NSTX-U

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Progress and plans for Li/Liquid metal and high-Z PFC development

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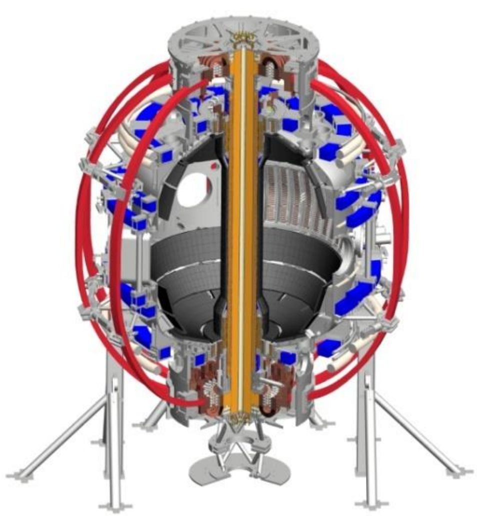
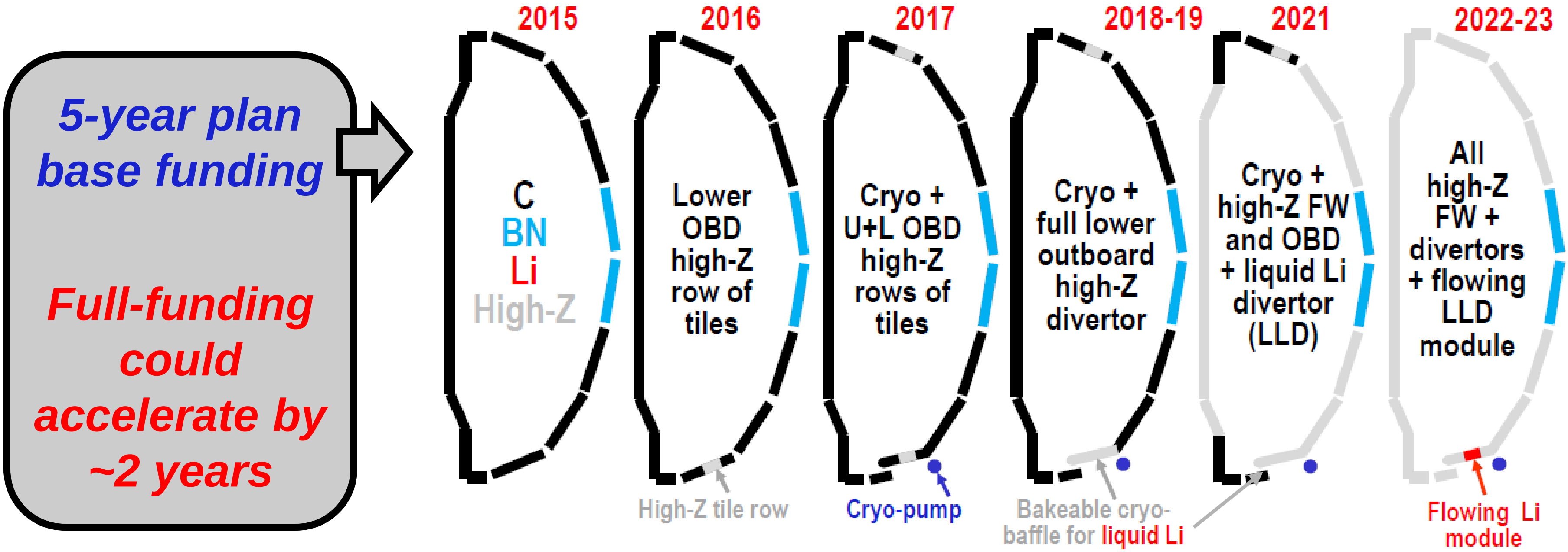


Outline

- Introduction to the Materials and Plasma-Facing Components (M&P) topical science group mission
- Research thrusts for Materials and PFCs from the NSTX-U 5-year plan
- Progress and plans on each thrust area
  - MP-1: Surface science for long-pulse
  - MP-2: Material migration and evolution
  - MP-3: Continuous vapor shielding
- Summary

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

- Conversion to all-metal PFCs enables examination of the role of PFCs on integrated scenarios with good core, pedestal, and divertor operation
- NSTX-U has two emphases for addressing power exhaust and PMI issues for next-step devices
  - Magnetic topology, radiative divertors (Soukhanovskii talk next)
  - **Self-healing/replenishable materials (e.g. liquids)**
- Significant uncertainties in both solid- and liquid-PFCs motivates parallel research



