NSTX-U
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Lithium vapor trapping at a high-temperature lithium PFC divertor target

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56th Annual meeting of the APS Division of Plasma Physics
New Orleans, LA – October 27-31, 2014

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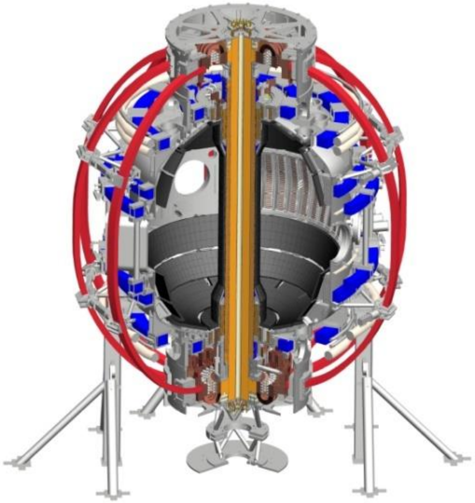

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Liquid metals offer potential advantages over solid plasma-facing components (PFCs)

- Liquid metals provide a self-healing plasma-facing material
    - Immune to thermo-mechanical stresses
    - Returns to equilibrium after perturbations
    - Replenishment eliminates net-reshaping by particle bombardment
- Separates neutron damage effects from plasma-material interactions
- Eliminates long time constants associated with solid-wall material transport and evolution

Arnoux, PFMC-14, Juelich

Coenen, et al., JNM 2013

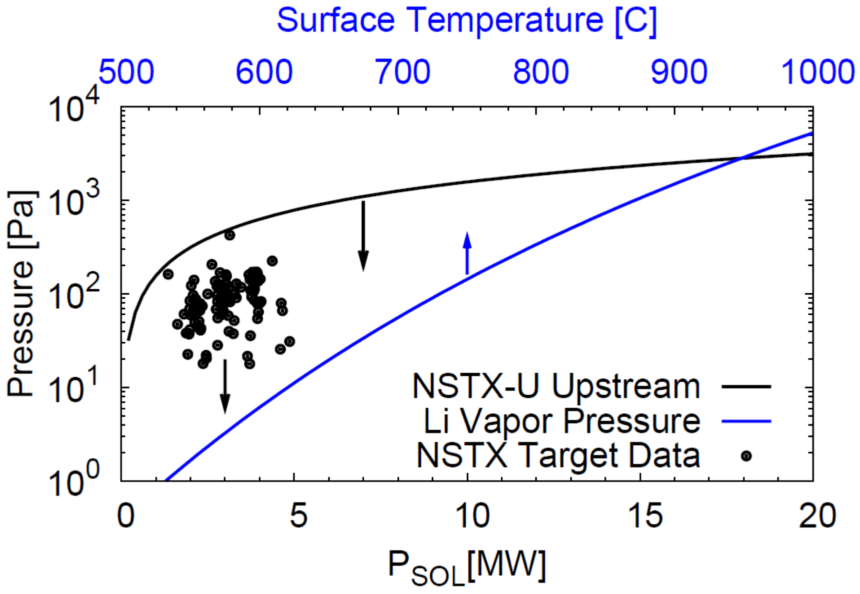
Replenishable surfaces changes the rules of divertor operation: high erosion is accepted, may be beneficial

- Lithium vapor cloud can potentially provide effective power and pressure loss ***(continuous vapor-shielding)***
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma pressure (see M. Ono NF 2013)
- Capillary-Porous System(CPS) targets have dissipated large incident heat fluxes: e-beam tested to 25MW/m^2 limited by Li inventory (Evtikhin JNM 2002)
- CPS limiter in FTU able to operate above 550C (Apicella PPCF 2012)
- **What is $T_{max,surf}$ for a lithium PFC in the divertor?**

Two-point model
Pressure balance

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

$$q_t^{plasma} = \gamma\Gamma_{sat}^{+}T_e = \gamma n_{es}c_sT_e = \gamma c_sp_t$$



Replenishable surfaces changes the rules of divertor operation: high erosion is accepted, may be beneficial

- Lithium vapor cloud can potentially provide effective power and pressure loss ***(continuous vapor-shielding)***
  - Non-
  - Li va press 2013
- Capillary- targets ha incident h to 25MW (Evtikhin
- CPS limit above 550C (Apicella PPCF 2012)

