NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
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M&P TSG Group Discussion of NSTX-U Polar Region Modifications

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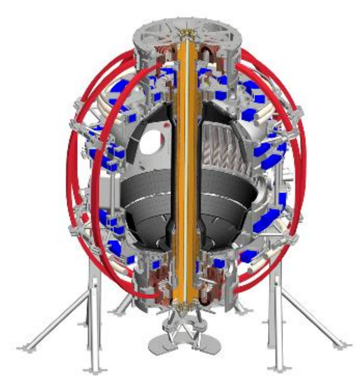
NSTX-U Materials and PFCs Topical Science Group
B252 – PPPL

May 11th, 2017

*Work supported by DOE contract DE-AC02-09CH11466

PPPL



Outline

- Two charges from Jon
  - Obtain input from team on impact of proposed polar-region changes to the TSG science mission using 5-year plan as a guide as well as the FY16-17 research campaigns
  - Document plasma shapes and parameters (e.g. strike-point position, heating power) necessary to accomplish TSG goals
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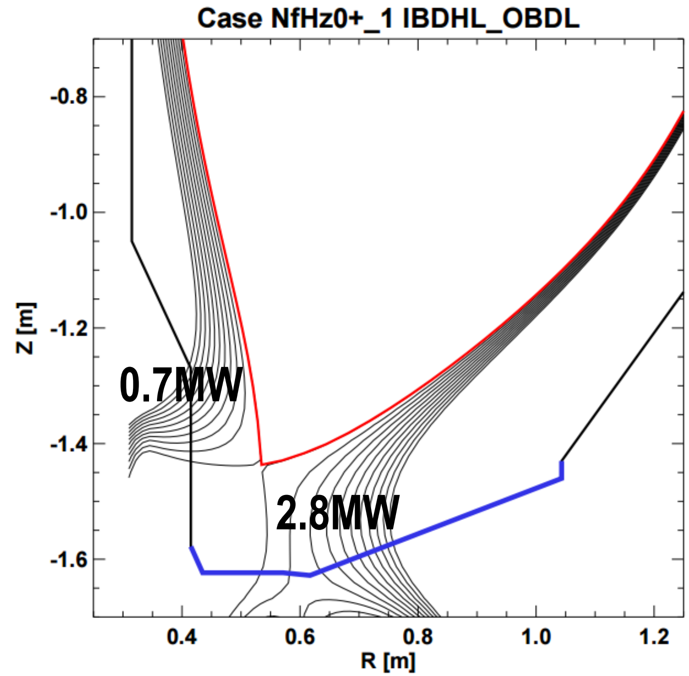
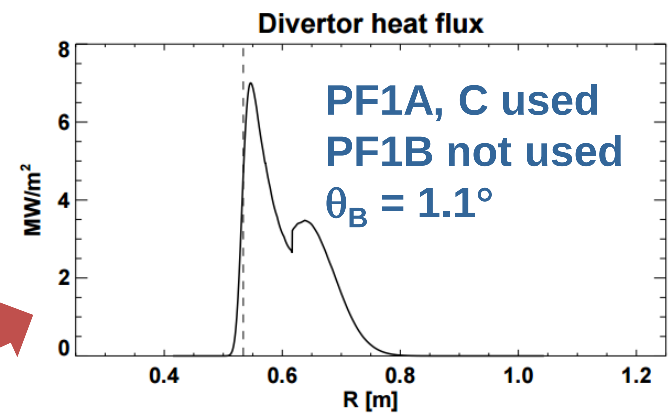
- Polar-regions review
- 5-year plan review
- Previous shots in NSTX-U
- Milestone discussion

Scan 1 example:
No PF1B, use PF1C for high flux expansion

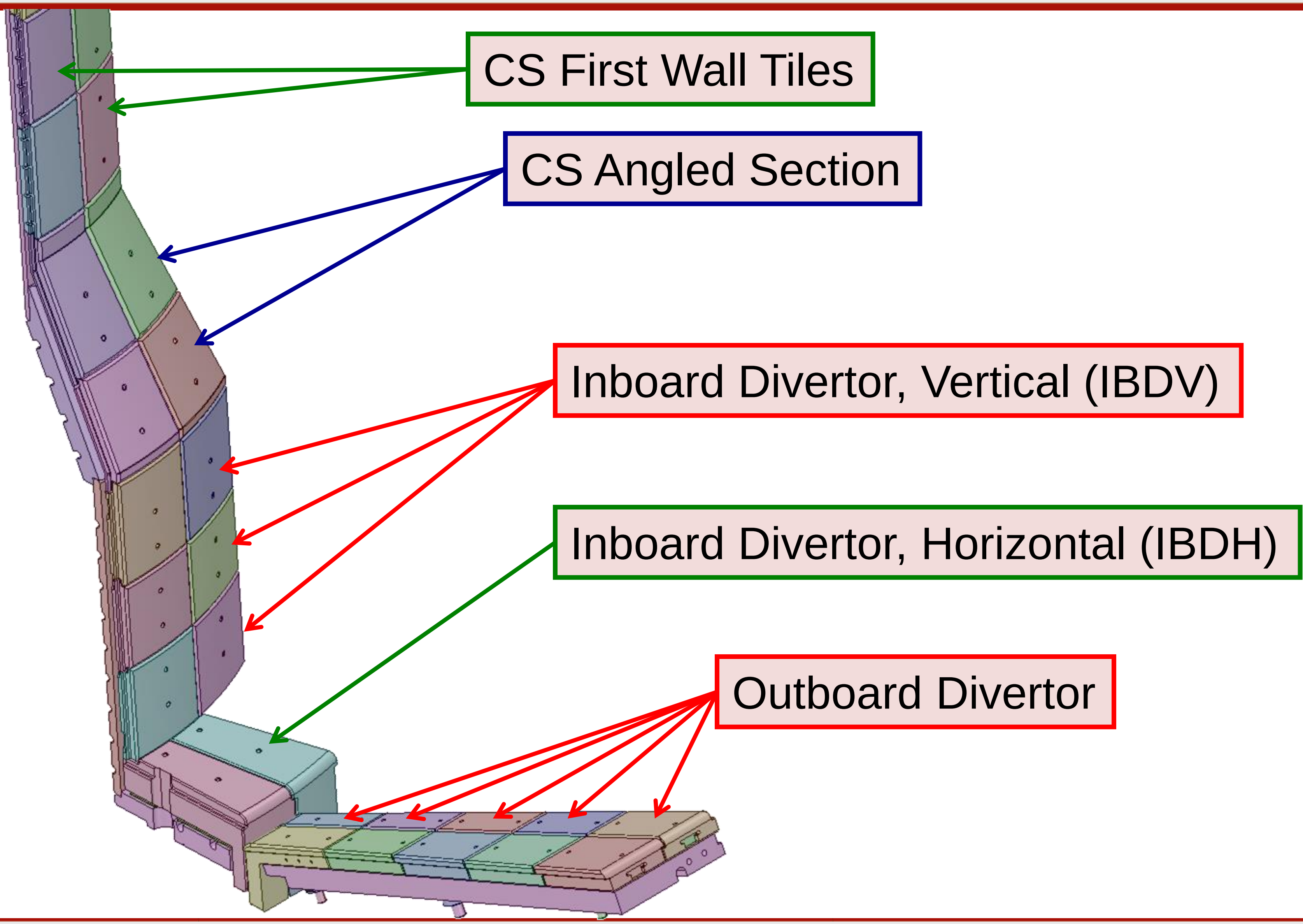
- Example case from scan:
  - $\kappa = 2.5$
  - $l_i = 0.6$
  - I_{OH} = -12kA (~mid/late flat-top)