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
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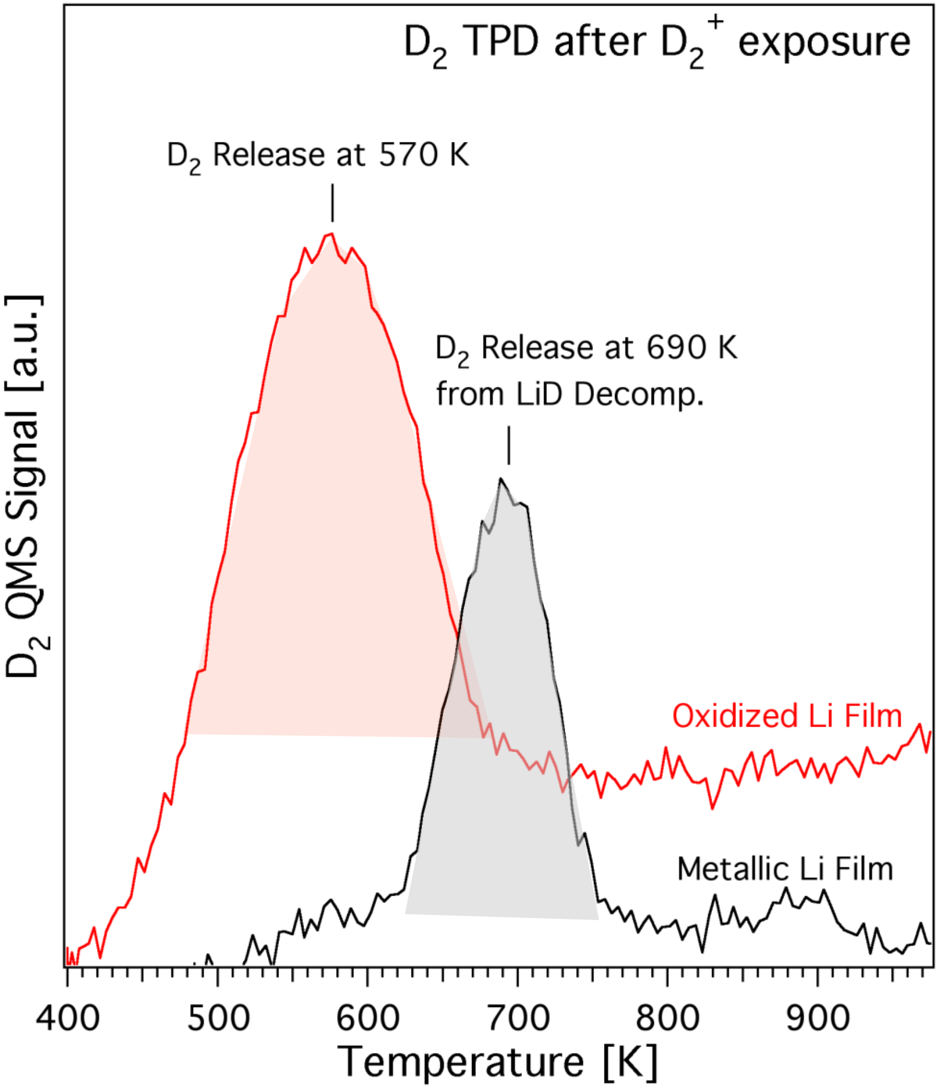
  - Determine core compatibility and extrapolations for extended durations and next-step device parameters

Surface-science laboratory studies probing effects of temperature and impurities on Li and LiD

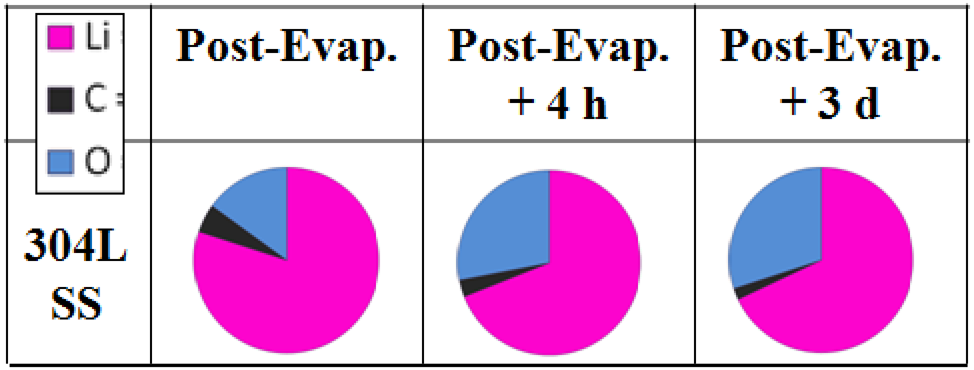
- Fundamental data on Li coatings on high-Z materials extending graphite work
- Thin films (few monolayers) of Li deposited on Mo
  - D_2 evolved below 750K with or without C and O impurities
  - Oxidation of Li film destabilizes LiD
- Implication for a reactor: high-temperature thin-films will not retain T



