High-temperature, liquid lithium plasma-facing component research for NSTX-U and next-step devices

M.A. Jaworski, T. Abrams, R. Goldston, R. Kaita, A. Khodak, J. Menard, M. Ono, J. Schwartz, C.H. Skinner, D.P. Stotler (PPPL), T.K. Gray (ORNL), G. De Temmerman, J. Scholten, M.A. Van den Berg, H.J. Van der Meiden (FOM-DIFFER)

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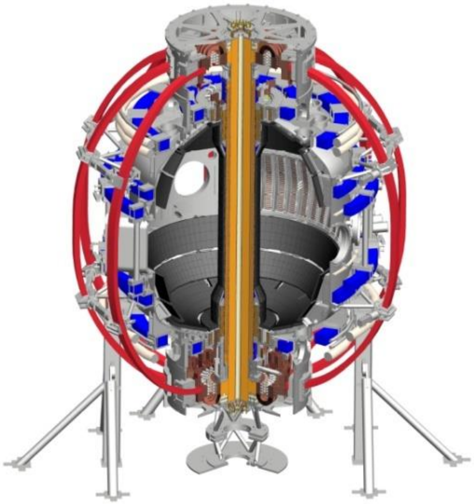

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Solid plasma-facing components may not extrapolate to future devices

- Tungsten components still subject to melting
  - Transient loading results in melt and motion
  - Repair of components needs $
  - **Liquids return to equilibrium positions by design**
- Wall erosion induces net reshaping of components even in steady state
  - Charge-exchange fluxes erode first-wall components
  - Rough estimates for a reactor-scale device indicates redistribution of **1000s of kgs**[1]
  - **Liquids can be replenished in real-time**

Arnoux, PFMC-14, Juelich

Coenen, et al., JNM 2013

$$\Gamma^{Gross}_{sputt.} \approx Y_{sputt,cx} \frac{P_{cx}/E_{cx}}{S_{plasma}}$$

Machine	P_{max}/S [MW/m^2]	τ_{annual} [s]	Yield [kg/yr]
DIII-D[1]	0.4	10^4	0.08 (C)
NSTX	0.2	3×10^3	0.012 (C)
NSTX-U	0.5	10^4	0.1 (C)
ITER[1]	0.15	10^6	92 (W)
ST-Pilot	0.98	10^7	1800 (W)
ARIES-AT	0.98	3×10^7	8000 (W)

[1] Stangeby, JNM 2011

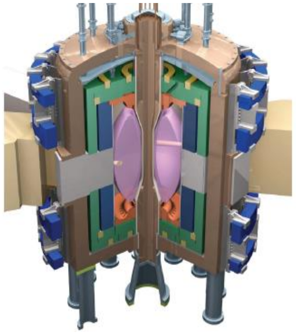
Key research challenges before liquid-metal plasma-facing components

- Stable operation of a free-surface, liquid-metal on the first-wall and divertor of the fusion device
  - Capillary-restraint via thin-layers and porous or textured surfaces demonstrated on limiter and divertor machines*
- Mass transport and material inventory control of the liquid metal (and any absorbed materials e.g. tritium)
- Establishing the operating temperatures of the liquid-metal plasma-facing components (PFCs) consistent with good core performance and efficient power extraction (i.e. an integrated scenario)
  - Both mass transport and integrated scenarios require a confinement device for study

*see Jaworski, et al., NF 2013 and Jaworski, et al., PPCF (accepted) for details of the Liquid-Lithium Divertor (LLD) experiments

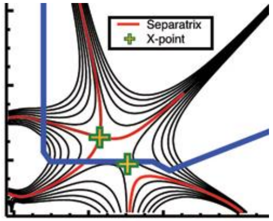
NSTX Upgrade mission elements

- **Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)**
  - Motivation for ST as FNSF: high neutron wall loading, potentially smaller size, cost, and tritium consumption, accessible / maintainable
- **Develop solutions for the plasma-material interface challenge**
  - Exploit strong heating + smaller R → high P/R and P/S approaching FNSF/Demo levels
- **Explore unique ST parameter regimes to advance predictive capability - for ITER and beyond**
  - Non-linear Alfvénic modes, fast-ion dynamics
  - Study electron gyro-scale turbulence at low ν^*
  - High β, rotation, shaping, for transport, MHD
- **Develop ST as fusion energy system**

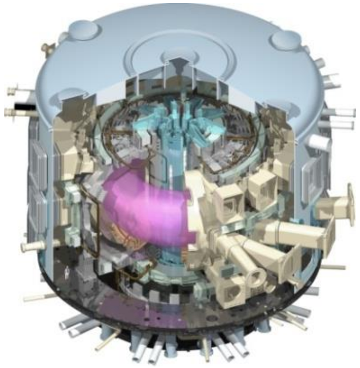


ST-FNSF

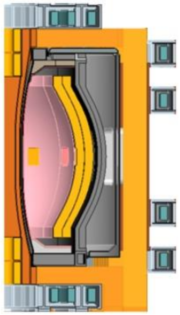
Lithium



"Snowflake"



ITER



ST Pilot Plant

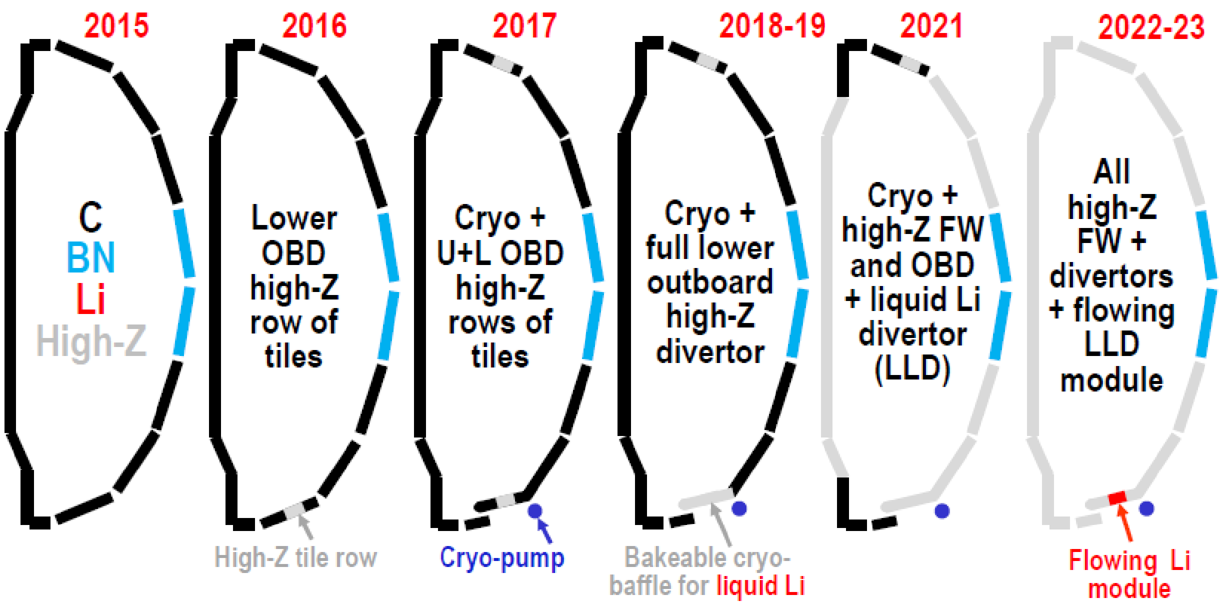
See M. Ono at NP8.00002 for more details