- **What is $T_{max,surf}$ for a lithium PFC in the divertor?**

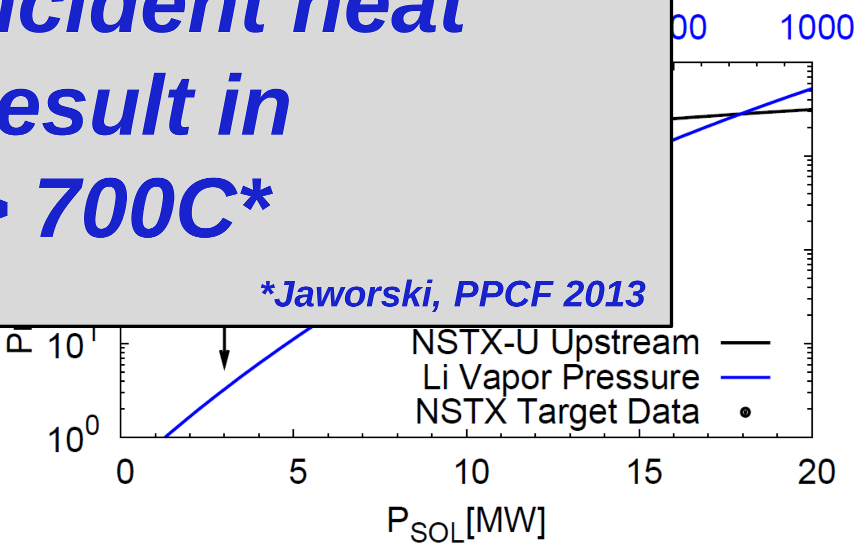
Two-point model Pressure balance

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

$$= \gamma c_s p_t$$

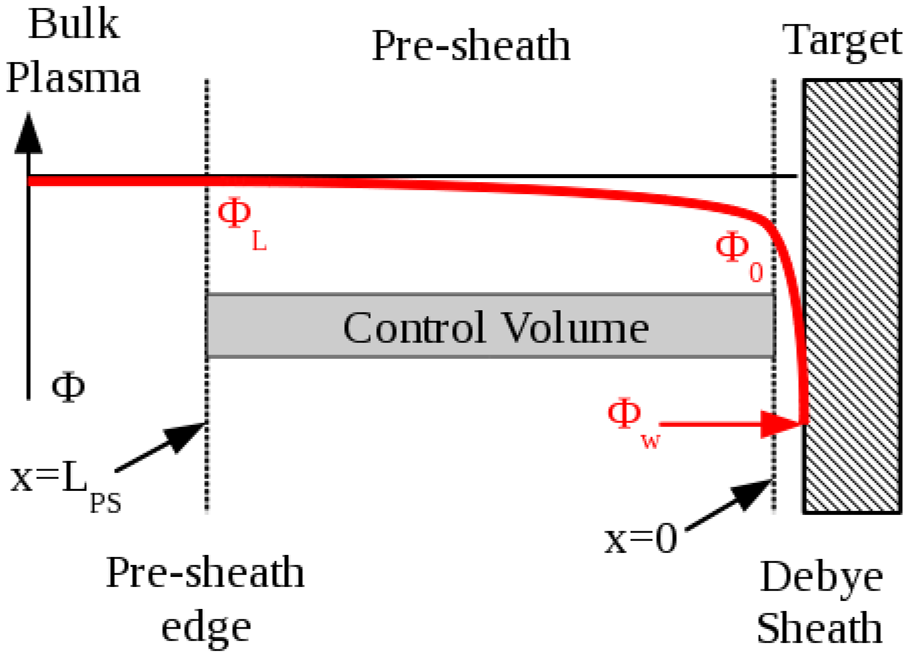
State-of-the-art gaseous cooling with 10 MW/m² incident heat fluxes result in $T_{surf,Li}$ > 700C*

**Jaworski, PPCF 2013*



Pre-sheath potential can trap particles emitted from surface before entering upstream plasma

- Pre-sheath arises to satisfy Bohm criterion for an attached plasma
- Depth of potential well determined by momentum sink terms in pre-sheath*
- Particles are confined if $E_n<\Phi(x)$ where E_n is the energy directed away from the wall and $\Phi(x)$ is the potential



Li ionization m.f.p. 10x longer than Debye sheath scale length

**Chung, 1988, Phys. Rev. A*

Simple plasma-fluid model can illustrate principles of ionization within pre-sheath

- Begin with mass conservation and momentum conservation
- Take volume integral of momentum equation over L_{PS} taking boundaries as known
- Pre-sheath potential drop increases with ionization and momentum exchange
- Potential well predicted to be **0.5Te (~1eV)** and **LPS~3mm** for Magnum-PSI experiments

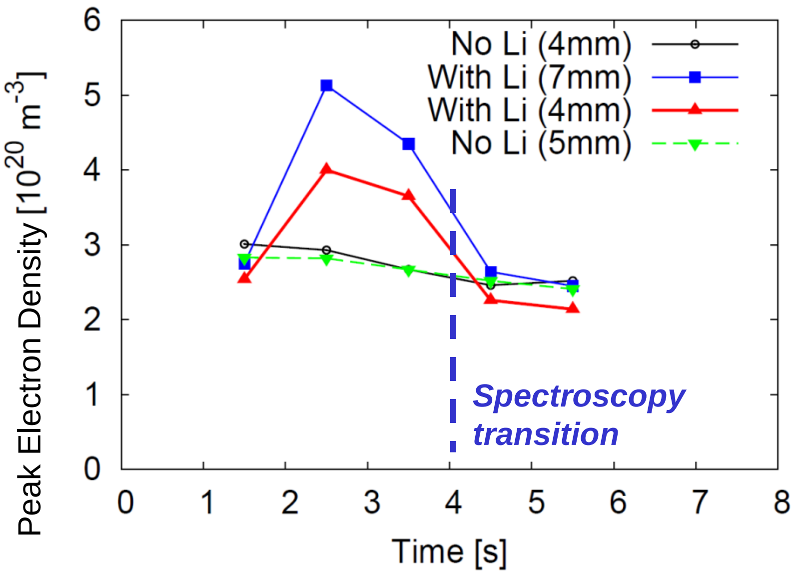
$$\frac{\partial nm}{\partial t} + \nabla \cdot (nmv) = S_{iz}$$

$$\frac{\partial nmv}{\partial t} + \nabla \cdot (nmv\ v) = -\nabla p + qnE - S_{mom}$$

$$\boxed{\begin{gathered} \frac{m(v_L^2 - v_0^2)}{2kT} + 2\frac{n_L - n_0}{n_L + n_0} + \\ \frac{e(\Phi_L - \Phi_0)}{kT} = -\frac{\bar{v}L\overline{(S_{iz} + S_{mom})}}{\bar{n}kT} \\ L_{PS} = \frac{(v_L^2 - v_0^2)}{2n_0\bar{v}(<\sigma v>_{iz} + <\sigma v>_{mom})} \end{gathered}}$$

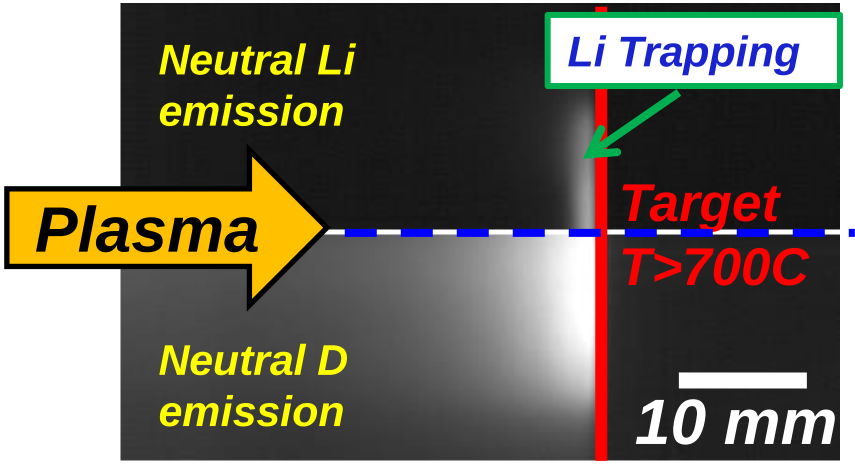
Lithium layers observed to persist for 3-4 seconds vs. <0.5s predicted via gross erosion estimates

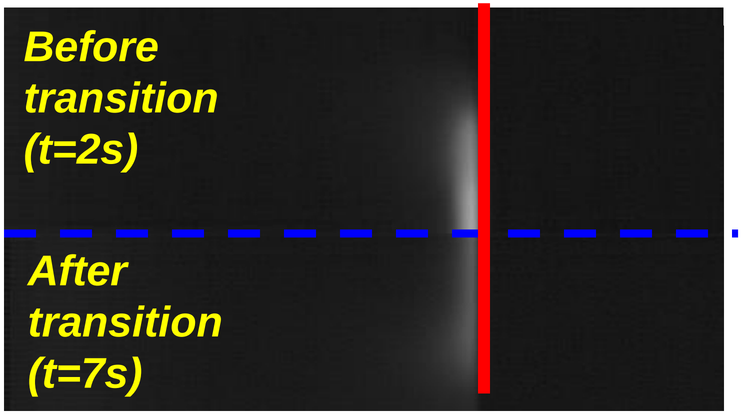
- Two states observed in Magnum-PSI experiments:
  - Intense emission 2-3mm in front of target, persisting 3-4s
  - Transition to diffuse cloud
  - Observable on OES chord as well
  - Transition seen in Thomson as well
- Demonstrates strong trapping near the target surface