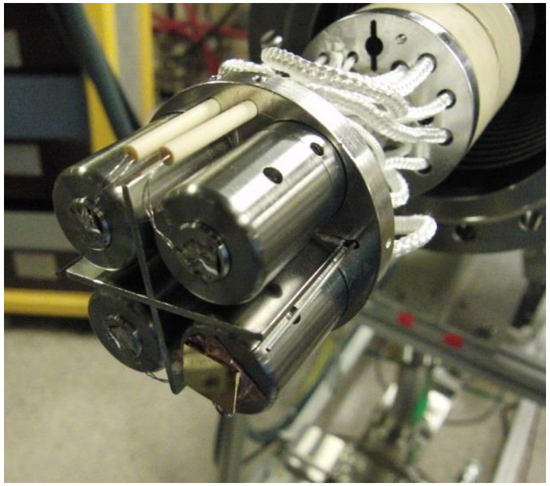
Material Analysis and Particle Probe (MAPP) in-situ diagnostic examining PFC surface composition of Li in prep for NSTX-U

- MAPP in regular use on LTX characterizing surface composition
- XPS of samples indicate rapid transition to oxidized state
- Link to plasma-performance being examined in LTX

Consistent with Li_2O



Probe end with four sample holders that can be heated independently



Probe end inserted into LTX vacuum chamber

FY14-16 research will continue to elucidate atomistic and material characteristics of the NSTX-U PFCs

- FY 14: research will continue in surface-science laboratories and in LTX
  - Wetting studies, deuterium uptake, surface energies
  - Role of impurities on the above
- FY 15: research will determine the surface composition during NSTX-U operations alongside material migration
  - MAPP, post-mortem witness plates and QCMs determine quantity and composition of PFC surfaces
  - Granule injection system will provide new method of depositing lithium into NSTX-U for comparison to boronization, and Li evaporations
- FY 16: Li wetting and removal of material will be examined
  - Surface composition of high-Z samples will be assessed to inform on expected composition of high-Z target PFCs
  - Wetting studies of Li on high-Z with and without contamination will aid in determination of critical parameters for protection of the high-Z substrate

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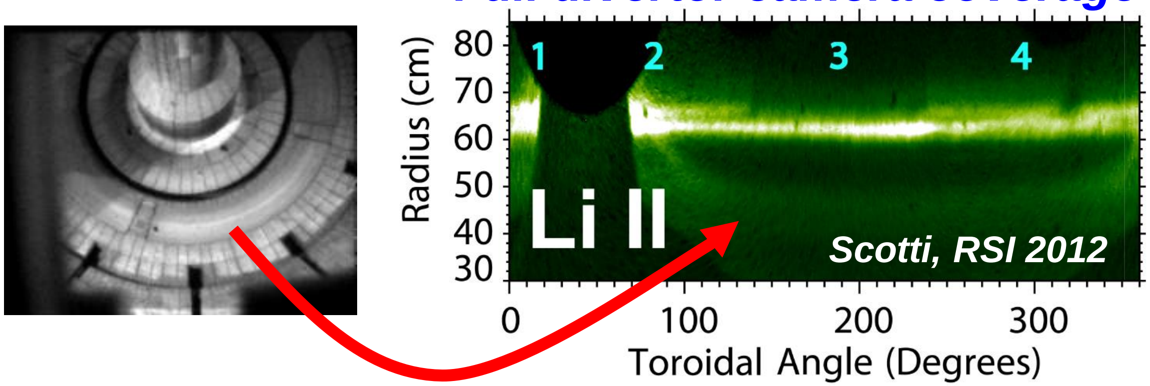
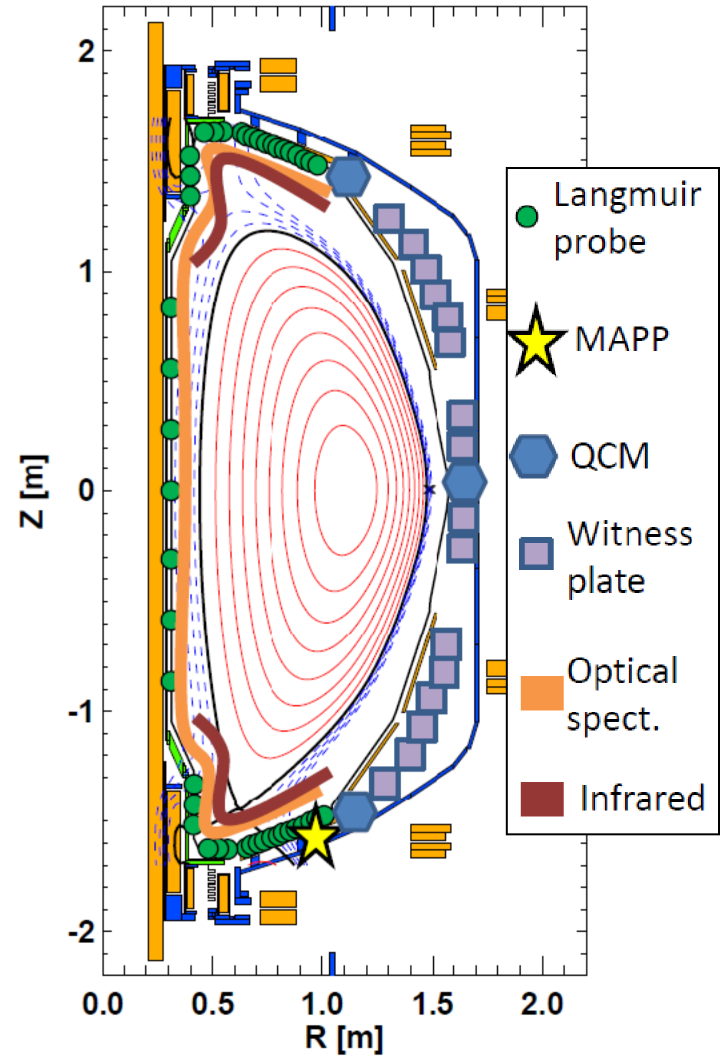
Diagnostics will be key to making strongest possible progress on material migration