High-level goals for NSTX-U 5 year plan

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ 1MW/m^2 neutron wall loading in FNSF
2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solutions for next-steps

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

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



See R. Kaita at NP8.00005 for more details

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

- MP-1: Understand lithium surface-science for long-pulse PFCs

  See A. Capece NP8.00010, J. Roszell NP8.00011

  - Assess impact of more complete Li coverage
  - Use the new 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

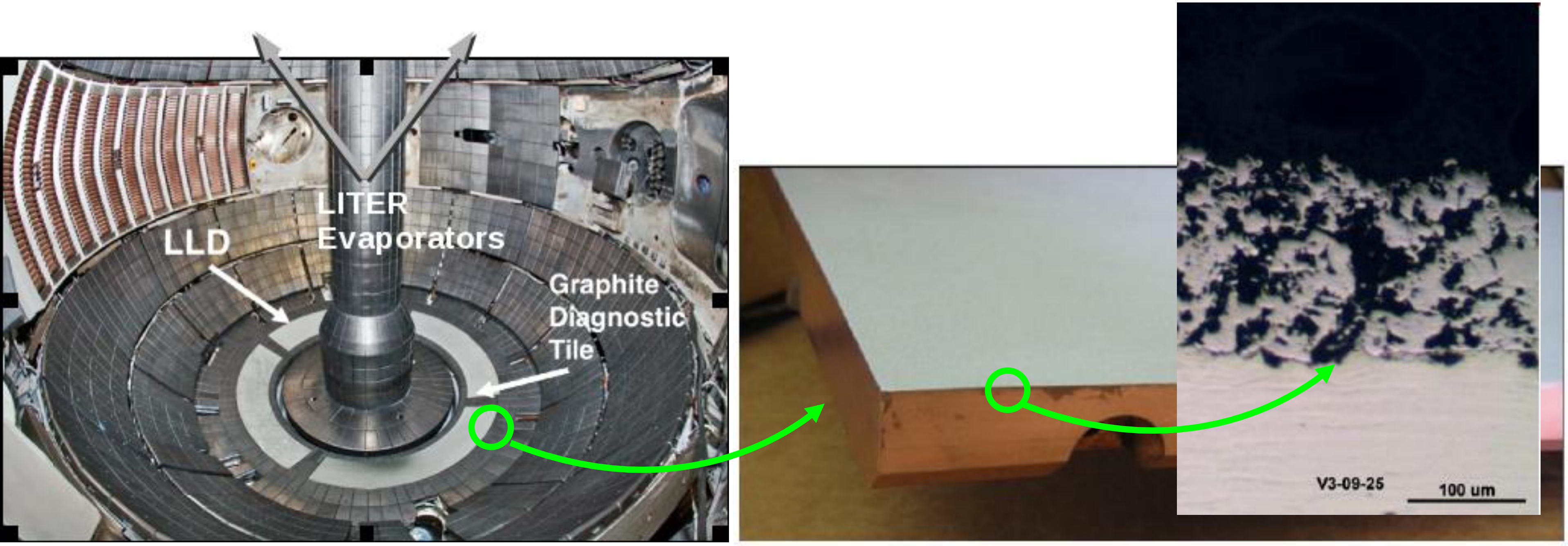
  See J. Nichols NP8.00008 and F. Scotti NP8.00007

  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solution
- 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 devices

See also T.K. Gray NP8.00009

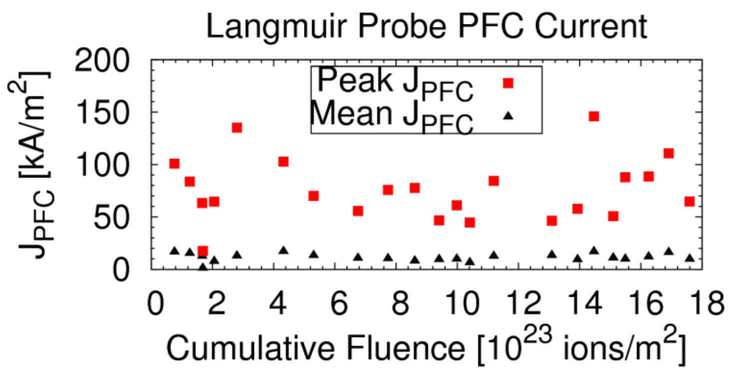
NSTX performed liquid-metal PFC experiments with the Liquid Lithium Divertor (LLD)...

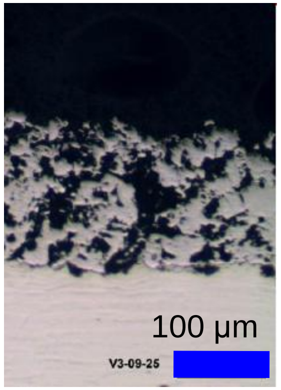
- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250um SS 316, ~150um flame-sprayed molybdenum porous layer; LITER loaded
- 37g estimated capacity, 60g loaded by end of run



...and demonstrated stable liquid metal PFC operation in a diverted tokamak

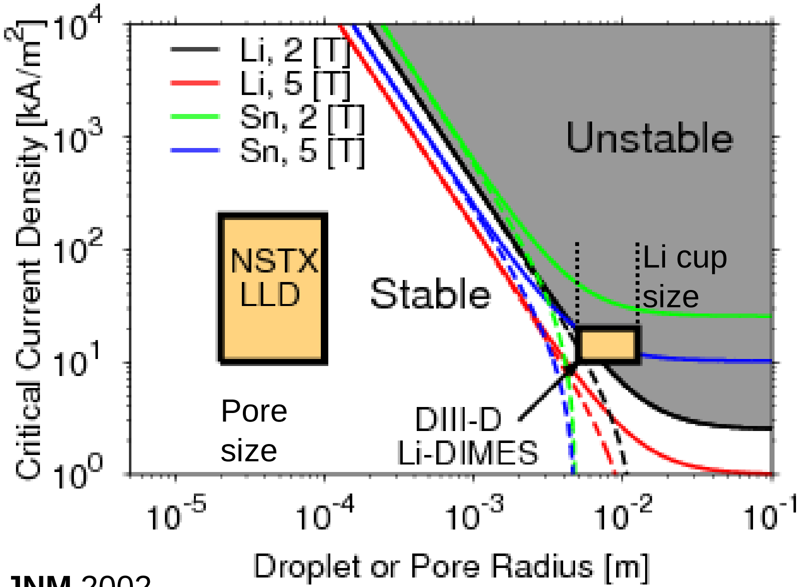
- Large transient currents measured with Langmuir probes, LLD porous geometry limits wavelength
- Raleigh-Taylor analysis provides marginal stability curves; NSTX LLD stable
- CPS tests also reduced droplet ejection with smaller pore sizes*





$$k_{Cr} = \sqrt{\frac{jB - \rho g}{\Sigma}}$$

For the fastest growing modes

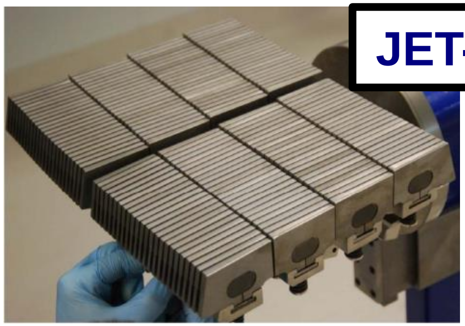


Jaworski **JNM** 2011, Jaworski IAEA FEC 2012, Whyte **FED** 2004, *Evtikhin **JNM** 2002