- No PF1B, use PF1C for flux expansion → R_{strike} variation
  - **Need to narrow or close CHI gap**



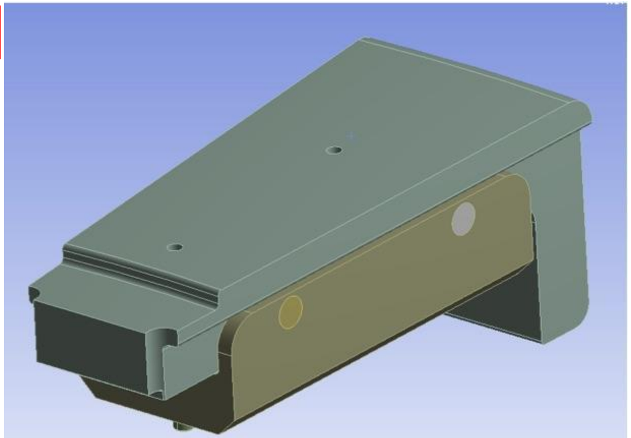


These are the Polar Region Tiles

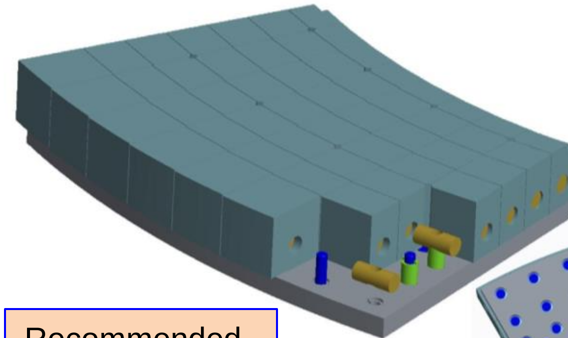


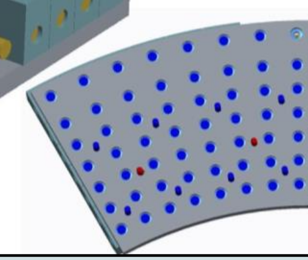
Assessed Two Concepts For New Inner Horizontal Target Tiles

A. Brooks



M. Mardenfeld



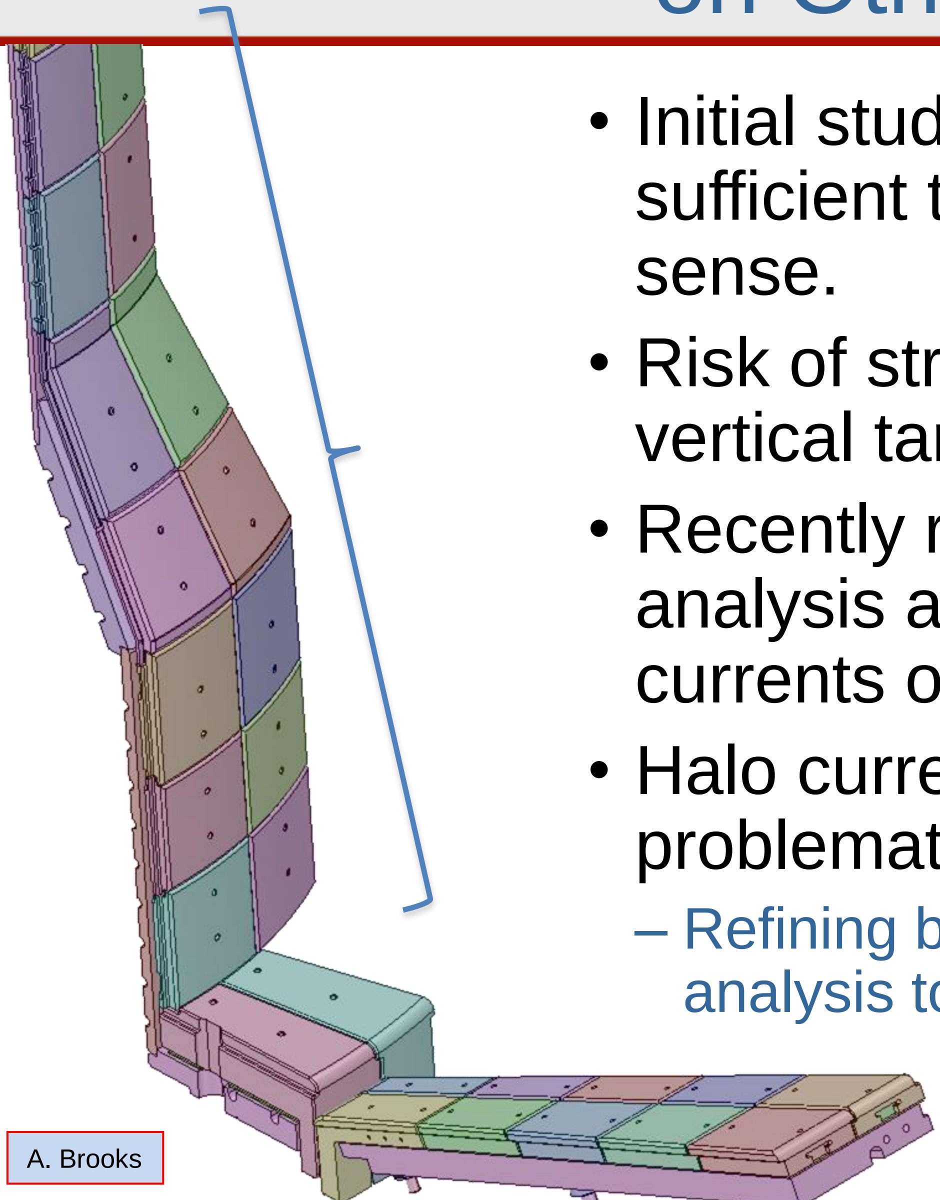


Recommended for further evaluation

Simple Cassette, Sigrafine, 1 or 2 sub-tiles		Fake Monoblock (Mardenblock)	
Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Meets GRD heat flux, especially with subdivided tiles	Will be thermal stress limited, likely less operating space	No surface features if fishscaled • No Leading Edges • No Stress Concentrators	Tends toward wanting fishscaling
Pins react radial halo currents force	Stress concentrations, surface features for bolt holes, diagnostic	Limited by max T	Substantial diagnostic redesign
		Replace cubes to change helicity	
		Halo Current Forces Smaller	