L_{PS} ~ 3mm predicted

Li-I emission, t=2.5s

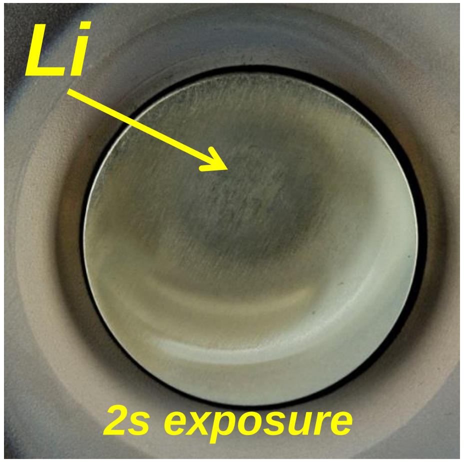


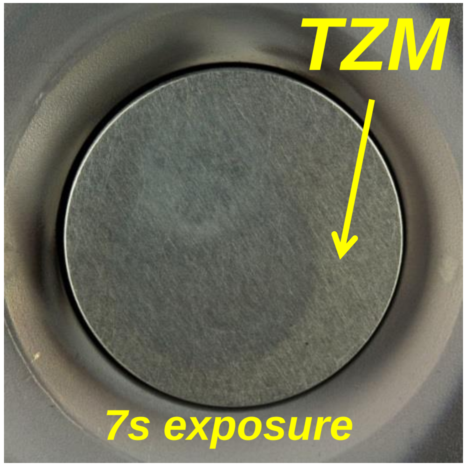


Strong trapping at the target has significant implications for high-temperature liquid lithium

- Previous temperature limits (~350-450C) derived on flux balance arguments should be re-evaluated
  - A) strong trapping at the target reduces transport upstream (less core contamination)
  - B) reduced gross erosion during high-flux deuterium bombardment and redeposition fraction > 0.99 measured (see T. Abrams PP8.00081)
- Stable vapor cloud and high redeposition demonstrated despite:
  - A) small pre-sheath potential drop predicted ~1eV (compare to E_{Li}~0.8eV=SBE/2)
  - B) Very high temperatures of the substrate (~1000C) at transition
- Strong trapping of material suggests concepts based solely on evaporative cooling would not function as expected (strong radiation required for power dissipation in mass-flux inhibited regimes)

Follow-up experiments confirm interpretation





Summary and Outlook

- Liquid plasma-facing components provide unique opportunity to overcome many outstanding issues facing solid materials

- DEMO-relevant engineering analyses indicate elevated temperatures for lithium surfaces with the possibility for continuous vapor shielding of surfaces

- Experiments in Magnum-PSI exhibit strong trapping of lithium at the target consistent with trapping in the pre-sheath potential well

- NSTX-U 5-year plan includes high-Z divertor upgrade which will enable tokamak-based vapor-shielding experiments

Backup

Simple plasma-fluid model can illustrate principles of ionization within pre-sheath

- Begin with mass conservation and momentum conservation
- Include pressure term (assuming isothermal conditions)
- Assume outside of Debye sheath, so quasi-neutral with Boltzmann electron fluid
- Make approximations and estimates to illustrate physics

$$\frac{\partial nm}{\partial t} + \nabla \cdot (nmv) = S_{iz}$$

$$\frac{\partial nmv}{\partial t} + \nabla \cdot (nmv\ v) = -\nabla p + qnE - S_{mom}$$

$$S_{iz} = mn_e n_o < \sigma v >_{ioniz}$$

$$S_{mom} = mn_i n_o < \sigma v >_{mom}$$

$$\nabla p = kT \frac{\mathrm{d}n}{\mathrm{d}x}$$

$$n(x) = n_\infty exp\left(\frac{e\Phi}{kT}\right)$$

$$E = -\nabla \Phi$$

$$\chi = \frac{e\Phi}{kT}$$

$$\frac{\mathrm{d}\alpha(x)}{\mathrm{d}x} \approx \frac{\alpha(x=L) - \alpha(x=0)}{L}$$

$$\bar{\alpha} = \frac{1}{2}[\alpha(x=L) + \alpha(x=0)]$$

Estimates indicate pre-sheath potential well deepens with mass and momentum sources

- Simplifications and estimates result in equation below relating change in velocity across pre-sheath region to density decrease, electric potential and source terms
- Pre-sheath potential drop *increases* in addition of momentum loss terms (ionization and collisions)
- Characteristic length determined by collisional processes similar to previous works (Riemann 1991 PoP)

$$\frac{m(v_L^2 - v_0^2)}{2kT} + 2\frac{n_L - n_0}{n_L + n_0} + \frac{e(\Phi_L - \Phi_0)}{kT} = -\frac{\bar{v} L \overline{(S_{iz} + S_{mom})}}{\bar{n} kT}$$

$$\chi + 2\tanh\left(\frac{\chi}{2}\right) = \frac{m(v_L^2 - v_0^2)}{kT} + \frac{\bar{v} L}{\bar{n} kT}\overline{(S_{iz} + S_{mom})}$$

$$L_{PS} = \frac{(v_L^2 - v_0^2)}{2n_0\bar{v}(<\sigma v>_{iz} + <\sigma v>_{mom})}$$

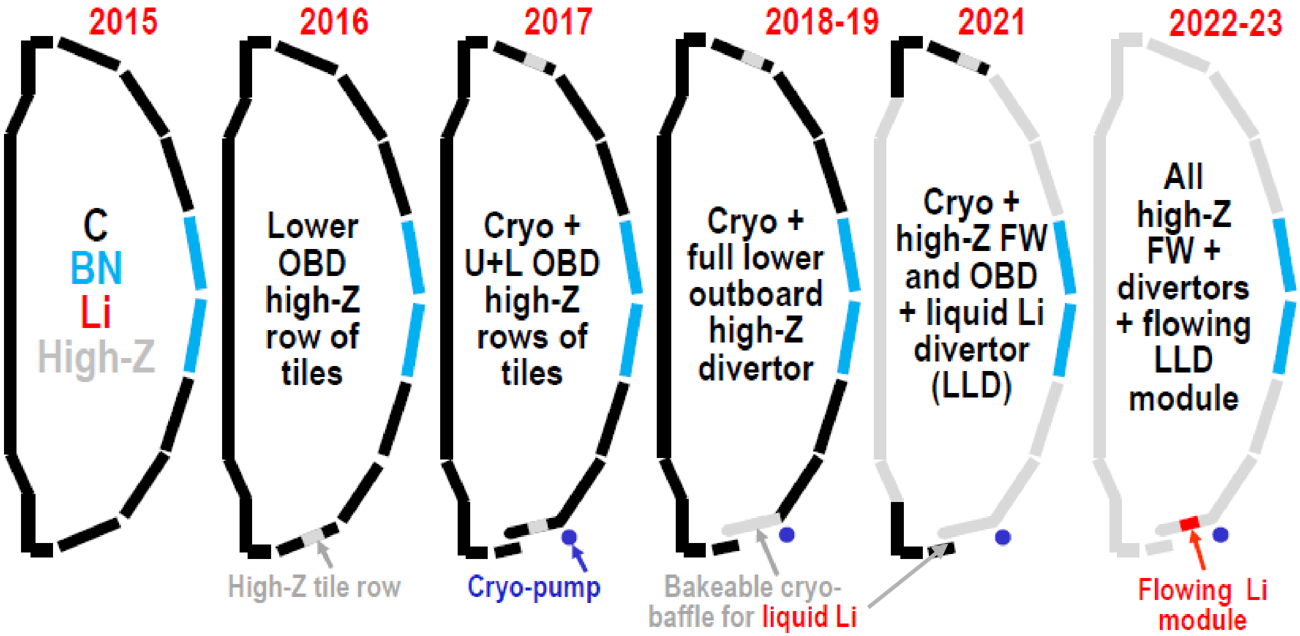
Presheath potential well expected to be ~0.5Te (~1eV) and LPS ~ 3mm for Magnum-PSI lithium experiments