NSTX-U examining the use of inertially-cooled targets for first high-Z upgrades of the divertor

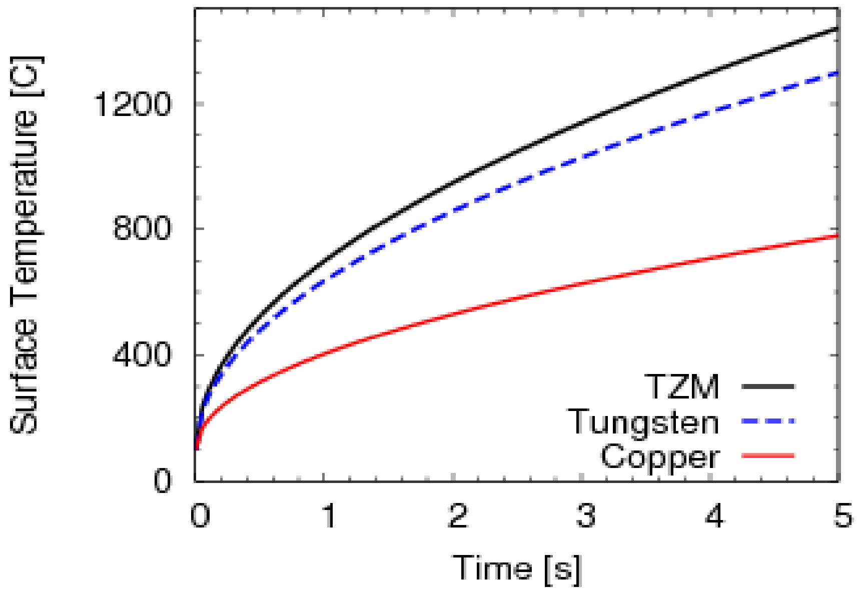
- High-Z PFC assessment
  - Lamellae demonstrated technique (e.g. C-MOD and JET-ILW) to reduce stress
  - Both W and Mo are compatible with Li
- Inertial cooling can be approximated with transient conduction into semi-infinite solid
  - 10 MW/m^2 incident
  - TZM and W reach over 1200C by end of 5s pulse

JET-ILW Divertor Cassette



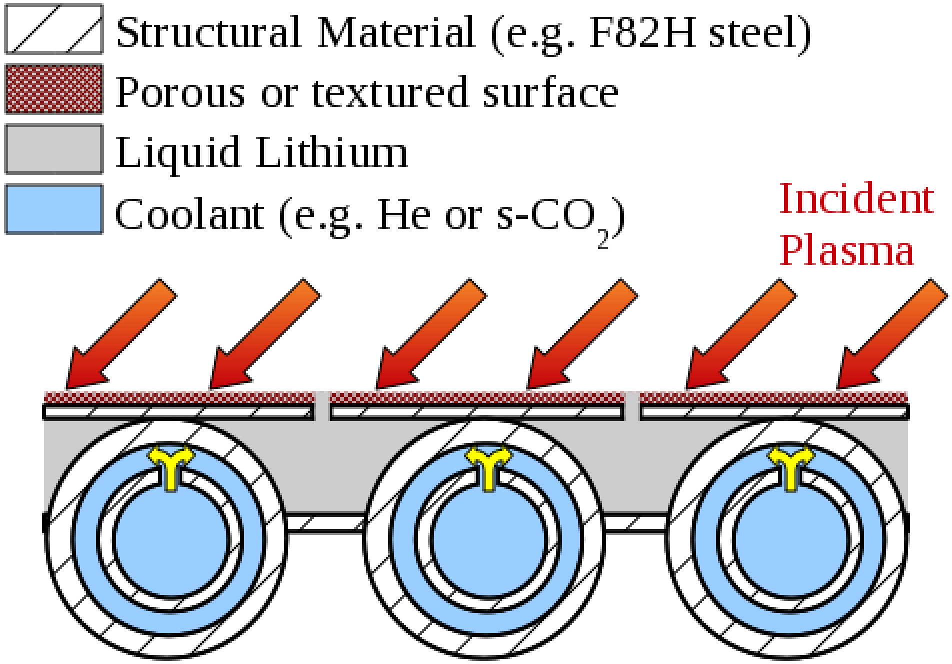
Ph. Mertens, 13th PFMC, 2011

$$T(x,t) = T_{initial} + \frac{2q_0\sqrt{\alpha t/\pi}}{k}\exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{q_0 x}{k}\text{erfc}\left(\frac{x}{\sqrt{4\alpha t}}\right)$$



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

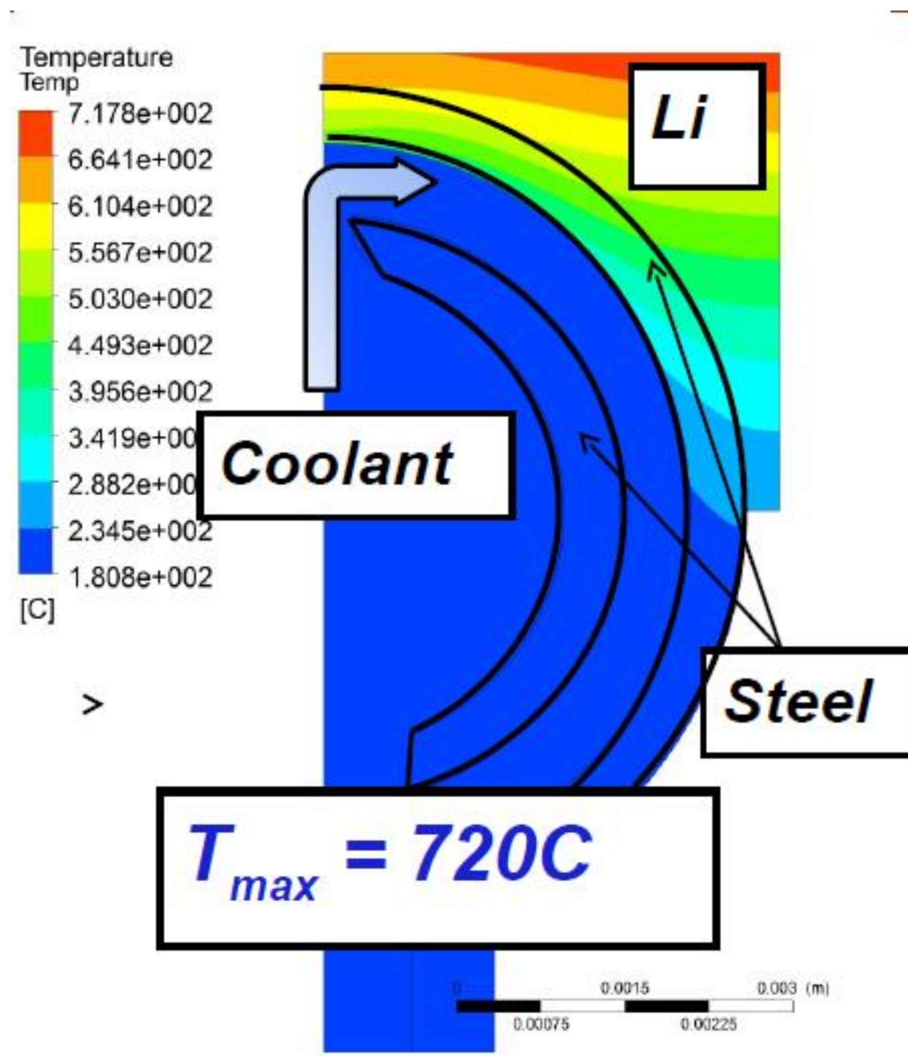
- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Multiple coolant options exist (T-tube impinging jets shown as example)