We continue to evaluate the optimal path forward, including optimal fish-scaling angles

Still Working to Resolve Our Final Position on Other Tiles



A. Brooks

- Initial studies indicate that their may be sufficient thermal margin in an average sense.
- Risk of strong leading edge heating on vertical target
- Recently revised both physics and analysis assumptions regarding halo currents on the CS.
- Halo current loads are large and likely problematic
  - Refining both the requirements and the analysis to better assess this issue.

Agenda

- FES perspective on Recovery / Research: Josh King
- Organizational Diagnosis Status / Next Steps: Rich and Jon
- Recovery:
  - – DVVR / EoC status and next steps (Rich Hawryluk)
  - – Updates on divertor heat flux and PF coil requirements (Jon Menard)
  - – Recent engineering design activities in polar regions (Stefan Gerhardt)
- Research:
  - – Status and plans for PFC Requirements working group (Matt Reinke)
  - – Impact of polar region options on research ops flexibility (Matt / Jon)
  - – Overview of upcoming FESAC and NAS workshops (Rajesh Maingi + Jon)

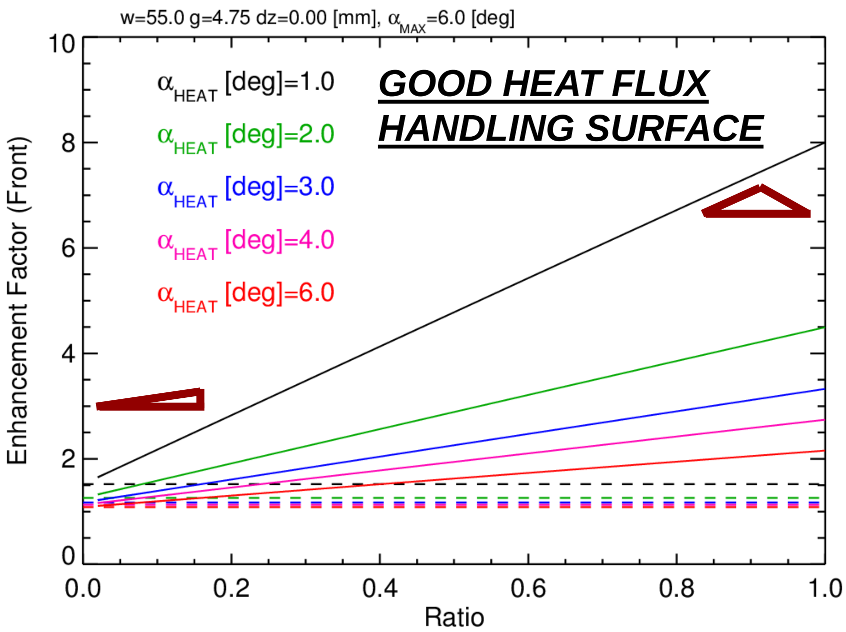
NSTX-U PFC Performance and Monitoring Requirements Working Group (PFCR-WG)

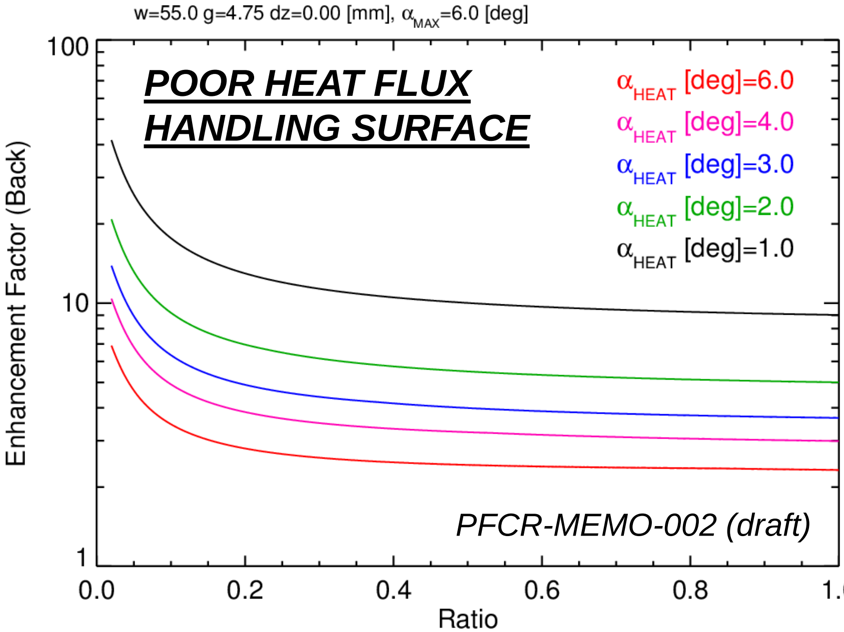
- Formed and charged by JEM after 3/22 Team Meeting:
  - 1. Define which (additional) parameters need to be specified in an updated requirements document for the NSTX-U PFCs
  - 2. Facilitate generation of updated requirements utilizing:
    - a. Available reduced models, empirical scalings, boundary simulations
    - b. Ultimately, a validated model for specifying heat loads to all plasma facing components for arbitrary NSTX-U scenarios
  - 3. Develop instrumentation plans and operational guidance
  - 4. Work closely with engineers and analysts to develop and implement requirements
- Kick-off meeting on 3/29 (Deputy: Mike Mardenfeld)
  - 38 members: theory, experiment and engineering participation
  - PPPL, ORNL, U. Wisconsin, U. Washington, UT-K, LLNL and CCFE
- Want to increase participation within the NSTX-U team
  - Many open questions that need physics input to guide engineering design and outline future operations guidance
  - See website for open ACTION ITEMS, please submit your own!
    - literature investigations, NSTX/NSTX-U data mining, interaction with other devices

