NSTX-U

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High-temperature liquid lithium divertor targets: analysis and experiments in support of NSTX-U and next-step devices

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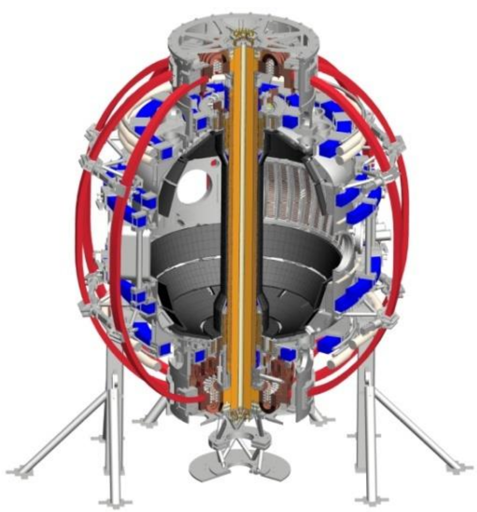

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Liquid metals offer potential advantages over solid plasma-facing components (PFCs)

- 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

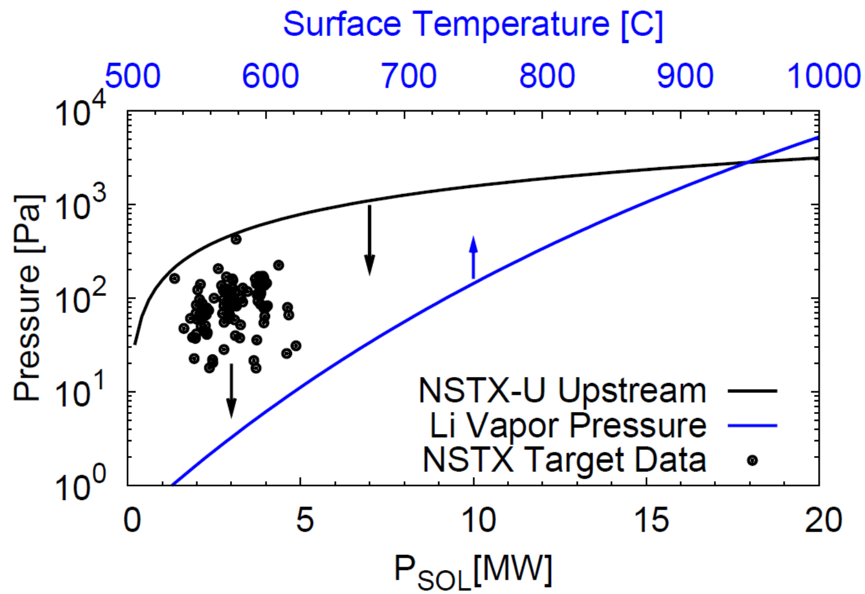
- Lithium vapor cloud can potentially provide effective power and pressure loss ***(continuous vapor-shielding)***
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma pressure (see M. Ono NF 2013)
- Capillary-Porous System(CPS) targets have dissipated large incident heat fluxes: e-beam tested 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?**