M. Jaworski, PPCF (accepted)

Advanced cooling techniques can be optimized for LM-PFCs for steady-state cooling

- 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-CO_2 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 (submitted)

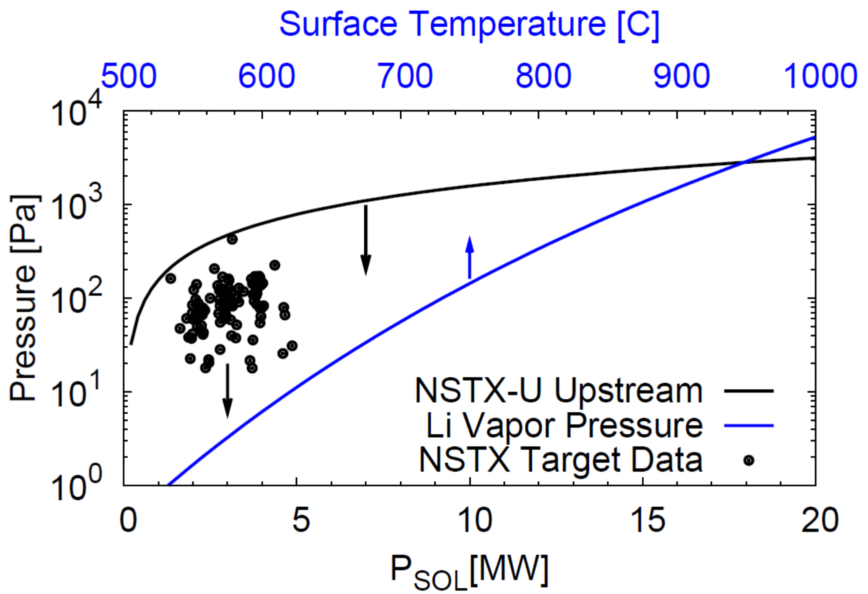
What are the physics ramifications of high temperature liquid lithium PFCs? What will an integrated scenario look like?

- 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 RLLD)
- 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?**
- Preliminary experiments being performed on Magnum-PSI plasma device

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

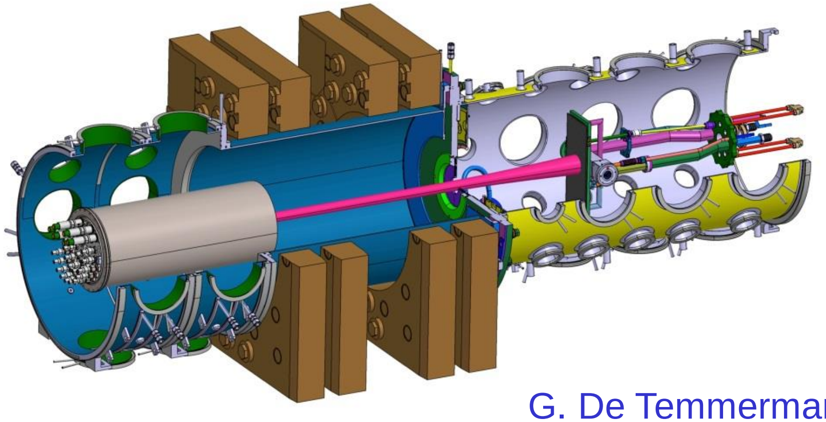
$$q_t^{plasma} = \gamma \Gamma_{sat}^{+} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$

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



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*



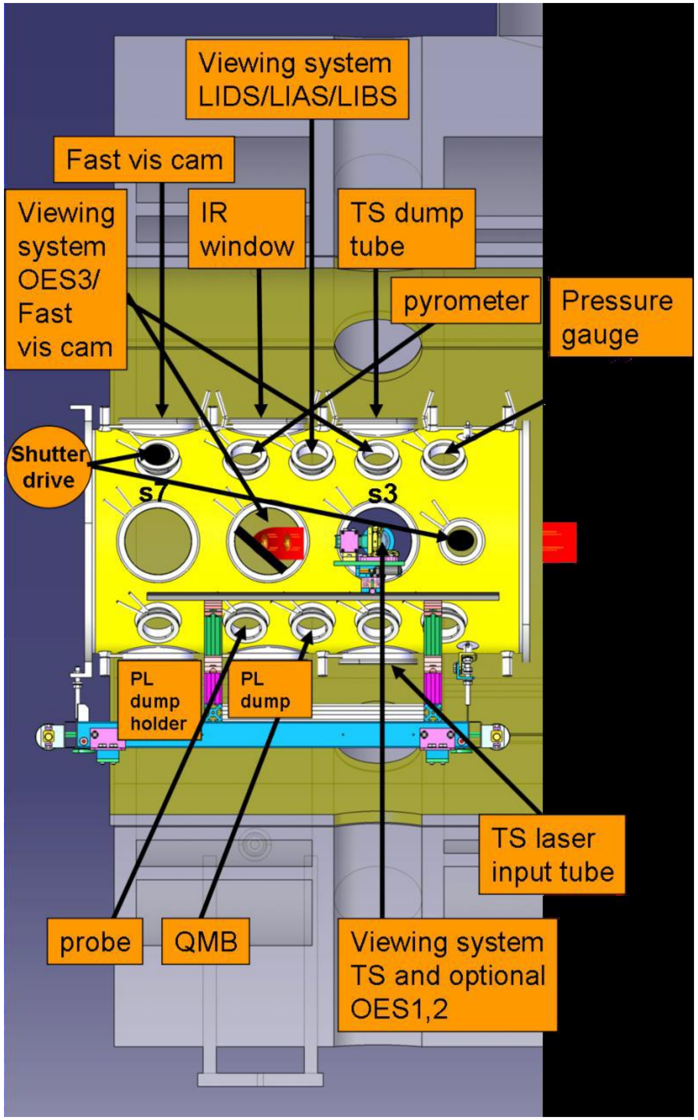
G. De Temmerman

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	$0.1–1^{\dagger}$
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