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
  - **Self-healing/replenishable materials (e.g. liquids)**
- Significant uncertainties in both solid- and liquid-PFCs motivates parallel research

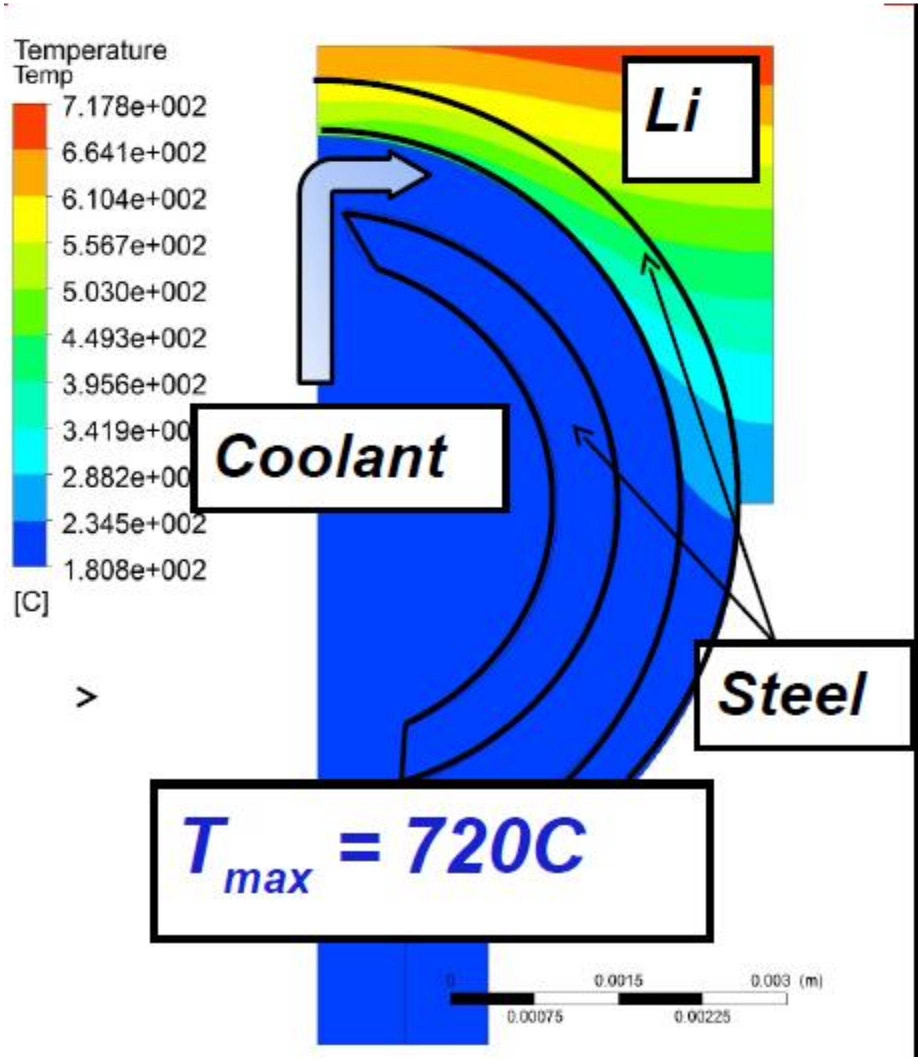
5-year plan base funding

Incremental funding could accelerate by ~2 years



Modern state-of-the-art active cooling with DEMO-relevant heat loads leads to elevated temperatures

- T-tube[1] uses impinging gas jets to increase local heat transfer coefficient
- Altered T-tube for these simulations to have:
  - Smaller radius
  - Steel structure, s-CO2 coolant **(No tungsten)**
  - 10 MW/m^2 incident
  - Consistent with strength limits of ODS-RAFM steel
- Previous studies considered <400C as limit for hydrogen retention

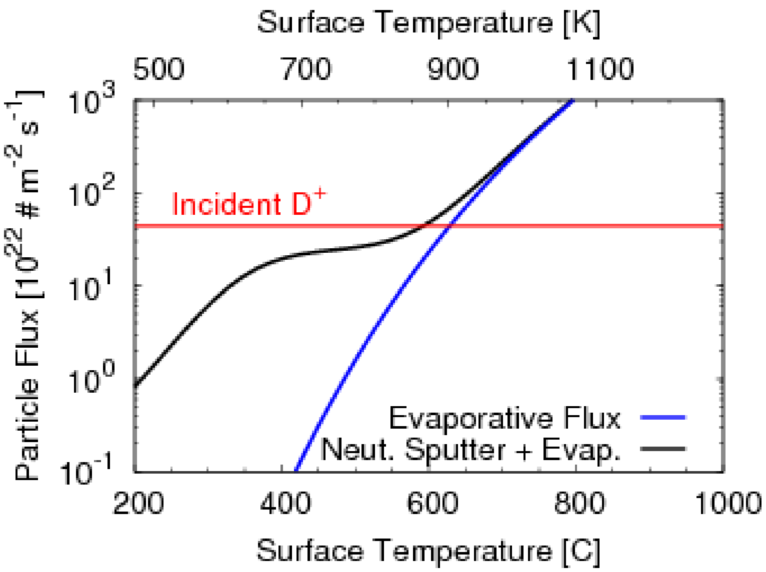


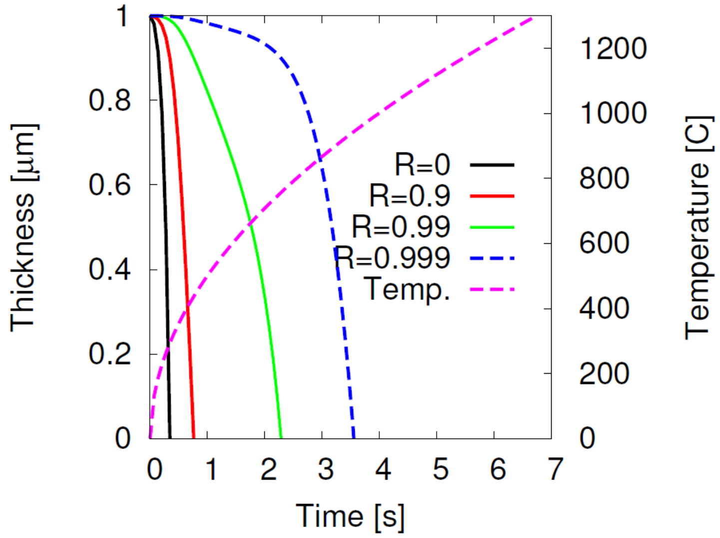
[1]*Abdel-Khalik FST 2008.*

3D analysis in A. Khodak, IEEE-TPS (accepted)