- Nearly complete PFC coverage available for gross-erosion measurements
  - Strong collaborator participation (LLNL, ORNL, UTK)
  - Whole-machine and high resolution camera optical systems available
  - More extensive probe coverage to aid interpretation with more plasma shapes
- QCMs, witness plates and MAPP provide complementary single-shot and campaign integrated data sets
- Wide-angle infrared diagnostics characterize PFC surface temp. and heat flux (ORNL)

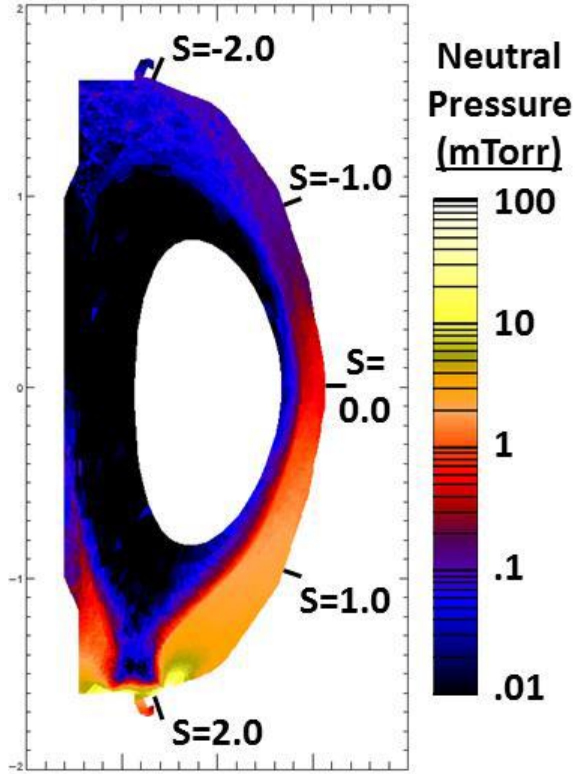
Full divertor camera coverage

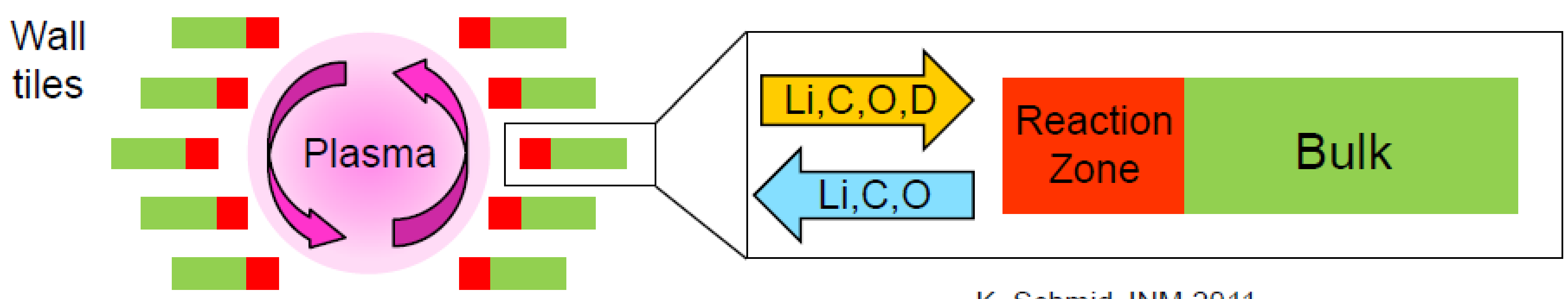




Interpretive modeling key tool to produce picture of whole-machine material migration including localized sources

- OEDGE simulations underway for planning FY15 experiments