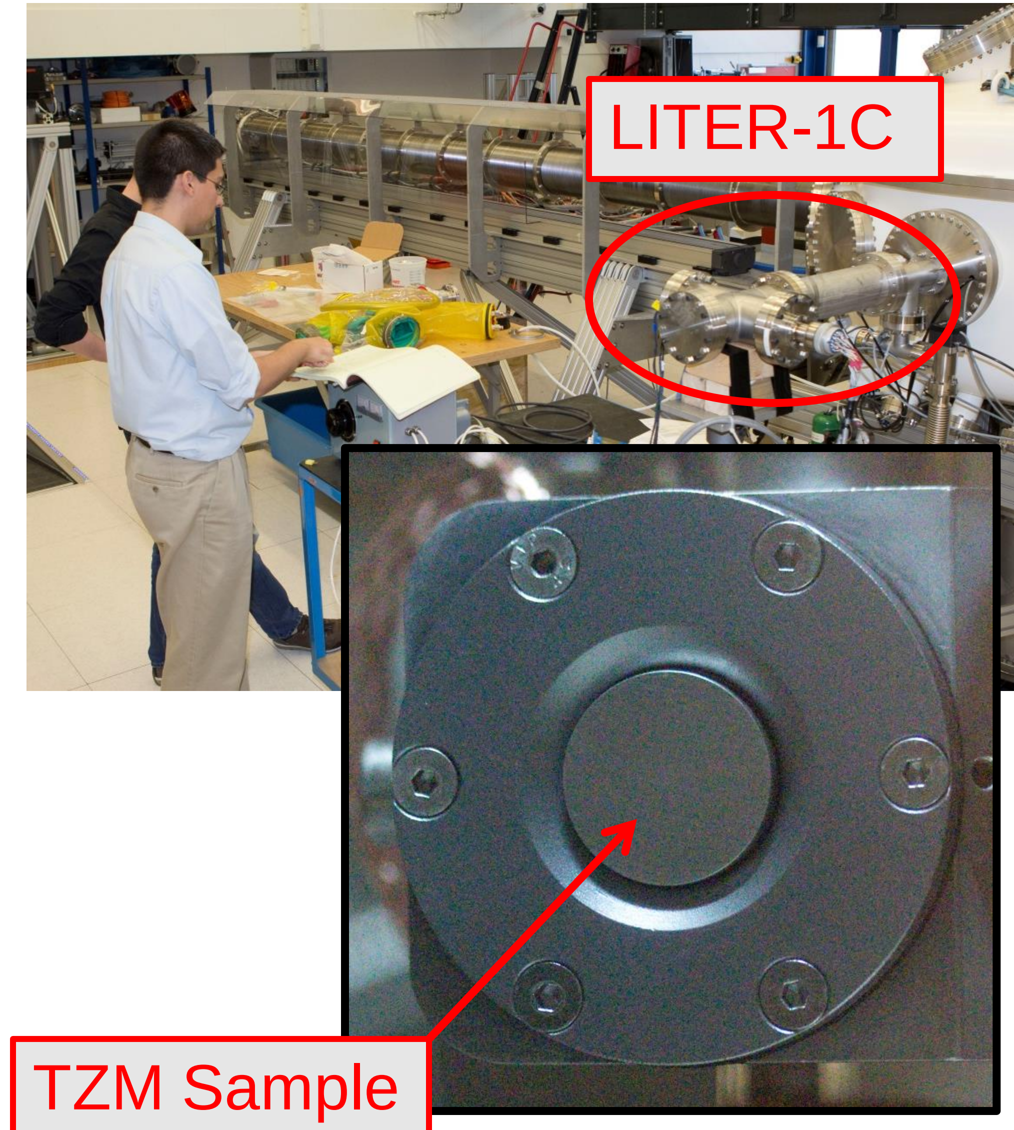
- Water cooling calorimetry provide absorbed energy per pulse
- IR diagnostics provide surface temperature
  - Spatially-resolved IR camera
  - Spectral pyrometer provides temperature and emissivity at single point
- Thomson scattering taken immediately in front of target
- Plasma emission (UV-NIR)
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



H.J. Van der Meiden PMIF 2013

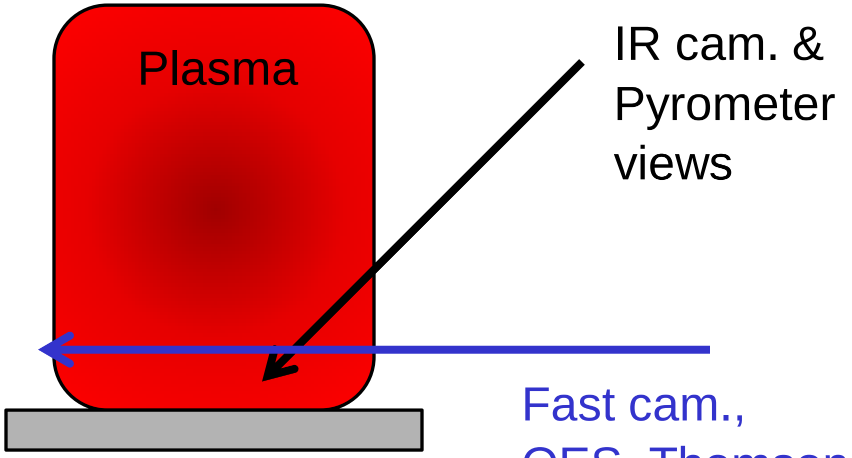
Samples coated with lithium in-vacuum using NSTX LITER-1C evaporator unit (on loan to FOM-DIFFER)

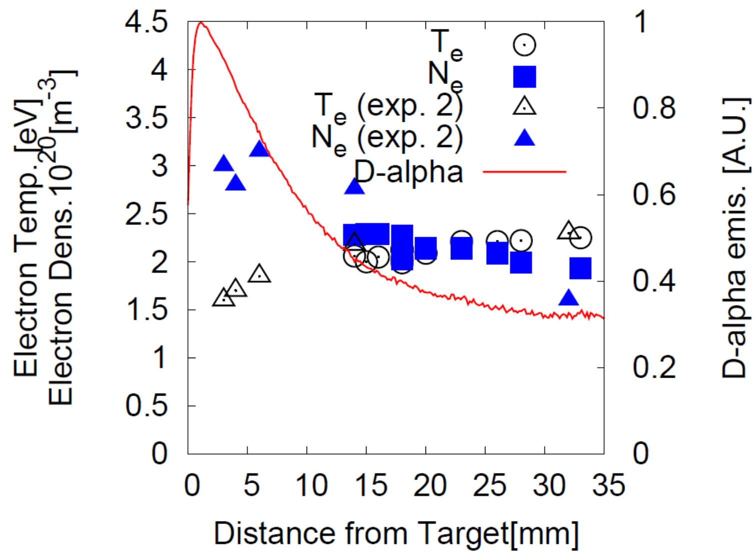
- 6mm-thick TZM-type molybdenum samples tested
  - Thick targets with graphoil “insulation” used to obtain large temperature rise
  - TZM being considered for NSTX-U divertor
- NSTX evaporator used on Magnum-PSI to perform coatings in vacuum
  - Larger capacity (~50g) than previous evaporators (~25mg)
  - Calibrated with QCM