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

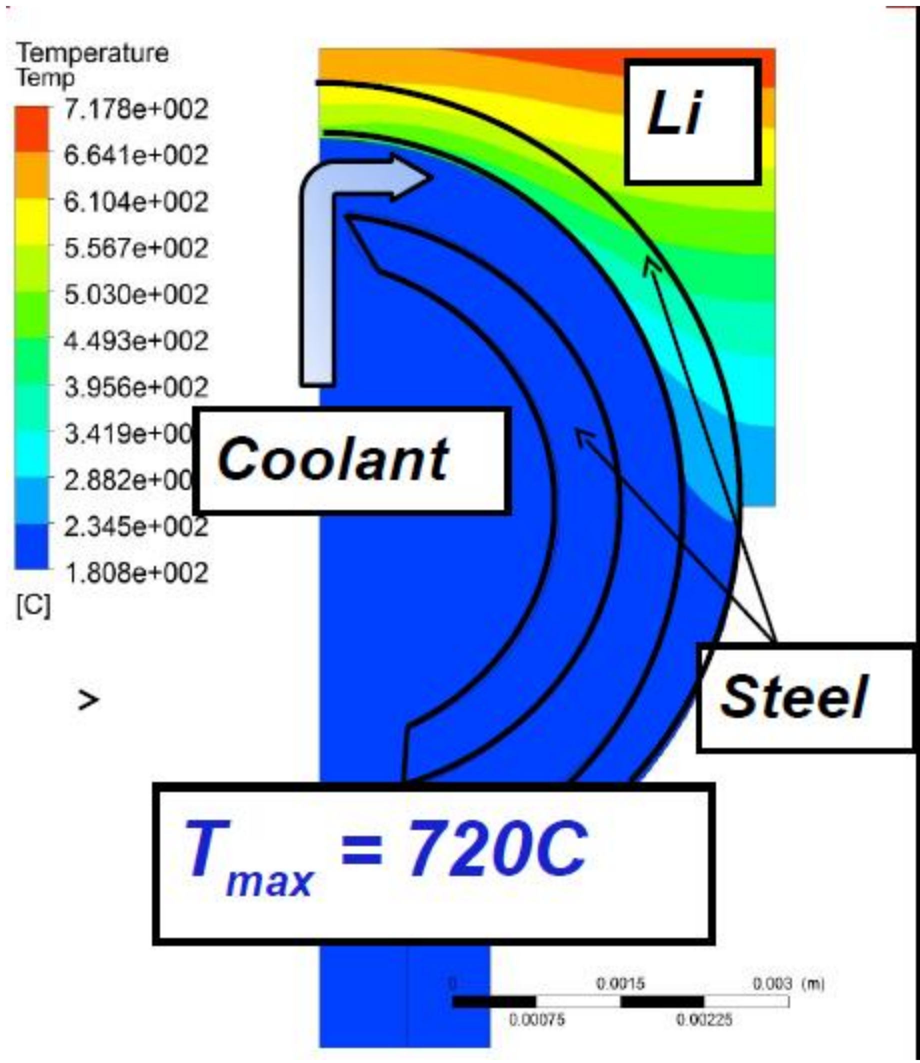
$$q_t^{plasma} = \gamma \Gamma_{sat}^{+} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$

$$P_{SOL} = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} n_u T_u = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} p_u$$