- WallDYN being obtained for use on NSTX-U (PhD thesis)
- Experimental data sets will provide constraints on plasma-backgrounds
- Both can leverage plasma modeling from UEDGE, SOLPS or other codes

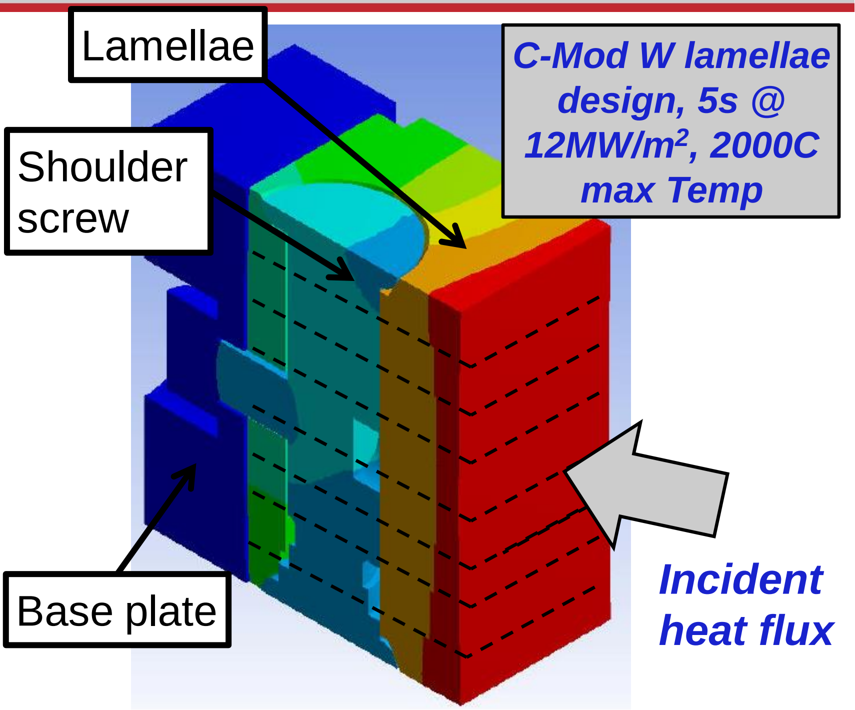




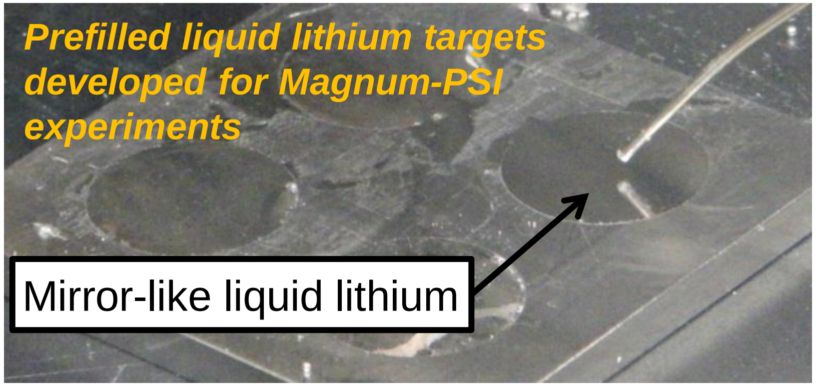
K. Schmid JNM 2011

C-Mod and JET high-Z PFCs designs inform design choices for NSTX-U

- Target will be located in outboard divertor to minimize risk (LLD logic)
- CMOD reference design provides compact example (Willard 2006)
  - 30mm total height minimizes profile changes on divertor floor
  - Will adapt to interface with NSTX-U mounting structures
- JET-ILW shallow melt experiments provide example of leading-edge experiments (Coenen PSI 2014)