Very short coating lifetimes expected without strong redeposition or suppression of erosion

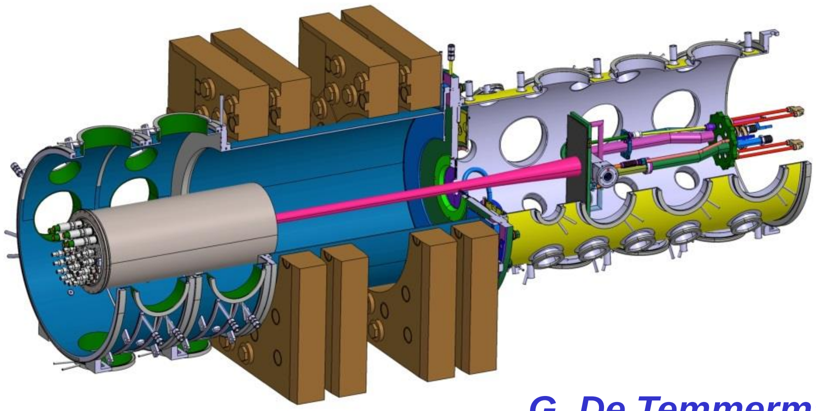
- Initial models of erosion used temperature-enhanced sputter yields and Langmuir-law evaporation
  - Adhoc model consistent with IIAX measurements by Allain and PISCES-B measurements by Doerner
  - Recent experiments indicate this is pessimistic (see T. Abrams P1-030)
- Very short lifetimes for 1 micron-thick coatings expected without redeposition





Magnum-PSI linear plasma device produces divertor-like plasmas on different target materials

- Plasma source and target de-coupled by neutral pumping and long connection length
- Currently operating with pulsed field coils
- Similar to NSTX divertor parameters*



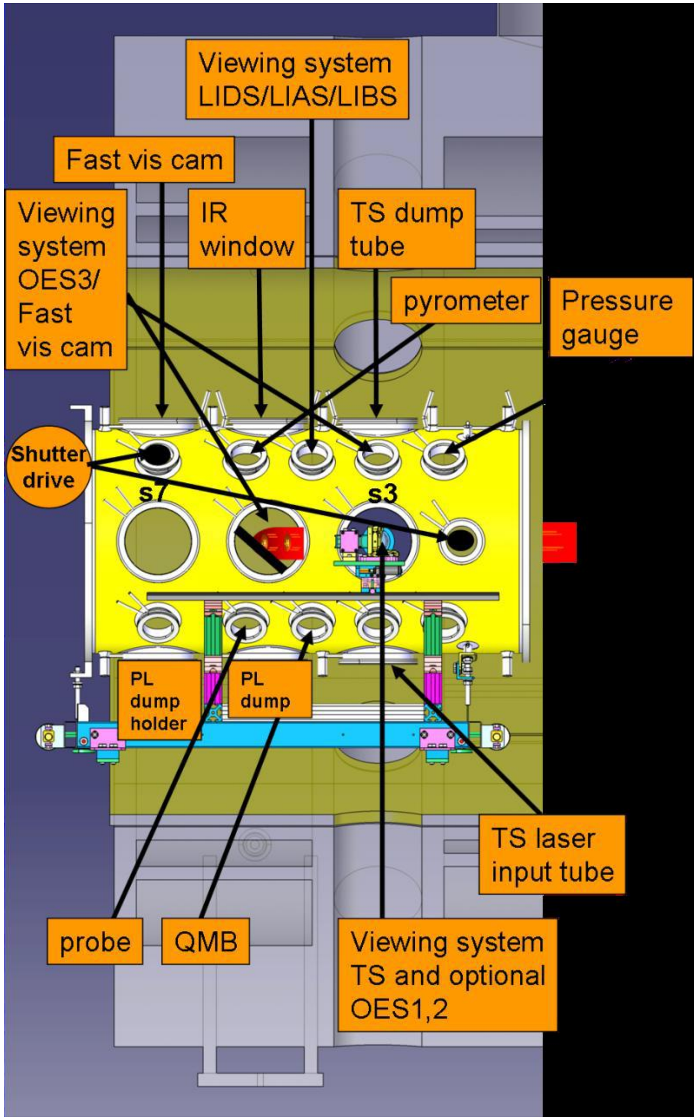
G. De Temmerman

Parameter	Magnum-PSI	NSTX discharges with heavy lithium (Liquid Lithium Divertor)
Power	60[kW]	4[MW] NBI (15[MW] NSTX-U)
Pressure (source)[kPa]	10	N/A
Pressure target[Pa]	< 3	0.1–1†
T_e target[eV]	0.1–10	1–15
N_e target[m^{-3}]	10^{20}–10^{21}	5×10^{20} at strike point
T_i target[eV]	0.1–10	Unknown
Ion flux target [m^{-2}s^{-1}]	10^{24}–10^{25} (Normal inc.)	2×10^{23} at strike-point ($\approx$ 3–5°)
Power flux [MWm^{-2}]	10	2–5 ($\approx$ 3–5°)
Magnetic Field[B]	1.9 max.	0.6 (1 NSTX-U)
Beam diameter[cm]	10–15	$\approx$4 FWHM med. triangularity
Pulse length[s]	12–110	1 (5–10 NSTX-U)
Bias [V]	$-100 < V_{target} < 0$	$-20 < V_{floating} < 20$

Jaworski JNM 2013

Diagnostic systems provide detailed information about plasma and target

- Water cooling calorimetry provide absorbed energy per pulse
- IR diagnostics provide surface temperature
  - Spatially-resolved IR camera
  - Spectral pyrometer provides temperature and emissivity at single point
- Thomson scattering taken immediately in front of target
- Plasma emission (UV-NIR)
  - Filtered fast camera for spatially resolved measurements
  - Avantes spectrometer system on single spatial chord



H.J. Van der Meiden PMIF 2013

Summary

- Strong trapping of eroded particles can be expected due to pre-sheath region satisfying Bohm
- Lithium experiments in Magnum-PSI demonstrate strong trapping at the surface and long-lifetimes of deposited layers
- Evaporative cooling of components alone not likely to be sufficient (requires active cooling)

- This work supported by US Dept. of Energy grant DE-AC02-09CH11466 and PPPL Laboratory Directed Research and Development grants R035 and R037