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

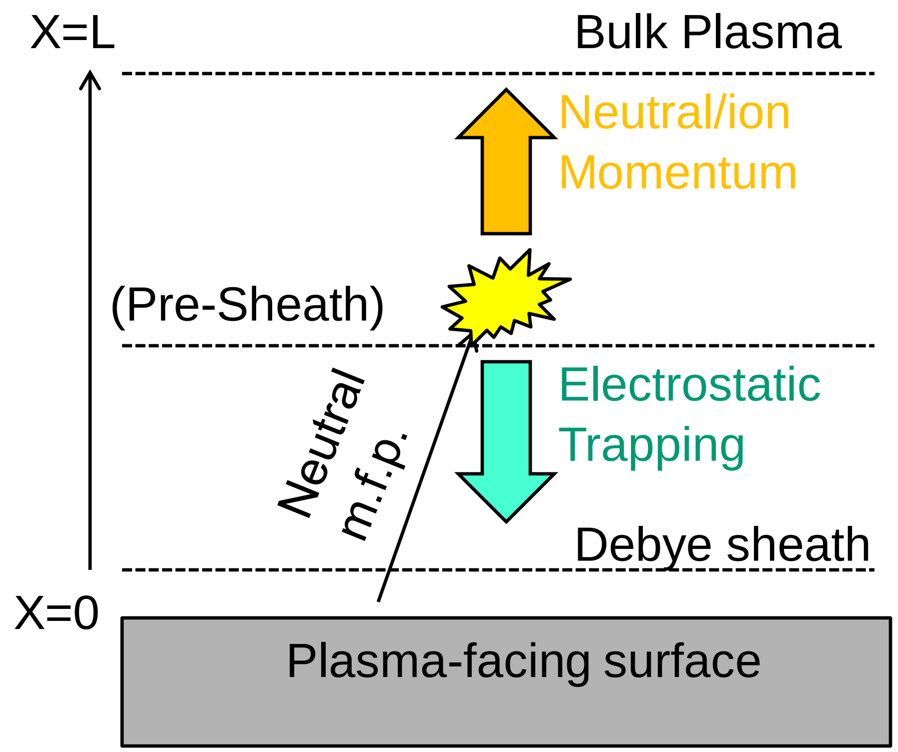


[1]*Abdel-Khalik FST 2008.*

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

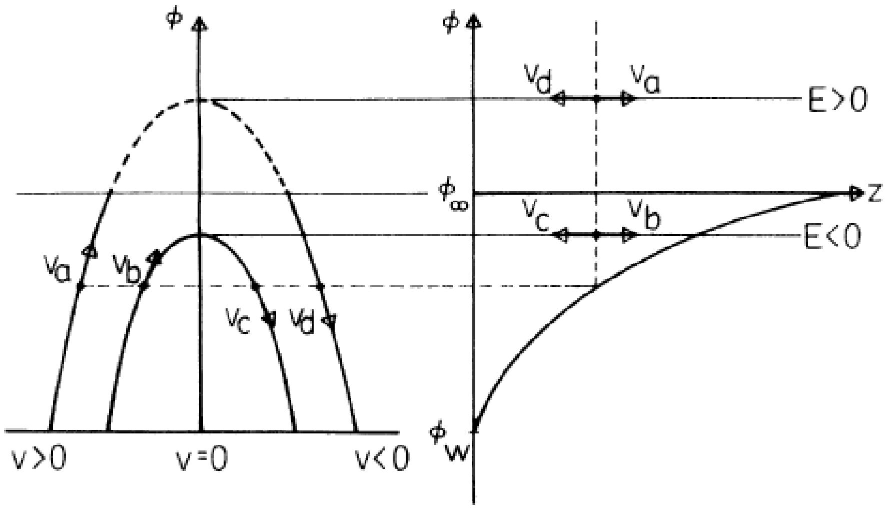
Eroded materials pass through several regions before reaching the bulk plasma

- Eroded neutrals are unconfined until collision event
- Region of strongest field is also the shortest spatial extent (Debye sheath)
- Prompt redeposition process often invoked: ionization within Larmor orbit of wall results in capture



Plasma pre-sheath region can also result in trapped particles

- Pre-sheath region arises to satisfy Bohm velocity criterion at sheath edge
- Particles introduced into potential by cross-field diffusion or ionization may be trapped in wall potential
- 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



Chung, 1988, Phys. Rev. A

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)

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

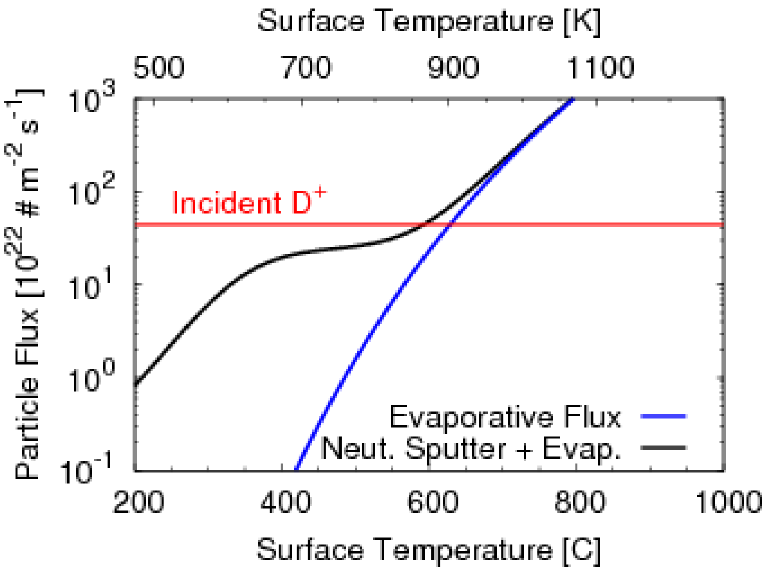
$$\chi + 2\tanh\left(\frac{\chi}{2}\right) = \frac{m(v_L^2 - v_0^2)}{kT} + \frac{\bar{v}L}{\bar{n}kT}\overline{(S_{iz} + S_{mom})}$$