- Pre-filled liquid lithium targets developed for Magnum-PSI experiments will be considered as targets on MAPP probe drive (Eindhoven Univ. student project)



FY 14-16 research plans for material migration will characterize transport of low and high-Z materials

- FY 14: Diagnostic check-out and modeling will guide development of XPs for FY15-16
  - Deployment of diagnostics to prepare for run (new array of Langmuir probes, existing and new spectroscopic systems)
  - WallDYN code will be obtained and first runs made to prepare for migration modeling for FY15
- FY 15: First experiments will provide data to validate integrated modeling
  - WallDYN will be compared to QCM, MAPP and witness plate measurements of shot-by-shot and campaign-integrated material migration
  - Reference discharges will be developed targeting the outboard high-Z tile location for comparison to FY16 data
- FY 16: Milestone R16-2 to assess high-Z divertor PFCs will be completed
  - Erosion from high-Z tiles will be assessed with and without low-Z coatings
  - WallDYN predictions of erosion/transport from high-Z tiles will be compared to measurements with QCM, MAPP, witness plates
  - Enhanced impurity production and impact on operation of distributed shallow-melts will be measured

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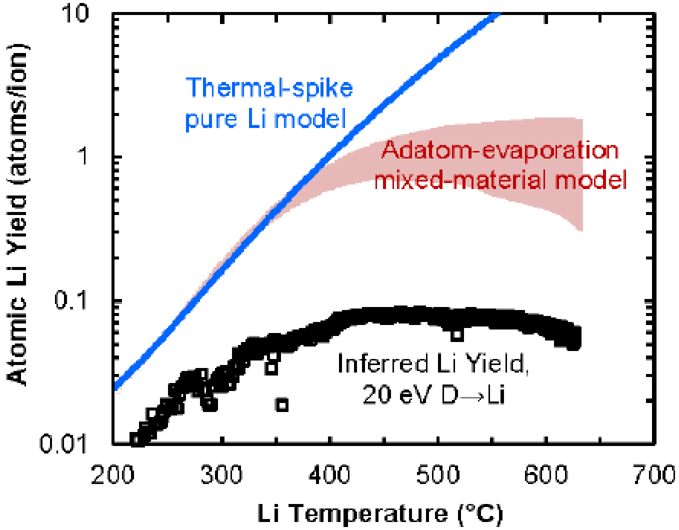
Magnum-PSI experiments on high-temperature Li show strongly reduced erosion and stable cloud production

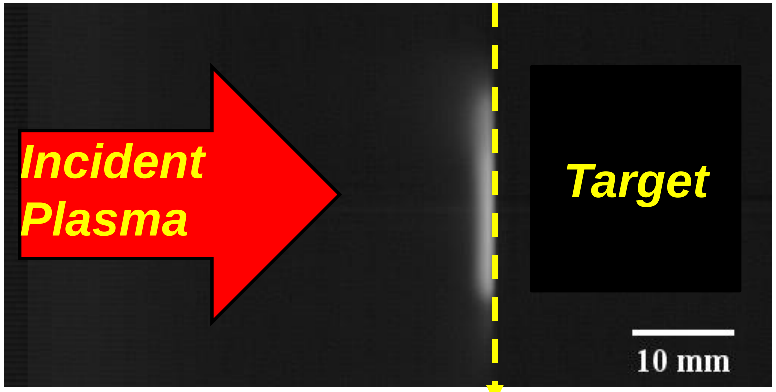
- Gross erosion measured spectroscopically in divertor-like plasma
  - Neon plasma reproduces Langmuir Law
  - Deuterium *suppresses* erosion
- Reduced gross erosion and strong redeposition result 10x longer lifetime of 1 micron coating
  - Consistent with Li trapping in pre-sheath
  - Pre-sheath scale length consistent with neutral Li emission region (~3mm)