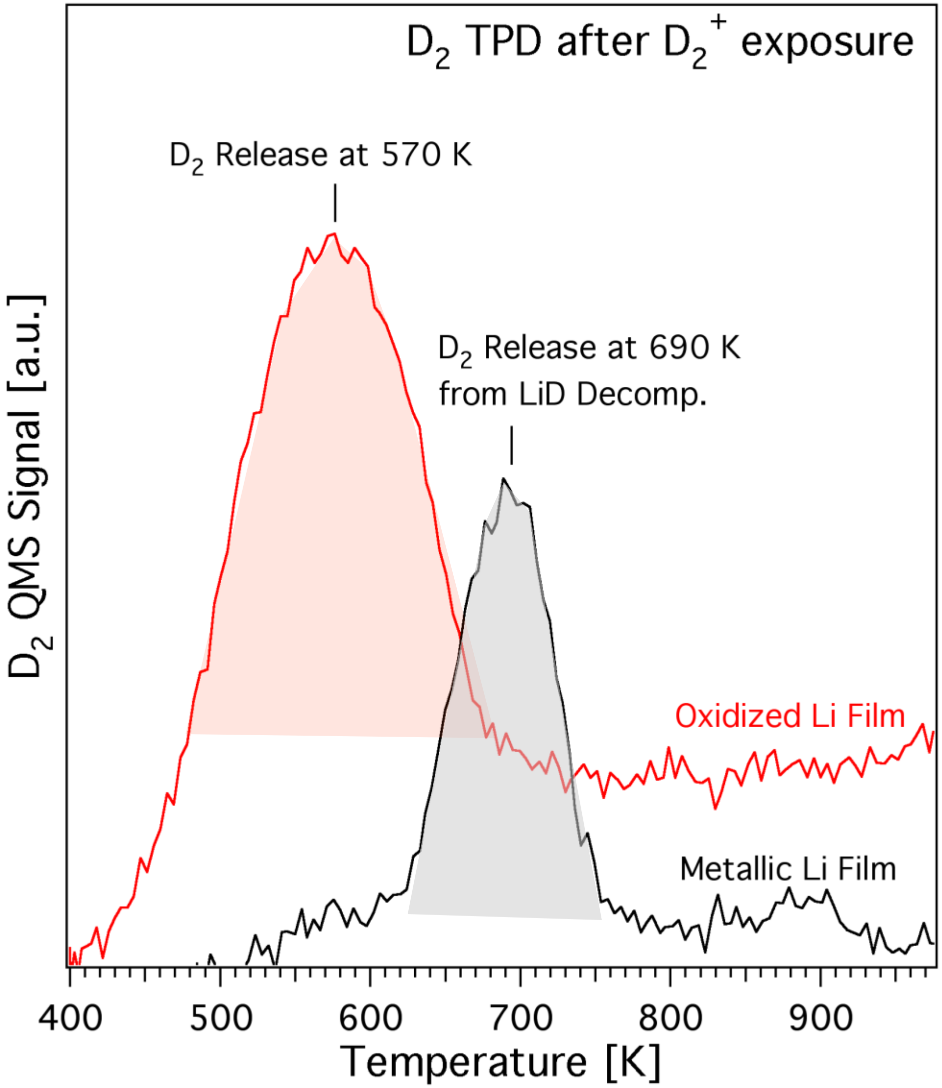
M&P research will develop understanding of material migration and heat-flux handling of high-Z and liquid Li PFCs

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

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

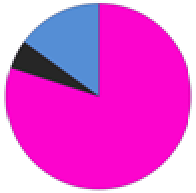
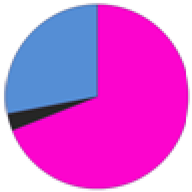
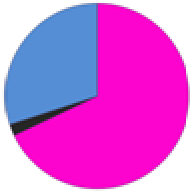
- Fundamental data on Li coatings on high-Z materials extending graphite work
- Thin films (few monolayers) of Li deposited on Mo
  - D_2 evolved below 750K with or without C and O impurities
  - Oxidation of Li film destabilizes LiD
- Implication for a reactor: high-temperature thin-films will not retain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

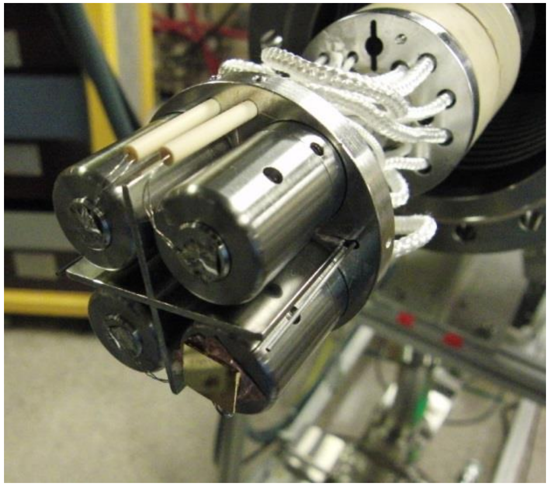


Material Analysis and Particle Probe (MAPP) in-situ diagnostic examining PFC surface composition of Li in prep for NSTX-U