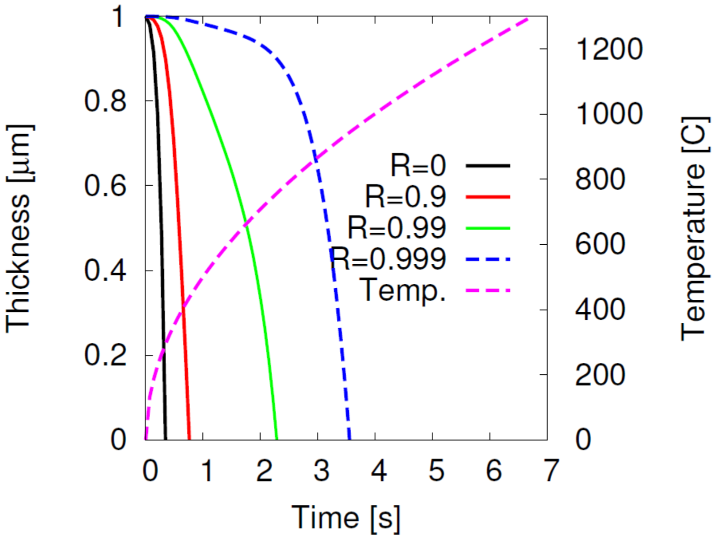
$$L_{PS} = \frac{(v_L^2 - v_0^2)}{2n_0\bar{v}(<\sigma v>_{iz} + <\sigma v>_{mom})}$$

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

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

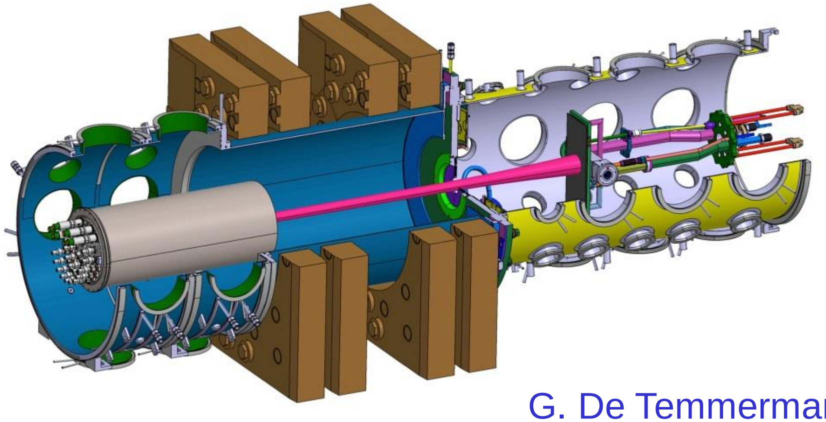
- Initial models of erosion used temperature-enhanced sputter yields and Langmuir-law evaporation
  - Adhoc model consistent with IIAX measurements by Allain and PISCES-B measurements by Doerner
  - Recent experiments indicate this is pessimistic (see T. Abrams P1-030)
- Very short lifetimes for 1 micron-thick 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*