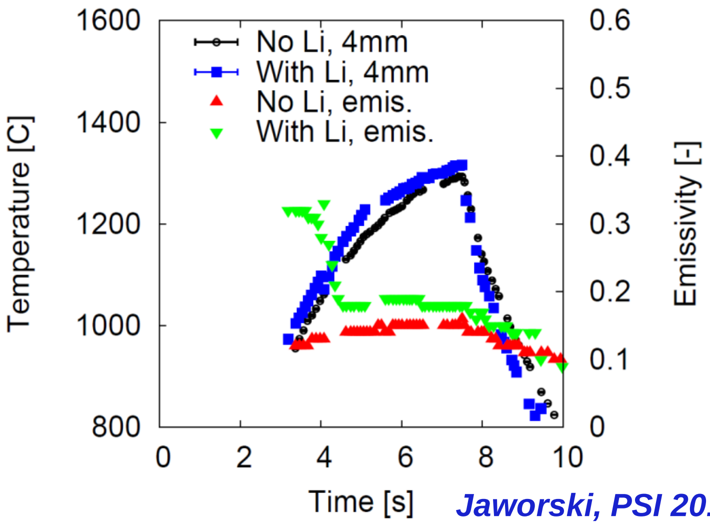
Abrams, PSI 2014

Atomic Li Yield Γ_{Li}/Γ_{D+} vs. Li Temperature



Neutral Li emission, t=2.5s





Jaworski, PSI 2014

Implications of lithium experiments on Magnum-PSI for NSTX-U and next-step devices

- Vapor shielding experiments with thin-coatings will be feasible in NSTX-U with the high-Z targets in FY16
  - Coatings of ~1 micron persisted up to 1000C, ~4s
  - Pre-filled targets under investigation to study effects of larger reservoir

- Previous lithium temperature limits being re-evaluated with momentum-conservation criterion accounting for suppressed erosion and strong trapping at the target

- Concepts based on pure evaporative cooling (e.g. CPS) or flat-plate targets need refinement to offset:
  - Strong trapping at target reduces mass flux, reduces energy transport
  - 100 micron thick layers observed to thin out from center of the sample

Continuous vapor shielding research plans for FY 15-16

- FY 15: Perform preliminary shot development for examining vapor-shielding with the high-Z upgrade in FY16
  - Examine lithium radiation in NSTX-U plasmas and compare to collisional radiative models (FOM-DIFFER student participation)
  - Develop discharges with high heat-fluxes at high-Z target location and range of scrape-off layer widths
  - Develop pre-filled liquid metal targets for possible inclusion as target on MAPP probe drive
- FY 16: Perform initial assessment of vapor-shielded regime on high-Z PFC row in NSTX-U
  - Determine whether the vapor-shielded regime can be produced in the present NSTX-U configuration
  - Determine if carbon/oxygen are strong impediments or can be overcome with suitable evaporations and/or pre-filled targets

Summary

- Materials and PFC topical science group developing tools and methods for examining key issues facing NSTX-U and future devices
  - Expanded diagnostic coverage backed up with interpretive modeling
  - Strong links to surface-science laboratories at PPPL/PU and U-Illinois
- High-Z and low-Z targets both face material migration challenges in NSTX-U and next-step devices
  - NSTX-U research will make inroads in addressing the behavior of mixed materials in an ST using state-of-the-art analysis tools
  - Material migration studies will determine the technological requirements of future solid and liquid PFCs
- Experiments on Magnum-PSI indicate liquid lithium PFCs need not be as temperature constrained as previously expected

Backup

Materials and PFC research is developing science and technologies for NSTX-U and DEMO-relevant machines

- High-Z, metal PFCs are expected for future power-reactors
  - Need to assess impact of high-Z components on core performance
  - Survival of the PFCs w.r.t. extreme heat fluxes (ITER-relevance)
- Will assess role of lithium as a wall-conditioning and bulk-PFC material (i.e. liquid)
  - Protection of the high-Z substrate
  - Protection of the plasma *from* the high-Z substrate
- High-power, high-performance discharges will be impacted by PFC performance
  - Integrated scenario demonstrations will be required for both liquid lithium and high-Z substrates to determine usefulness of either in FNSF and beyond

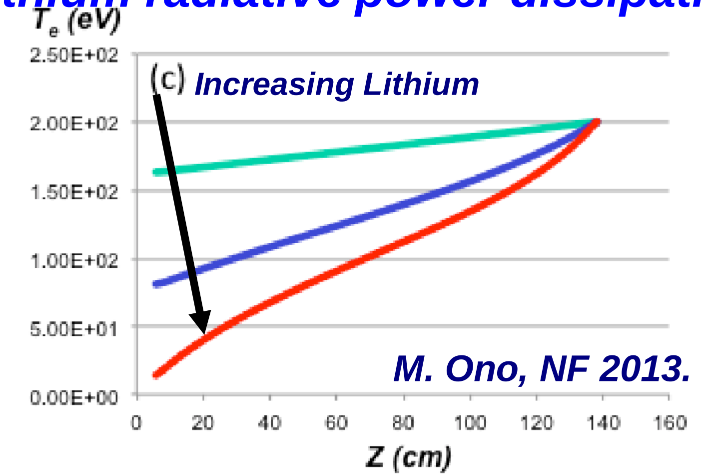
Assessment of high-Z row will provide first look on issues facing a future full-metal upgrade (Milestone R16-2)