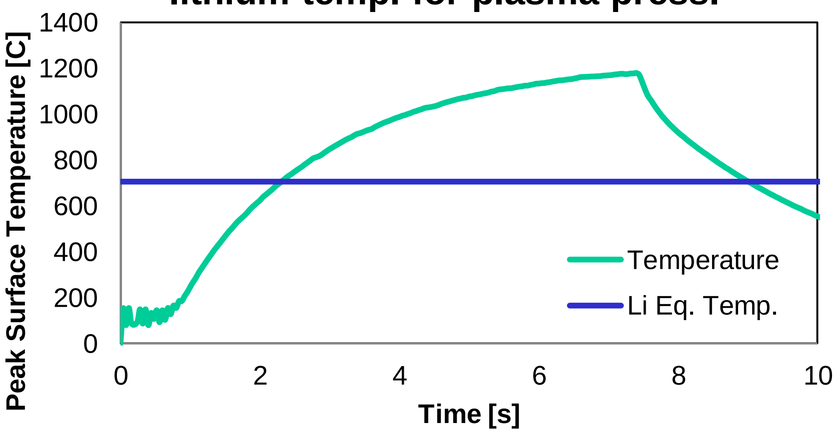
No Lithium plasma conditions and temperature rise

- Plasma profiles measured in front of TZM target
- IR camera cross-calibrated with pyrometer
- Calorimetry indicates 4.8kW average heating



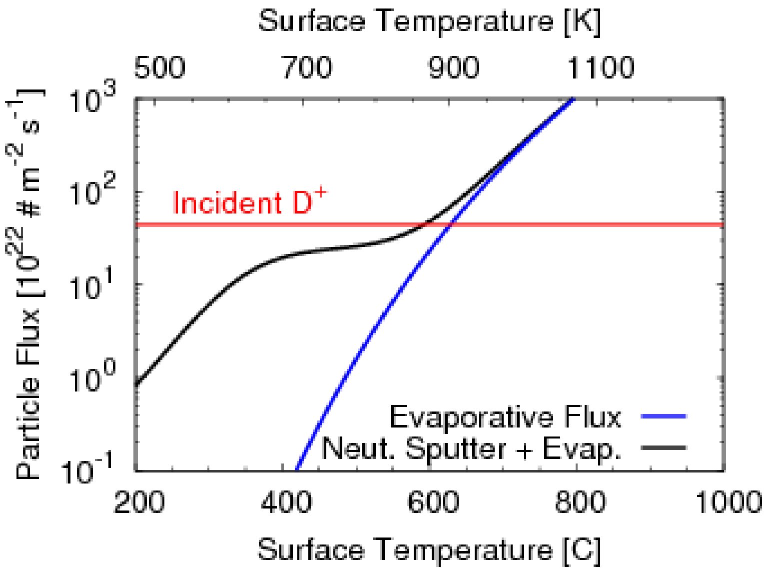


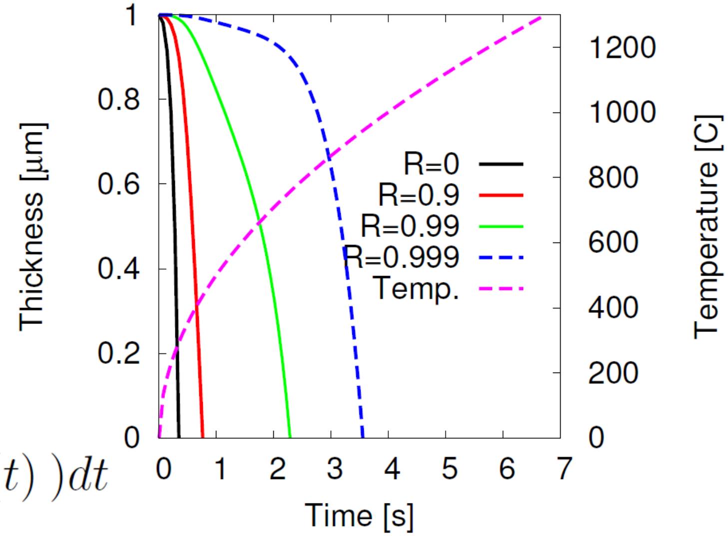
Surface temperature rise and equiv. lithium temp. for plasma press.



Initial estimates of coating lifetime for these temperatures indicated very rapid depletion without redeposition

- Initial models of erosion used temperature-enhanced sputter yields and Langmuir-law evaporation
  - Consistent with IIAX measurements by Allain and
  - PISCES-B measurements by Doerner
  - See T. Abrams talk for why this is pessimistic
- Very short lifetimes for 1 micron-thick coatings expected without redeposition

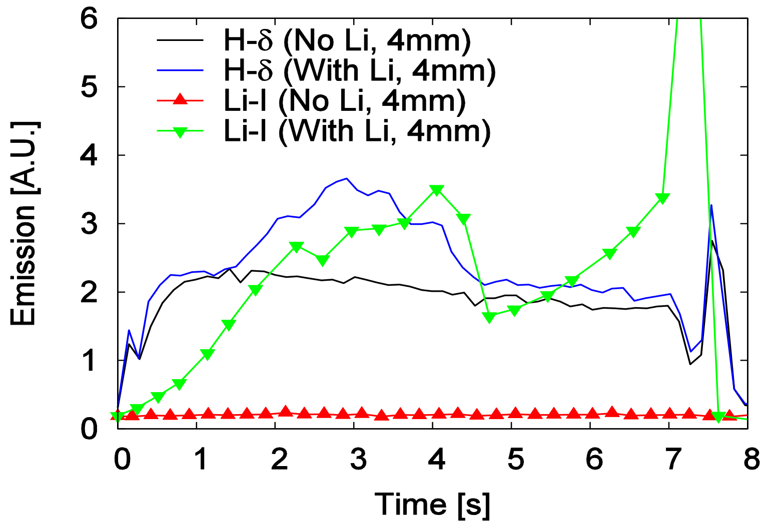




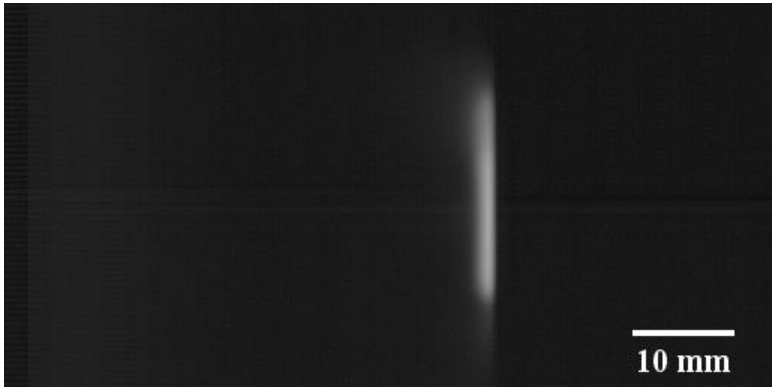
$$h(t) = h_0 - \int_0^t (1-R)\Gamma_{Li}(\,T_s(t)\,)dt$$

