by faster unfiltered AXUV diode arrays presently installed
- future expansions anticipated





Midplane Bolometer
CDR Nov. 2015

Exploring New Bolometry Innovations to Support NSTX-U Research Thrusts



thin Pt foil, heated by radiation, imaged by IR camera

testing 32-ch system for viewing lower x-pt late in FY16 campaign

- spatial resolution and coverage of radiation diagnostics critical for power-balance, radiative exhaust physics, etc.
- developing prototype IR video bolometer (IRVB) to improve resolution for expected 2D radiation structure in divertor
  - ORNL and PPPL collaborating w/ NIFS and DIFFER
- results will inform possible future expansion at NSTX-U and could influence diagnostics at other US/international labs

Line of Sight Layout for Bay-J & Bay-I

- final adjustments to be made using FY16 ops; want to play w/ range of equilibrium
  - manage isolated sensor absence with present stock
- vertical position relative to divertor gap (X) needs to be managed, requires access

ANALYSIS GOALS:

- divertor radiated power
- (R,Z) tracking of peak emission region(s)
- rough size and shape of the radiating region