Recent Work and Future Plans

- Directly contributed to the drafting of the requirements document which was reviewed at PFCR-WG meeting
  - charge 1, close to being complete (rev0 of requirements soon)
  - summarized evolution of requirements process on MAST-U
- In-progress/near complete contributions (MEMOS!)
  - guidance to Recovery Project on EoC recommendations for real-time protection of PFCs (needs further WG consensus)
  - guidance on reversed field requirements and tile shaping options (next slide)
  - impact of error fields like CS alignment on tile shaping (Ferraro)
  - review of literature/designs on carbon temperature limits (Raman)
- Need to start working on Charge 2 to help improve the accuracy in the heat loading data that is in the requirements (future meeting)
  - start from Menard model, check accuracy & question assumptions
    - examine uncertainties in the IBDV that could impact design decisions
    - respond to PFC Engineering team as they analyze other regions of the machine
    - try and bound physics uncertainty to ensure requirements are accurate
  - eventually move to proven community tools (PFCFlux, SMARDDA?) that can robustly handle shaped tiles
    - not the first facility to deal with this and should take advantage of existing knowledge

Challenge to Shape Tiles for Flexibility





- high heat flux divertors typically shape tiles toroidally to hide leading edges created by tooling gaps, diagnostics and installation/fabrication tolerance
  - necessarily give up heat flux handling to gain operational flexibility
  - ‘fish-scaling’ (uni-directional) or ‘roof-top’ (bi-directional)
- plotted ‘enhancement factor’ qualitatively means either dropping heat flux (proportionally) or operational time (squared) [it’s really a bit more complicated than this]
- optimal tile shape driven by desired operational space
  - desired range of field line angles, expected heat flux on forward/rear surfaces
  - even if we decided on an optimized case, still need operational space to get to it!

Impact of polar region options on research flexibility

- No ceramic breaks would eliminate CHI capability
- Tile fish-scaling required in several regions to manage high heat fluxes of 2MA/10MW/5s → Eliminates reversed B_T
  - Langmuir probes, gas feeds / divertor MGI, other sensors in tiles will also need to be redesigned in concert with PFCs
- (Near) perfect snowflake divertors (SFDs), other advanced divertors will have reversed helicity for some tile regions
  - Need requested SFD equilibria ASAP to assess tile impact / options
  - Bi-directional tiles may be an option for lower $q_{\perp}$ divertor regions
- Pedestal/ELM/H-mode threshold studies - need additional specs of requested range of ΔR_{SEP}, duration, κ, δ, R_{strike}
  - Up/down asymmetric boundary increases q_{peak}, reduces Δt_{flat}
- BP SG/TT TSG charged to provide info to PFCR-WG/JEM

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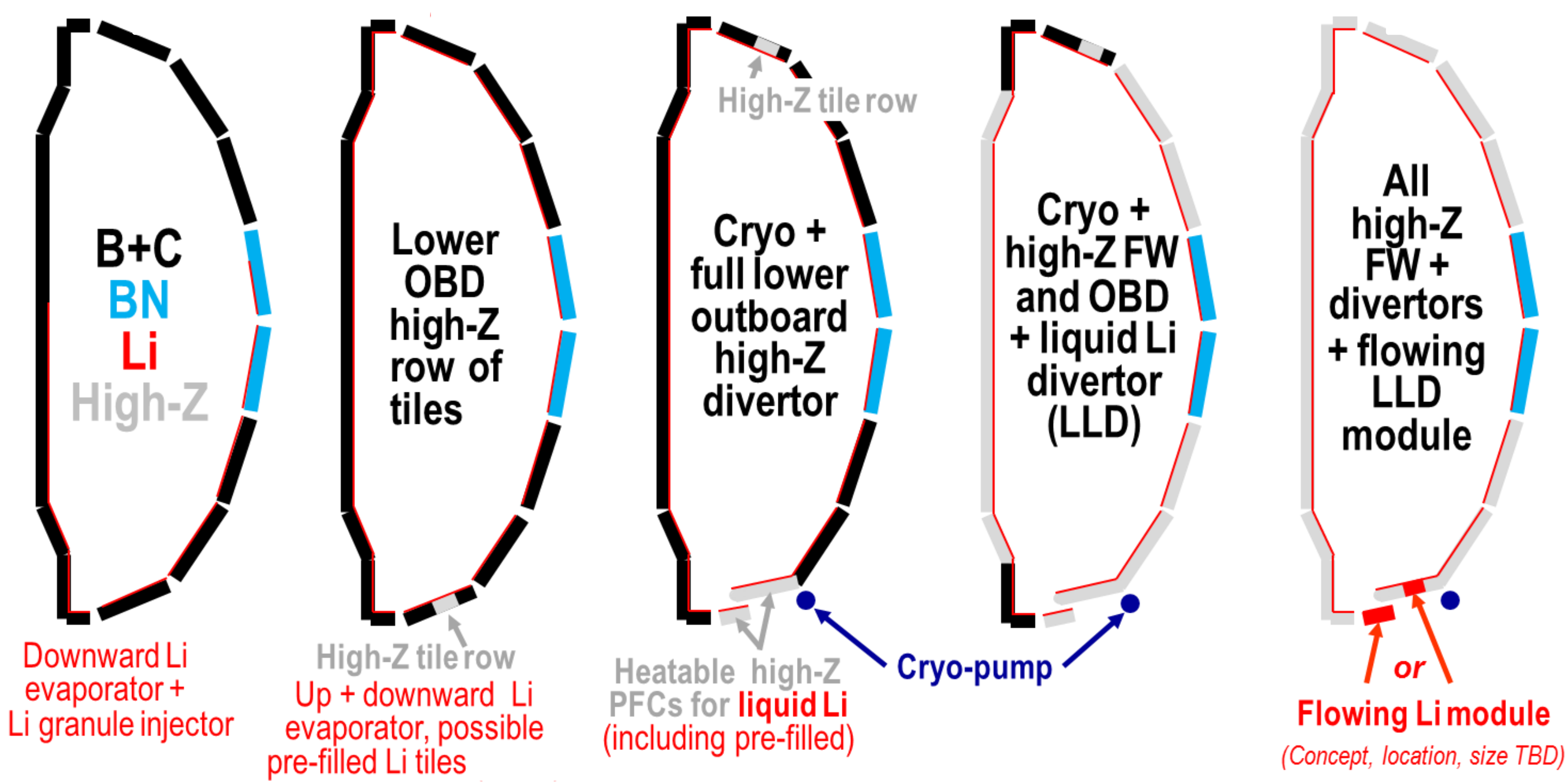
M&P research will develop understanding of material migration and heat-flux handling of high-Z and liquid Li PFCs

5-Year Plan Research Thrusts

- MP-1: Understand lithium surface-science for long-pulse
  - Assess impact of more complete Li coverage
  - Use the Material Analysis and Particle Probe (MAPP) and laboratory studies to link tokamak performance to PFC surface composition
- MP-2: Unravel the physics of tokamak-induced material migration and evolution
  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solutions
- MP-3: Establish the science of continuous vapor-shielding
  - Determine the existence and viability of stable, vapor-shielded divertor configurations
  - Determine core compatibility and extrapolations for extended durations and next-step device parameters