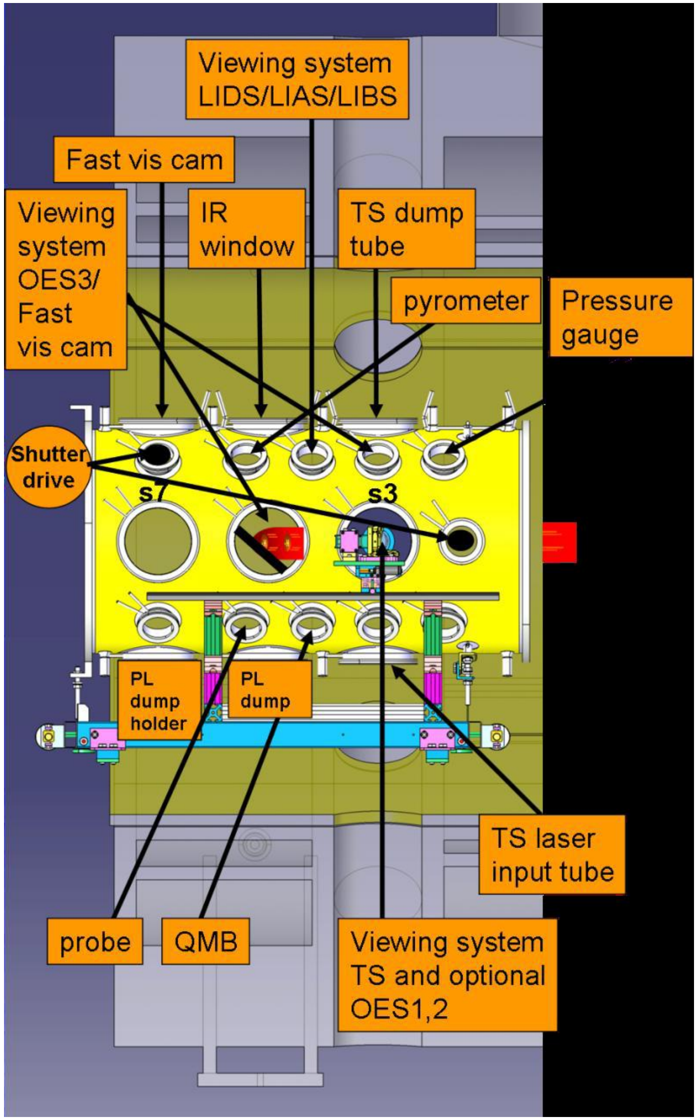
G. De Temmerman

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 (≈ 3–$5°$)
Power flux [MWm^{-2}]	10	2–5 (≈ 3–$5°$)
Magnetic Field[B]	1.9 max.	0.6 (1 NSTX-U)
Beam diameter[cm]	10–15	≈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

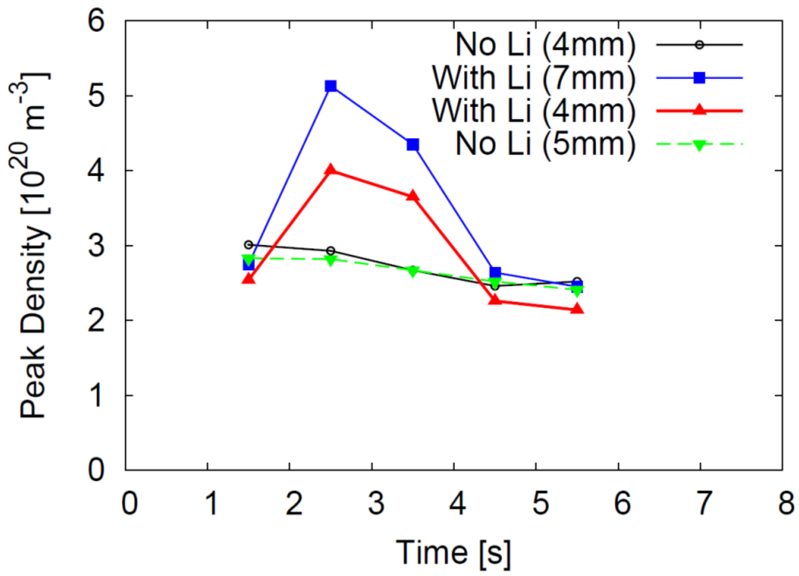
- Water cooling calorimetry provide absorbed energy per pulse
- IR diagnostics provide surface temperature
  - Spatially-resolved IR camera
  - Spectral pyrometer provides temperature and emissivity at single point
- Thomson scattering taken immediately in front of target
- Plasma emission (UV-NIR)
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