- 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

🟪 Li ■ C 🟦 O	**Post-Evap.**	**Post-Evap. + 4 h**	**Post-Evap. + 3 d**
304L SS			



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

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

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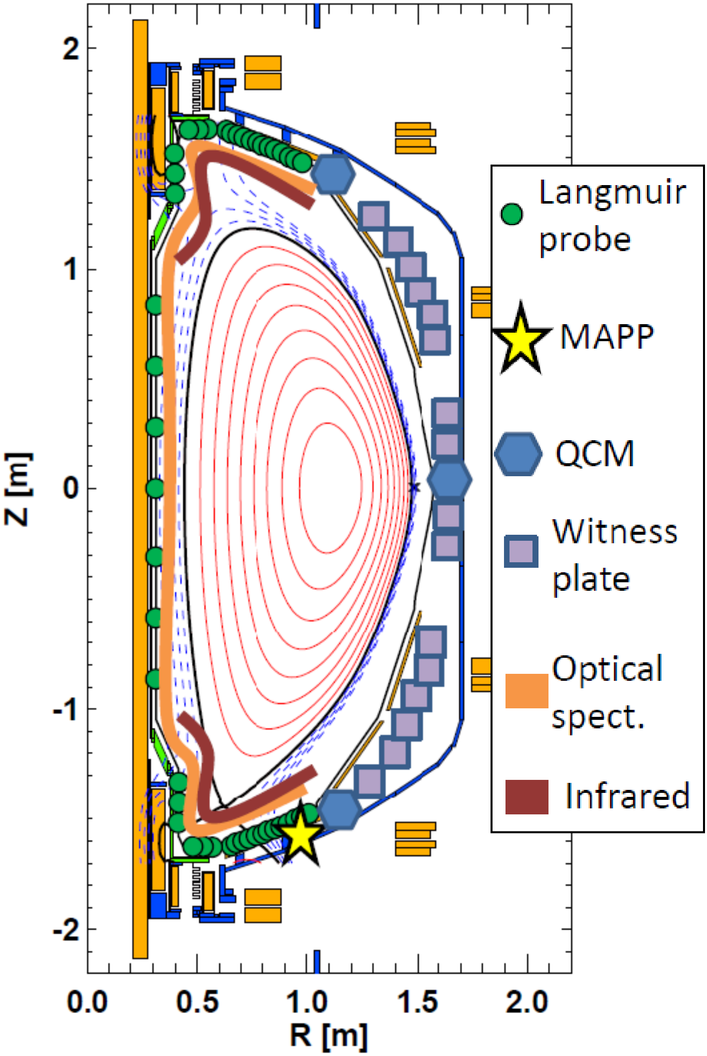
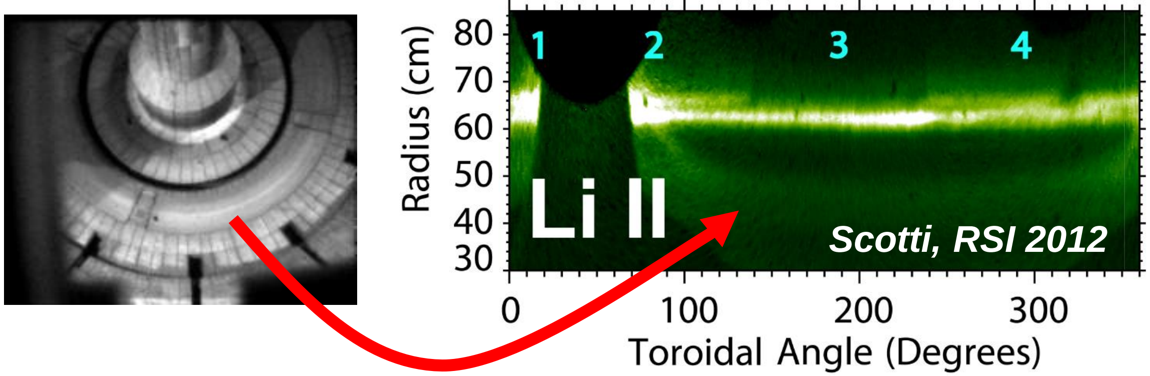
Diagnostics will be key to making strongest possible progress on material migration

- 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)