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)

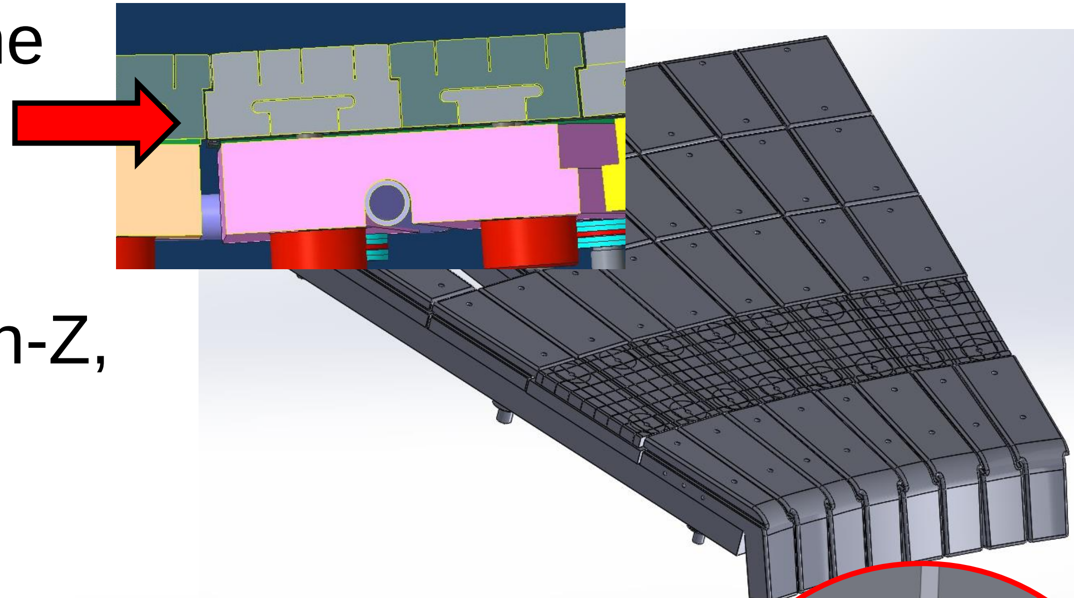


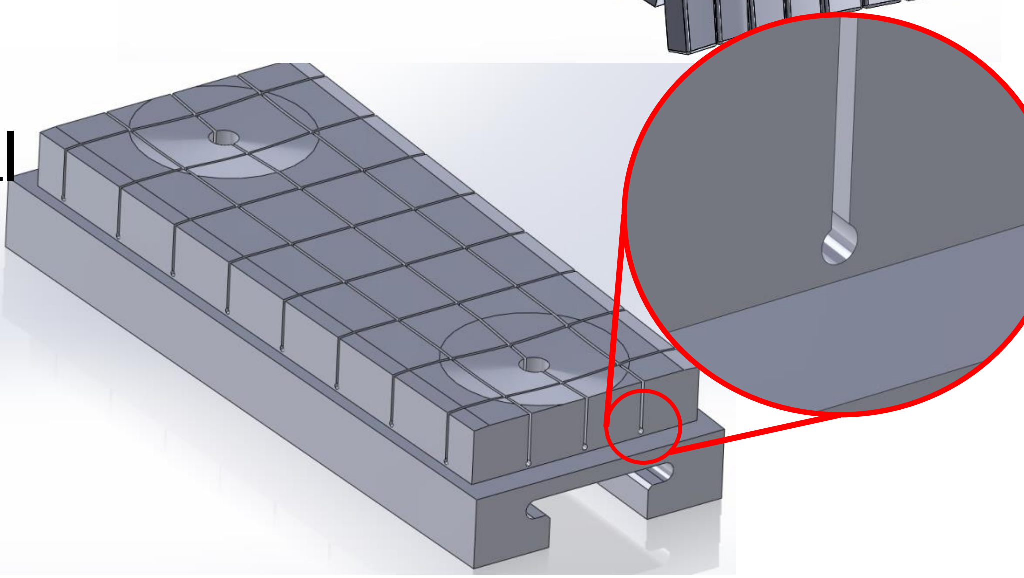
High-Z tile row will provide design and engineering assessments

- 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

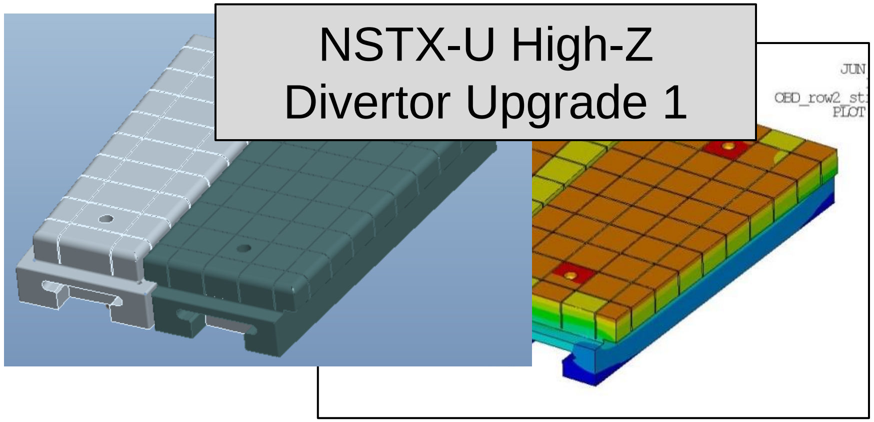
- Machine installation time minimized with 1-for-1 replacement
- TZM-alloy provides high-Z, Li-compatible substrate and machinability
- Surface castellations relieve thermo-mechanical stresses
  - Separate peak stress from peak temperature
  - Several design iterations to optimize for NSTX-U tile shape





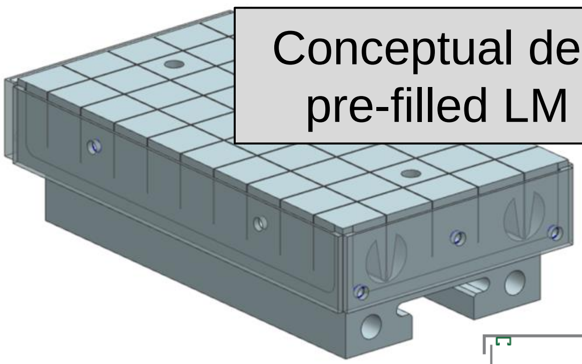
A three-step progression leads to flowing, liquid metal PFCs