H.J. Van der Meiden PMIF 2013

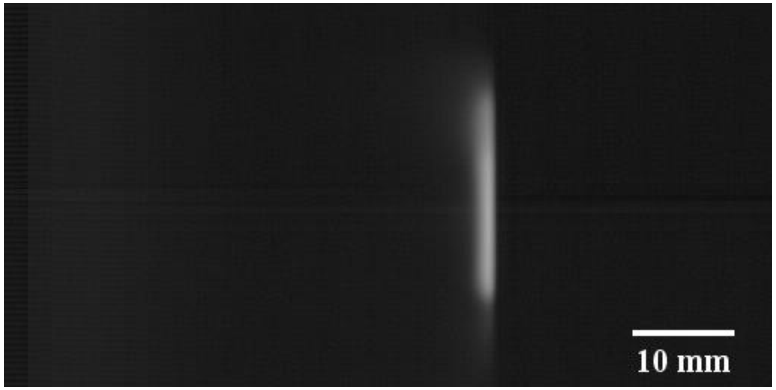
Lithium layers observed to persist for 3-4 seconds(!)

- Two states observed:
  - 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

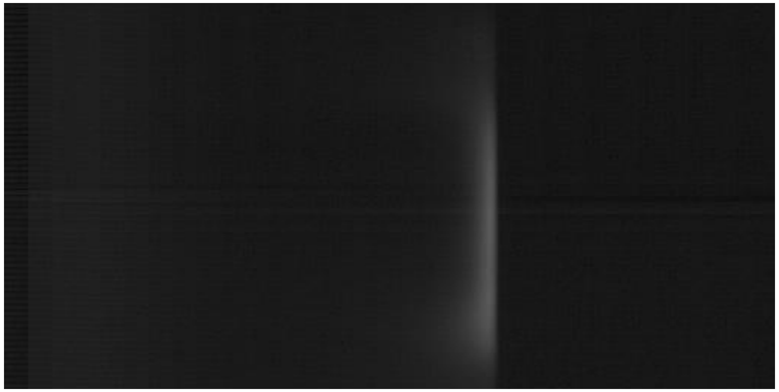


L_{PS} ~ 3mm predicted

Li-I emission, t=2.5s



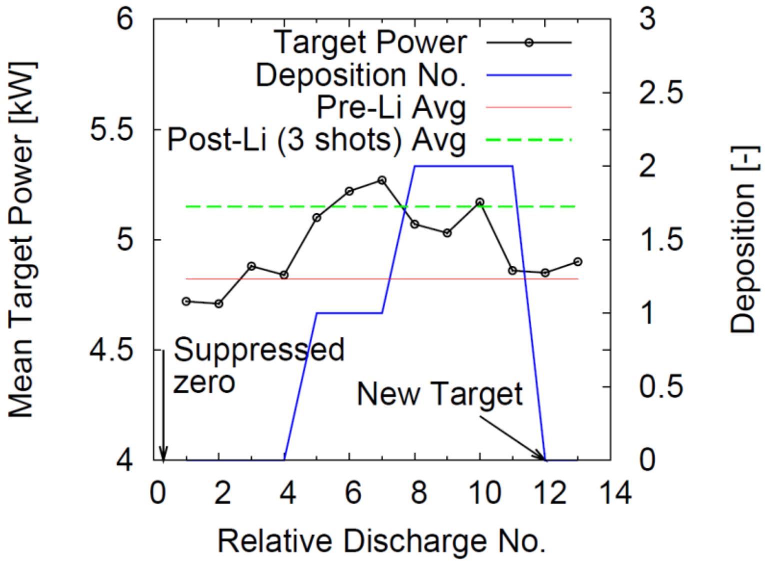
Li-I emission, t=6s

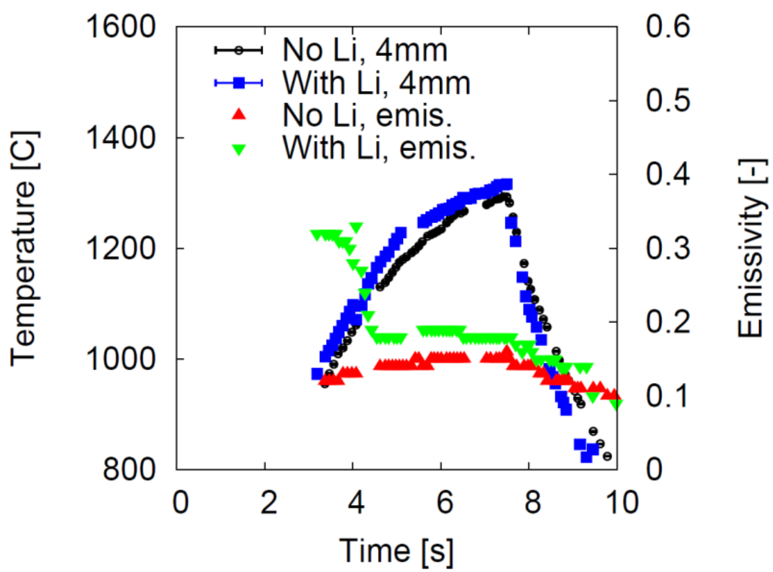


Calorimetry and pyrometer indicate similar or increased heat flux with lithium

- Water-cooling calorimeter indicates increased power deposited
  - 4.8kW vs. 5.2kW
  - Target returns to “pre-Li” levels after several exposures
  - Very close to shot reproducibility level, however

- Pyrometer indicates slightly higher temperatures with Li
  - 1295C vs. 1315C
  - Rapid change in emissivity measured at transition

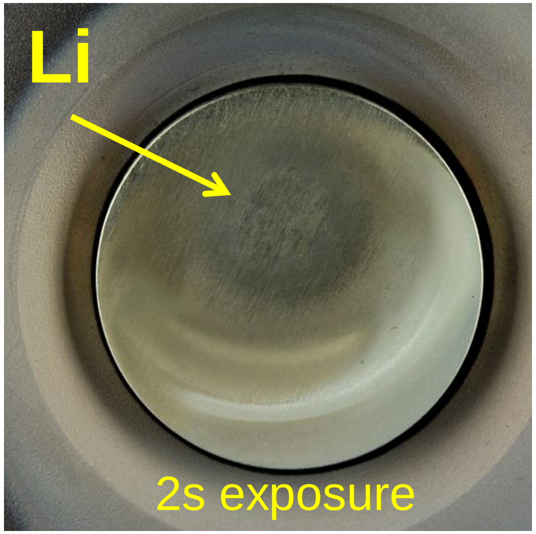


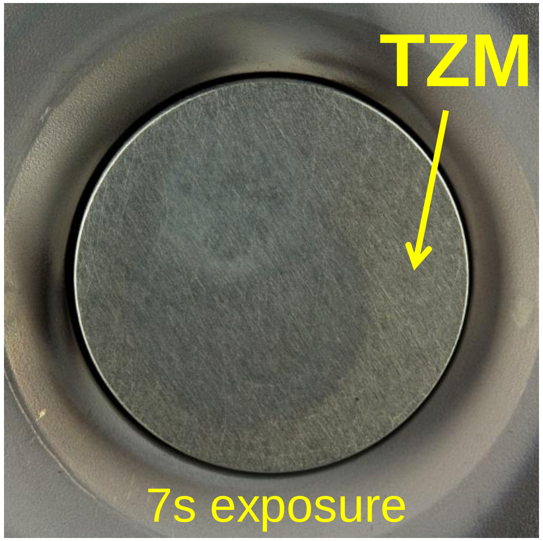


Ongoing analysis to understand all observations made during lithium experiments

- Two states are interpreted as the presence of a macroscopic layer of lithium on the TZM
  - Confirmed in subsequent experiment
  - Rapid change in infrared emissivity could be additional indicator of depletion
- Presence of cloud seems not to be sufficient to reduce incident power **(No Li-II emission)**

- **Long-life of the vapor cloud provides initial feasibility study of vapor-shielding experiments in NSTX-U with evaporated lithium**





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 in light of:
  - A) strong trapping at the target resulting in large redeposition
  - B) reduced gross erosion during high-flux deuterium bombardment

- 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 since mass-flux is strong reduced away

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)

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