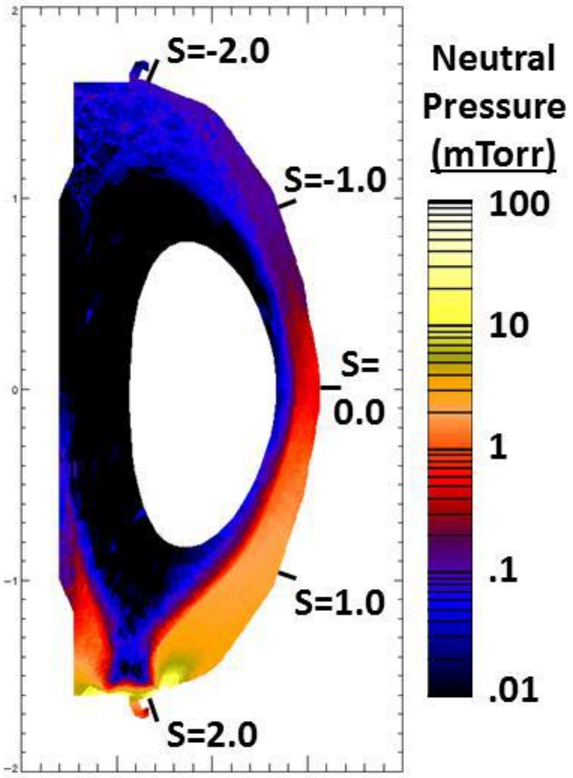
Full divertor camera coverage

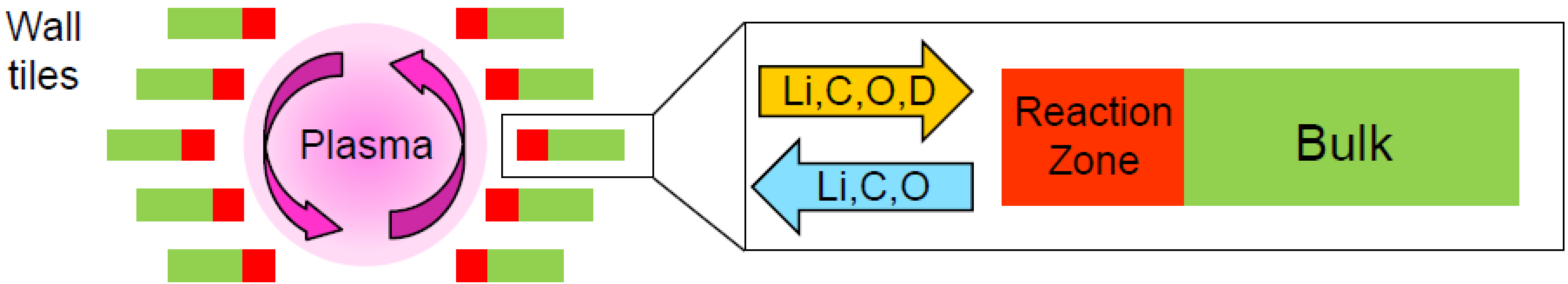


Scotti, RSI 2012

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



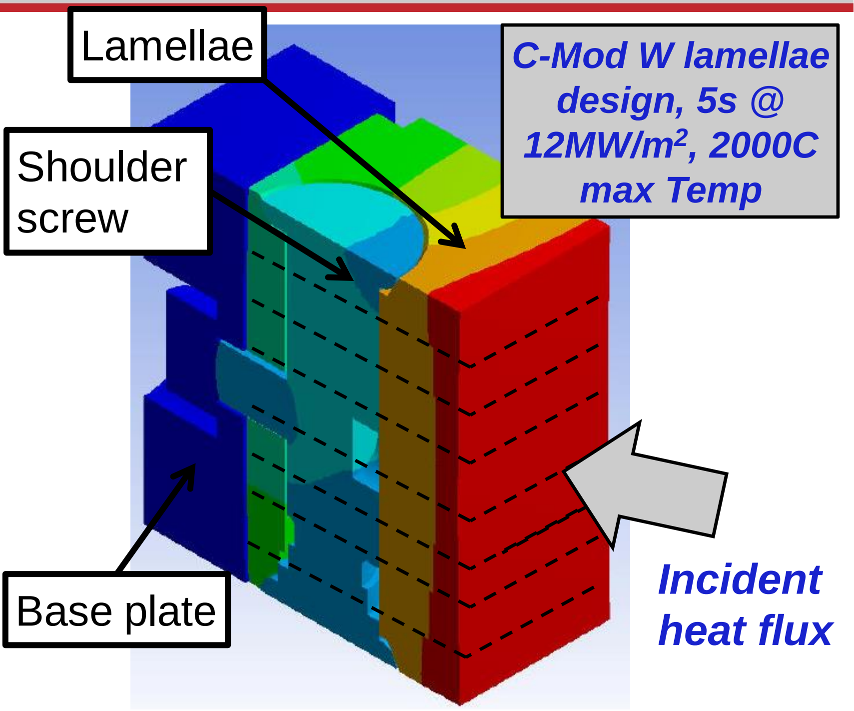


K. Schmid JNM 2011

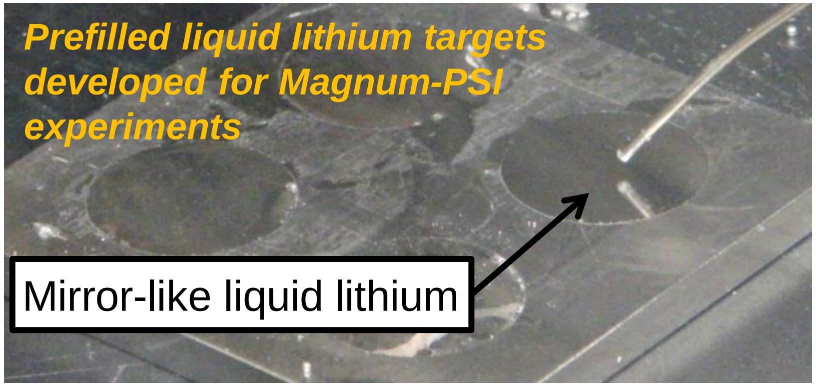
C-Mod and JET high-Z PFCs designs inform design choices for NSTX-U

- 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)



C-Mod W lamellae design, 5s @ 12MW/m^2, 2000C max Temp



Prefilled liquid lithium targets developed for Magnum-PSI experiments

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 if aggressive schedule adopted

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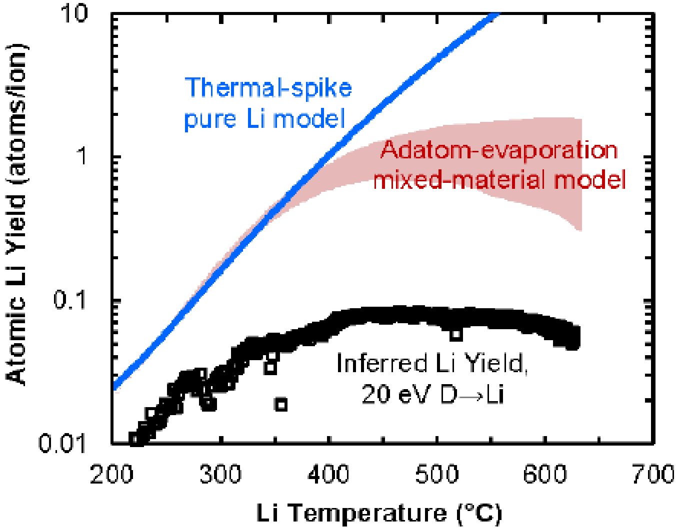
  - Determine migration patterns to optimize technical solutions
- MP-3: Establish the science of continuous vapor-shielding
  - Determine the existence and viability of stable, vapor-shielded divertor configurations
  - Determine core compatibility and extrapolations for extended durations and next-step device parameters

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

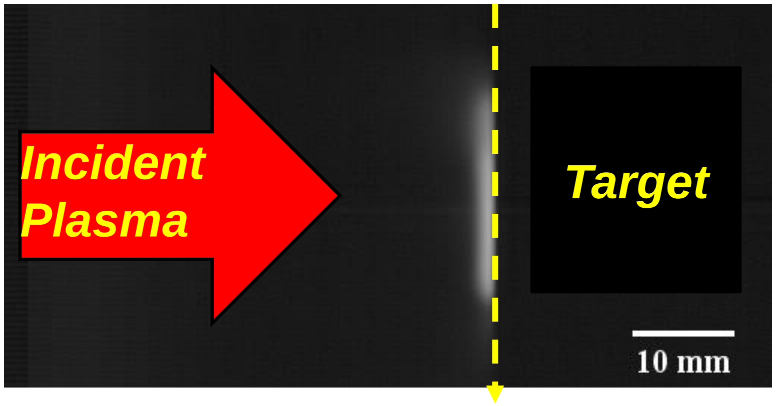
- Gross erosion measured spectroscopically in divertor-like plasma
  - Neon plasma reproduces Langmuir Law
  - Deuterium *suppresses* erosion
- Reduced gross erosion and strong redeposition result 10x longer lifetime of 1 micron coating
  - Consistent with Li trapping in pre-sheath
  - Pre-sheath scale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

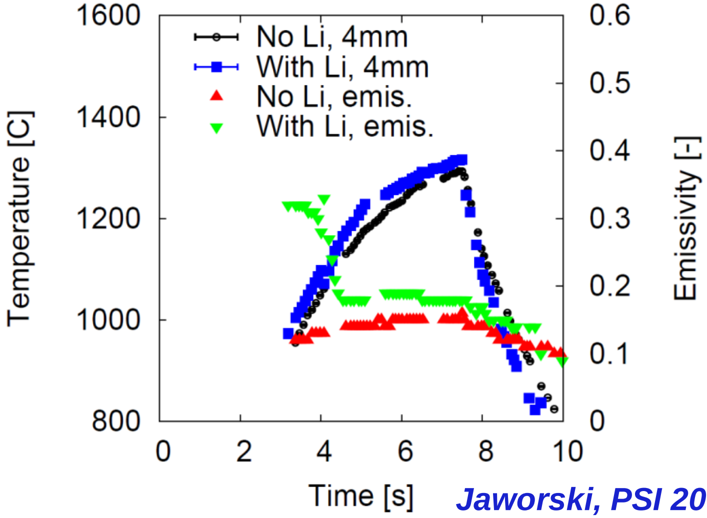
Abrams, PSI 2014

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

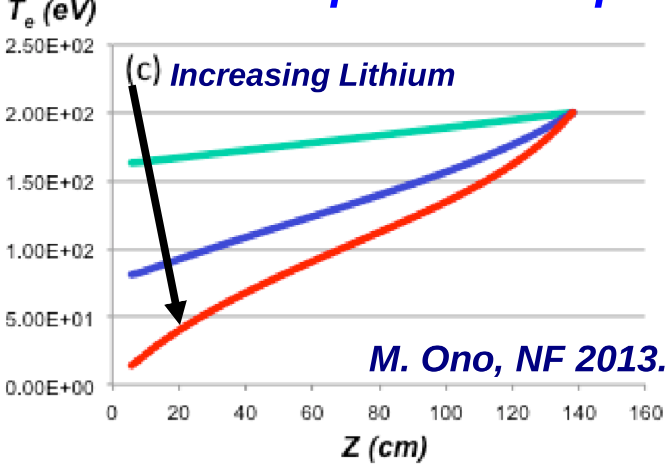
Assessment of high-Z row will provide first look on issues facing a future full-metal upgrade (Milestone R16-2)

- 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



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

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