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

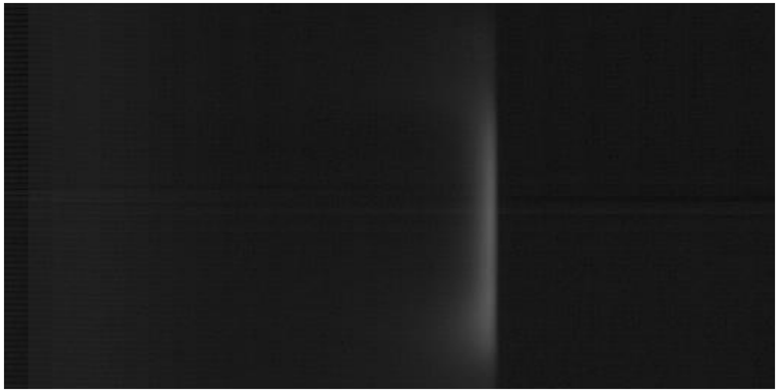
- Two states observed:
  - Intense emission 2-3mm in front of target, persisting 3-4s
  - Transition to diffuse cloud
  - Observable on OES chord as well
  - See also T. Abrams talk
- Still implies large redeposition fraction despite pessimistic erosion estimate



Li-I emission, t=2.5s

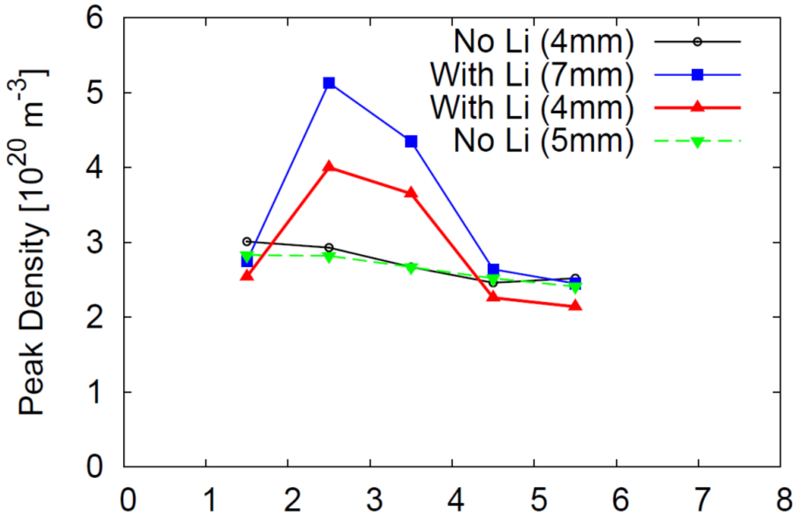


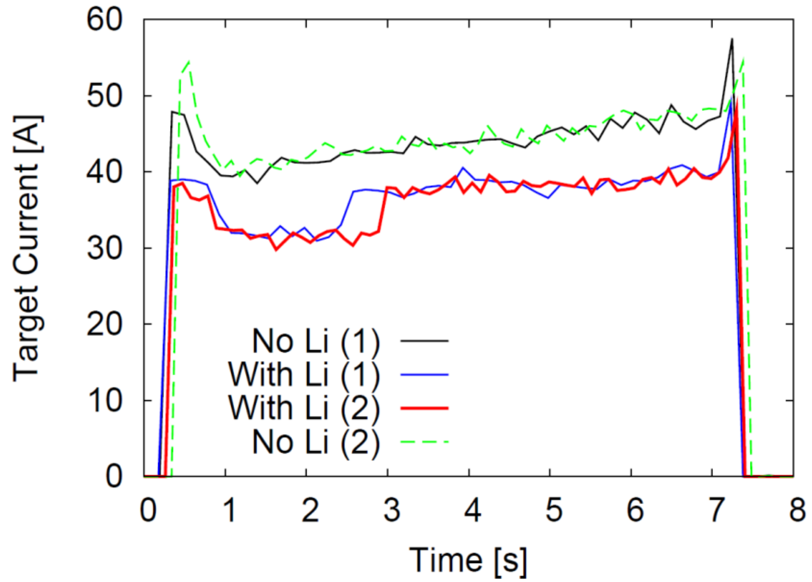
Li-I emission, t=6s



Density increases in front of target but current draw decreases

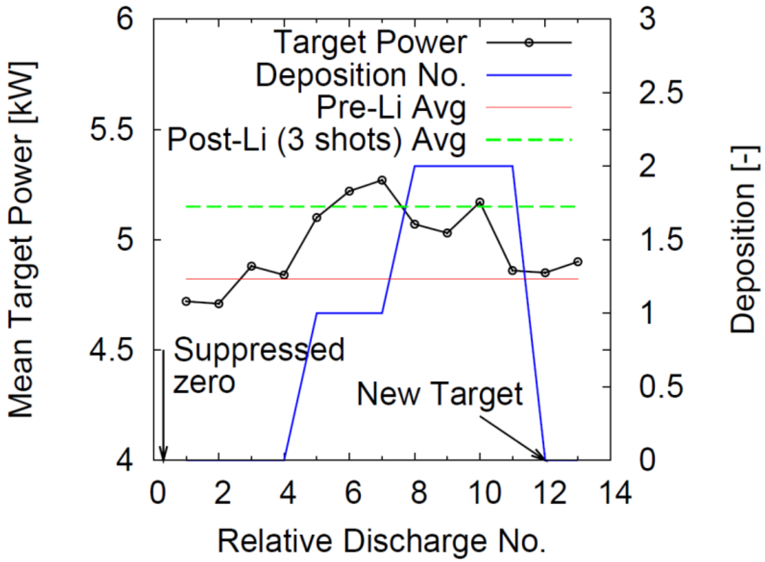
- Thomson scattering indicates increased density
  - Transient increase and decrease similar to OES signals
  - Electron temperatures not significantly altered at this measurement location
- Current drawn by target decreased (~25% reduction) initially and then increases again