1. High-Z divertor tiles + LITER



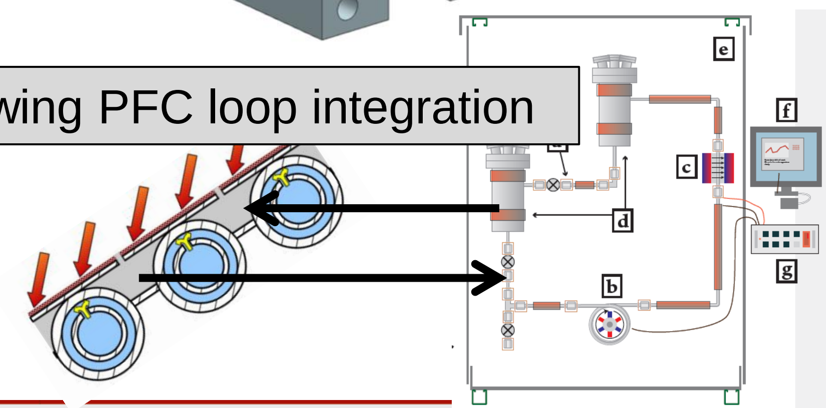
NSTX-U High-Z Divertor Upgrade 1

2. Pre-filled liquid-metal target



Conceptual design for pre-filled LM target

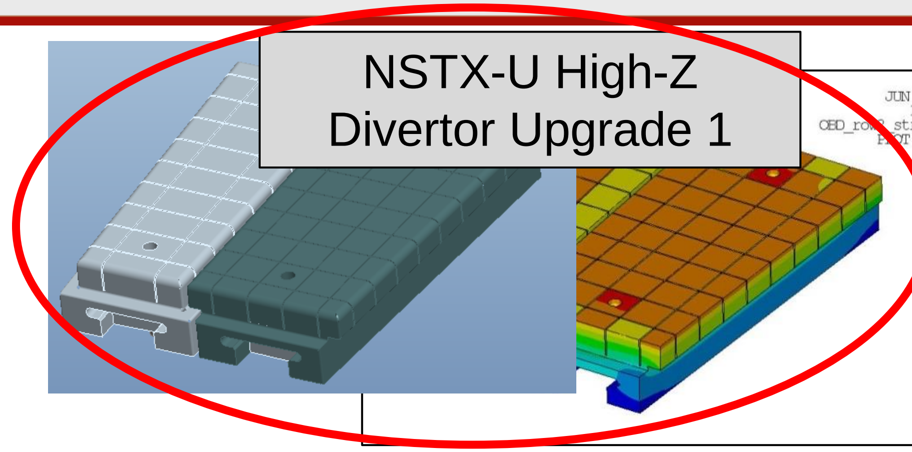
3. Flowing LM PFC



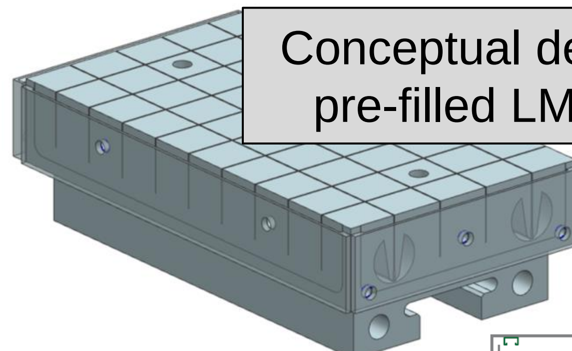
Flowing PFC loop integration

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



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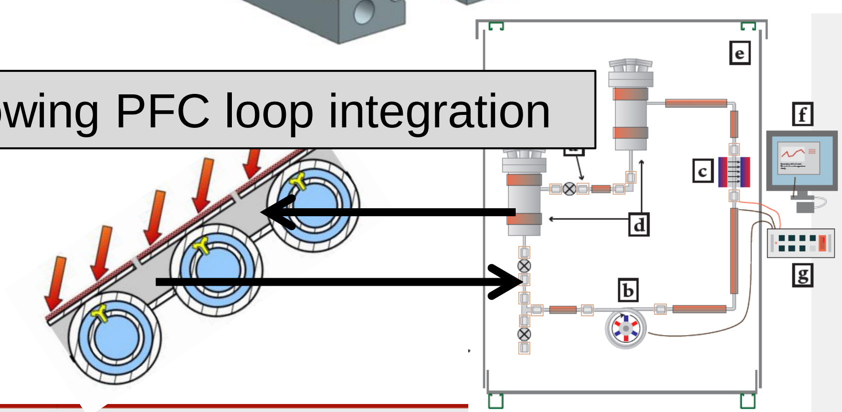
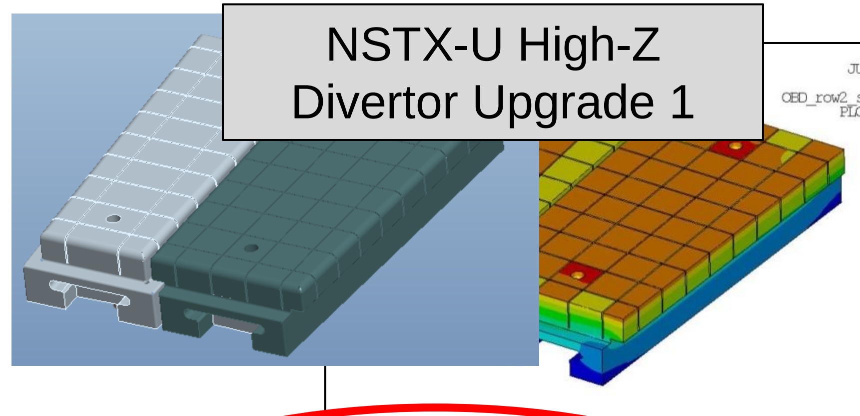
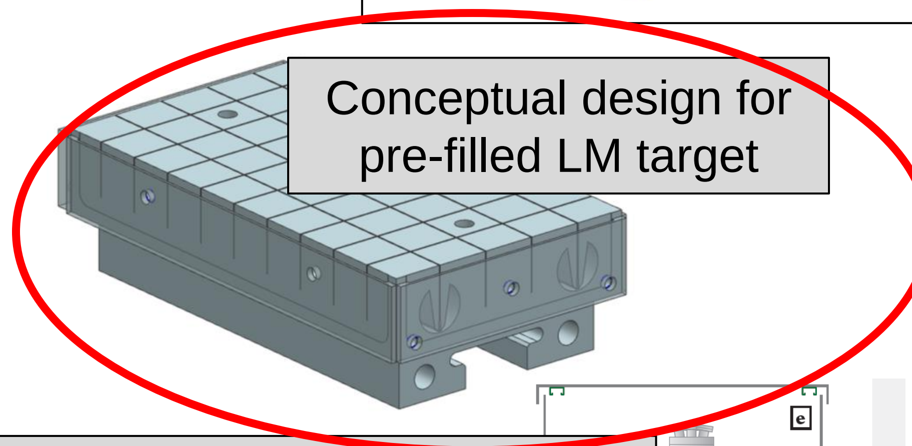