- Requirements on power exhaust mitigation determined by PFC thermal limits
  - Develop experiments to determine true limit of the high-Z design
  - Intentional leading edges can locally increase heat fluxes, validate design
  - Focused visible camera can diagnose melt-layers during and between discharges
- Criticality of avoiding PFC damage and subsequent impurity influx will determine margin of error in heat-flux mitigation
  - Assess impurity influx under local-melt conditions with a significant, distributed source (e.g. 12 toroidally separated locations)
  - Penetration factors from divertor target to main plasma should be measured as well as impact of material influx on local plasma parameters (e.g. via radiative cooling)
- Lithium as a protective material and potentially pumping surface can be re-evaluated with post-LLD experience
  - Surface science laboratory providing new insight into wetting and deuterium uptake of thin and macroscopic films
  - Heating and biasing of targets will be considered as means of removing impurities from lithium layers
  - Pre-filled liquid lithium targets will be considered as a means of providing significant reservoir of material to avoid fast saturation

High temperature lithium surfaces may be able to provide a self-healing surface and intrinsic low-Z impurity radiation

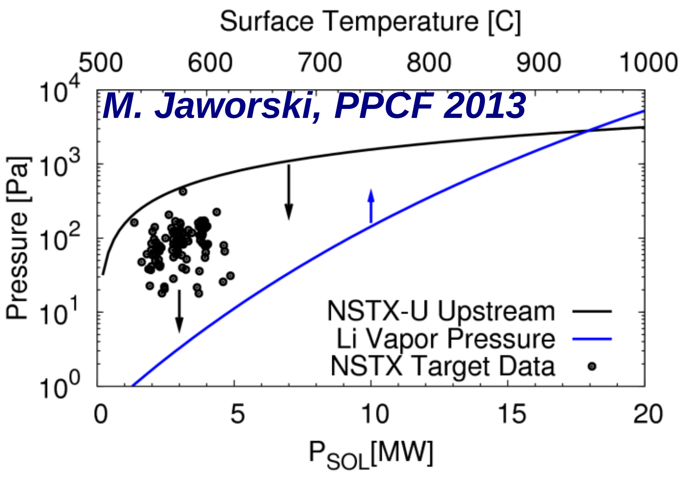
- Lithium vapor cloud can potentially provide effective power and pressure loss at divertor target
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma press.
- Capillary-porous system targets have dissipated large incident heat fluxes – tested to 25MW/m^2 (Evtikhin JNM 2002)
- Diagnosis in NSTX-U via complementary diagnostics
  - Langmuir probes for target pressure, n_e, T_e
  - Optical, VUV emission and bolometry for P_{rad}
  - DBIR thermography and TCs for heat flux and energy deposited

Lithium radiative power dissipation



$$p_u = p_t(1 + M_t^2) + p_{Li}$$

$$q_t = \gamma \Gamma_{sat}^{+} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$



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  - Pre-filled targets under investigation to study effects of larger reservoir
- Previous lithium temperature limits being re-evaluated with momentum-conservation criterion accounting for suppressed erosion and strong trapping at the target
  - Suppressed erosion under high-flux D bombardment and strong-trapping at the target indicates little would escape upstream (parallel indications in NSTX that divertor exhibits strong retention)
  - Particle balance criteria previously utilized should be updated with momentum conservation criteria
  - An integrated power-cycle analysis will be presented at the IAEA FEC 2014
- Concepts based on pure evaporative cooling (e.g. CPS) or flat-plate targets need refinement
  - Strong trapping at target reduces mass flux, reduces energy transport
  - 100 micron thick layers observed to thin out from center of the sample

M&P program providing support for students and collaborators

- Two Princeton PhD students examining high-temperature erosion and material migration
- Senior and junior PU undergraduate thesis students in 2013-14 participating in diagnostic and liquid loop development
- Two international graduate students going to participate in liquid-metal PFC design and Li radiation measurements in coming year (Eindhoven U. and FOM-DIFFER)
- Several undergraduates (3) via National Undergraduate Fellowship (NUF), Science Undergraduate Laboratory Internship (SULI), and Princeton Energy Institute (PEI) fellowship students participating in experiments this summer
- Strong collaborator-led diagnostic systems enabling pioneering and comprehensive measurements of in-vessel PFCs and tokamak modified surfaces