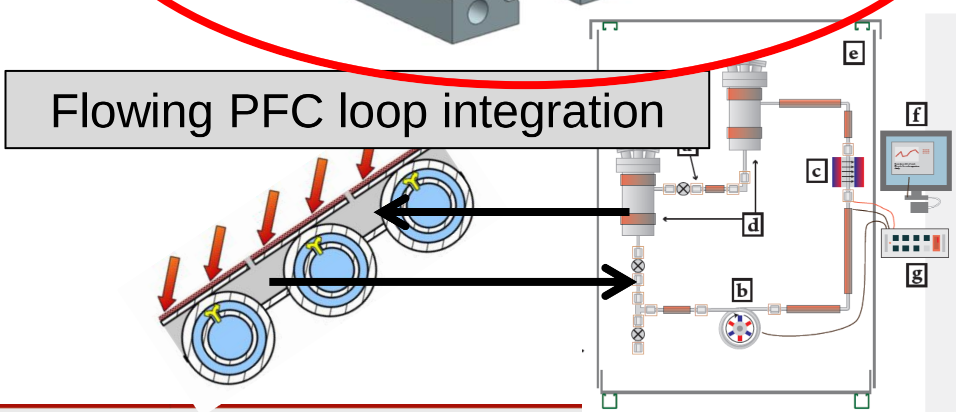
Flowing PFC loop integration

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



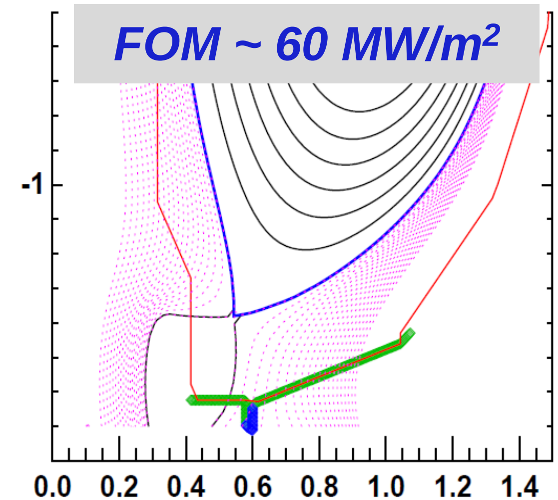




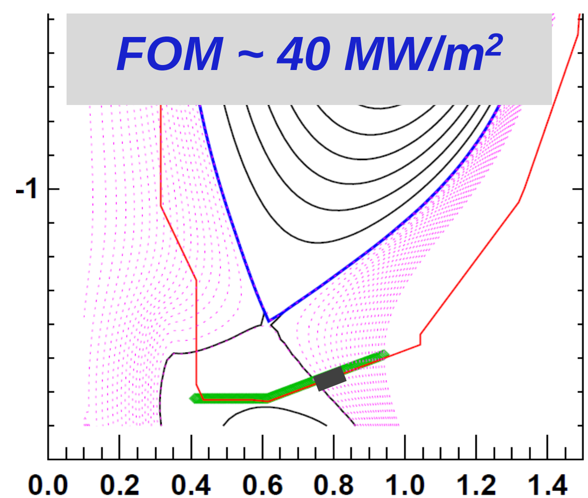
Replacement of outboard row of tiles provides significant heat-flux and maintains operational flexibility

- 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

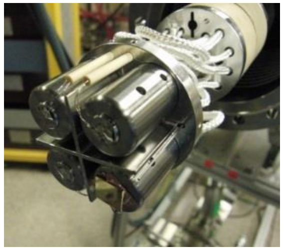


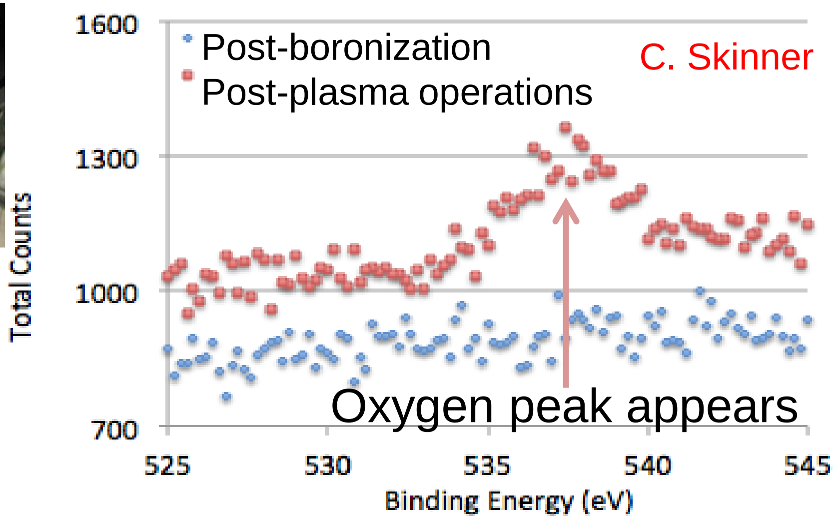
High-Z reference discharge



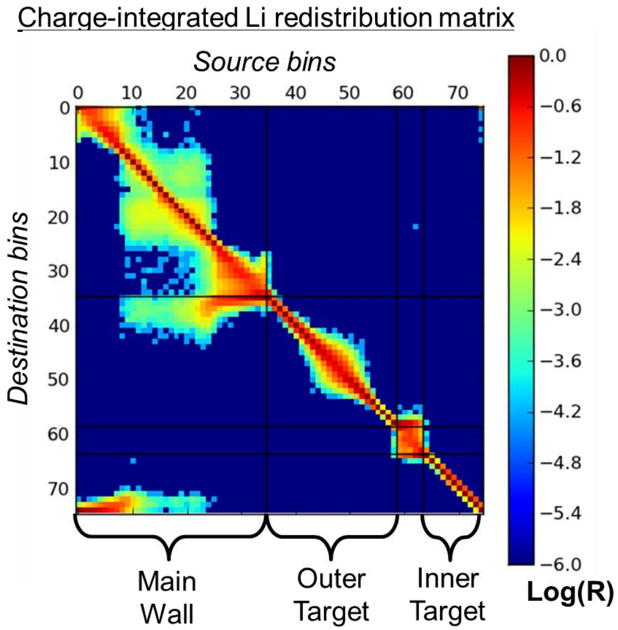
High-Z progression highlights mixed-material PMI and coordinated lab studies

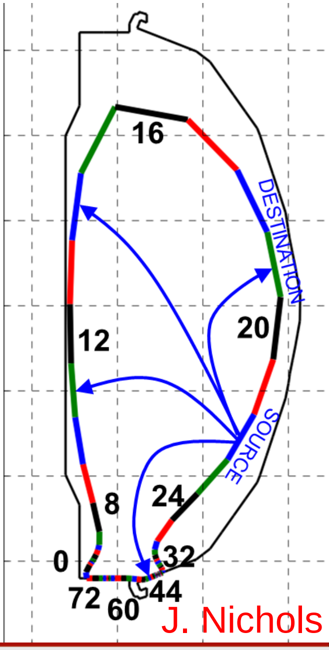
- Material Analysis and Particle Probe enables compositional analysis
  - Measurements of C, Li, Mo, B, O via XPS
  - D retention via TPD





- 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**

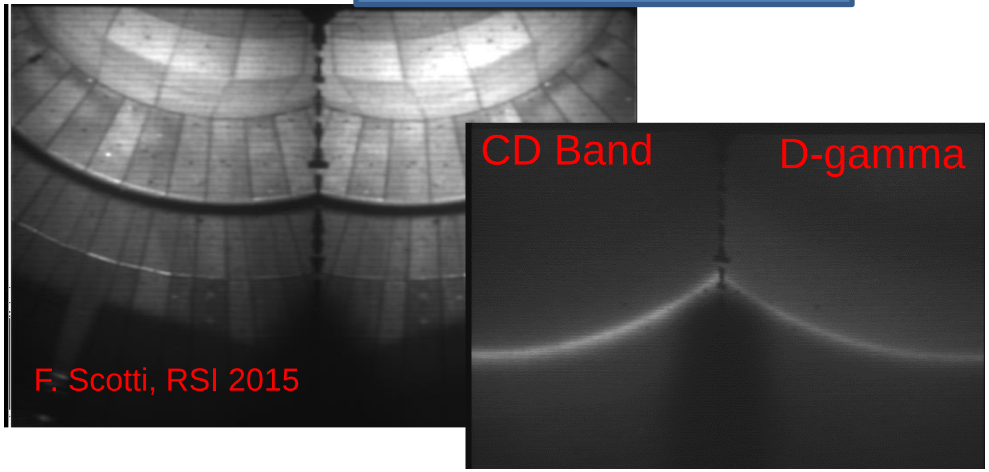




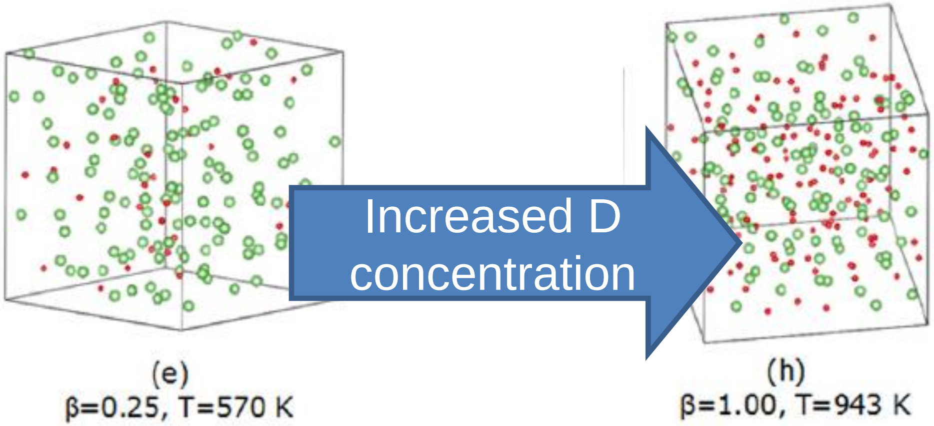
High-Z, mixed-material erosion examined in experiment and with quantum modeling

- Extensive diagnosis of PFCs via plasma
  - Multiple imaging systems, spectrometers
  - Langmuir probes
  - Infrared thermography

2-color simultaneous imaging



- 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)



$\beta = N_D/N_{Li}$

Chen, NF 2016

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Current Milestone R18-2

- **R(18-2): Performance evaluation of high-Z candidate design and materials for NSTX-U**
- *Description:* The NSTX-U has a multi-year program to transition the interior plasma-facing components from the existing graphite materials to metallic substrates. This transition is expected to mimic conditions expected in future power reactors as well as enable more reactor-relevant studies of lithium as a plasma-facing component. The NSTX-U conducted a project in FY15-16 to develop a continuous row of high-Z tiles for installation in the NSTX-U outboard divertor. The design was optimized for high-heat flux performance under the criteria that the existing mounting scheme be re-used. The analysis conducted during the project highlighted certain critical thermo-mechanical properties as well as the need for cyclic fatigue data in stress and temperature conditions expected in the NSTX-U. This research milestone will undertake accelerated-time testing of these relevant properties in a range of experimental devices. In particular, the impact of surface recrystallization and stress concentrators will be evaluated to determine if there are significant impacts on the overall life-time of refractory-metal components. Prototype diagnostics relevant to the high-Z material program will also be tested in order to further optimize the NSTX-U implementation. The data obtained in this research milestone will be used to validate the engineering efforts conducted in the high-Z design project and provide additional guidance for future, high-heat flux upgrades of the NSTX-U plasma-facing components. Models of boron- and lithium-coated metals will be further developed and compared to experimental results as appropriate.

Proposed Milestone Revision

- Modify to reflect current NSTX-U Recovery activities and questions
  - High-Z deferred to later date; Considering fish-scaled tiles design and/or CFC
- Evaluate stress-limits of proposed graphite design and high-Z design in high-heat flux facility (e.g. Magnum-PSI, e-beam, other?)
  - Current, rounded-corner tiles predicted to exceed engineering allowable stress at 1400C
  - Current draft of Requirements document allows 1600C on surface, 2000C at corner for carbon ablation
  - Previous High-Z tile design activity allowed 1400C on TZM due to recrystallization
- Evaluate self-limiting materials behavior of high-temperature graphite
  - Philipps 1992 TEXTOR paper observed clamping of temperature of graphite limiter well below radiative self-cooling limit at ~3000C
  - Also concluded that radiation-enhanced sublimation not an issue due to redeposition of thermally-emitted carbon
  - High-similarities to vapor-trapping phenomenon observed on Magnum-PSI with lithium and part of the general physics of self-limiting materials

- **If carbon self-limits at a temperature below the structural limitation of graphite, then PFC will be robust to plasma-loading and increases reliability of NSTX-U to operate**

Discussion for other impacts

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