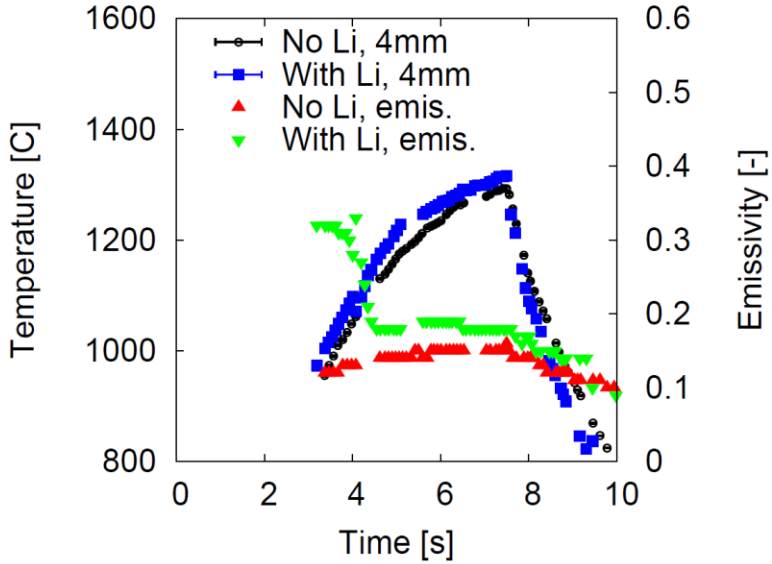


Calorimetry and pyrometer indicate similar or increased heat flux with lithium (!)

- Water-cooling calorimeter indicates increased power deposited
  - 4.8kW vs. 5.2kW
  - Target returns to "pre-Li" levels after several exposures

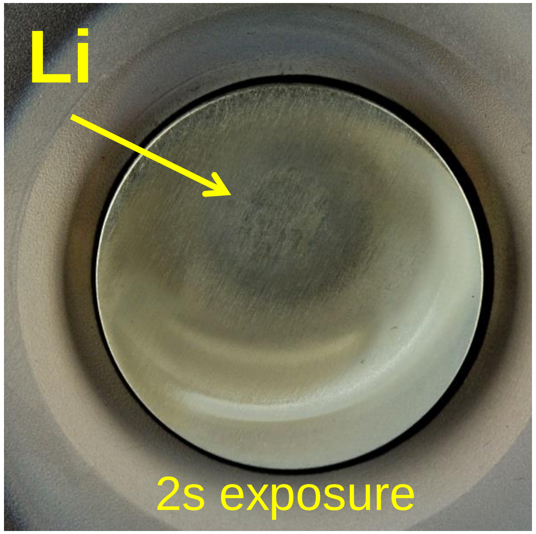


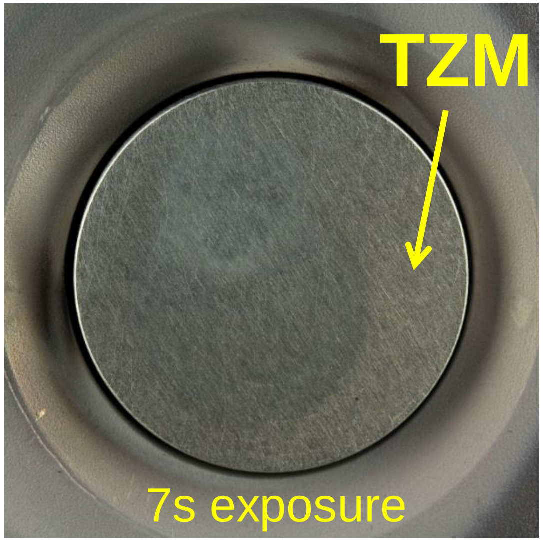
- Pyrometer indicates slightly higher temperatures with Li
  - 1295C vs. 1315C
  - Rapid change in emissivity measured at transition



Close attention to plasma-material interaction effects may explain these observations

- Two states are interpreted as the presence of a macroscopic layer of lithium on the TZM
  - Confirmed in subsequent experiment
  - Rapid change in emissivity could be additional indicator of depletion
  - See T. Abrams talk for more on erosion regimes
- Detachment indicators and counter indicators
  - Decreased current and increased optical emission (standard tokamak signatures)
  - Increased power deposition
  - Current does not decrease to zero
- **Differences in particle reflection and ion exchange may reconcile these measurements**





Heat flux to a surface

$$q_{tot} = q_{pl} + q_{neut} + q_{rad}$$

$$\begin{aligned} q_{pl} \;=\; & \Gamma_+\{[2.5T_i - eV](1 - R_{iE}) + && \text{ion heating} \\ & \left[\frac{2T_e j_e(V)}{1-\delta}\right](1 - R_{eE}) + && \text{elec. heating} \\ & E_{pre.sh.} + \chi_i + \chi_r(1 - R_{iN})\} \end{aligned}$$

c.f. Stangeby 2000, chapter 25

$$q_{neut} = \Gamma_0\left[E_0(1 - R_{iE}) + \chi_r(1 - R_{iN})\right]$$

$$q_{part.} = \Gamma_+\left(\frac{q_{pl}}{\Gamma_+} + \frac{f q_{neut}}{\Gamma_+}\right) \qquad \text{where} \quad \Gamma_0 = f\Gamma_+$$

- R_{iN} and R_{iE} are particle number reflection and particle energy reflection coefficients respectively
- $E_{pre.Sh.}$ Is pre-sheath energy drop (fraction of T_e)
- X_i is the ionization energy of incident ions (13.6 for D)
- X_r is the recombination energy of incident ions (2.2/ion)
- E_0 is incident neutral energy

Large fraction of lithium can produce reduced current despite increased density

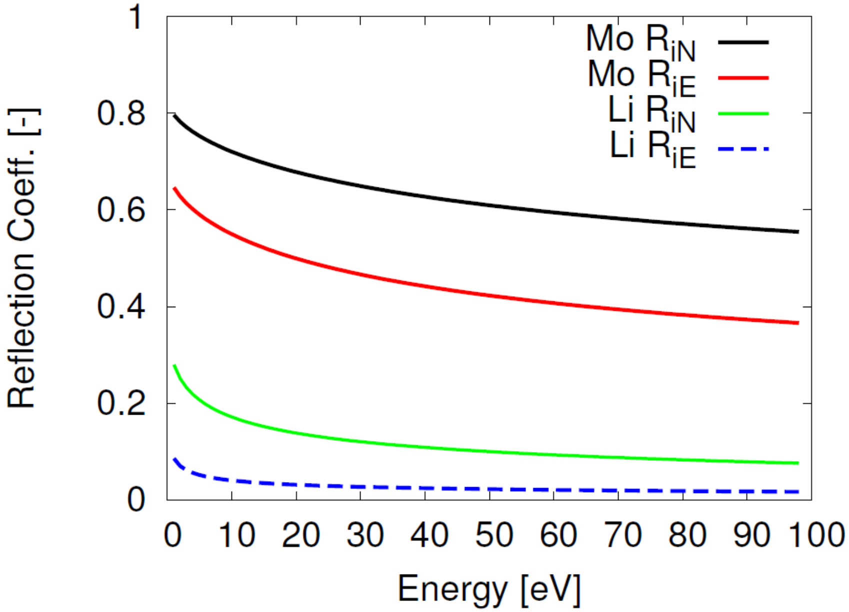
$$J_{ion} \approx e n_{se} c_s \approx e n_{se} \sqrt{\frac{kT_e}{M_i}}$$

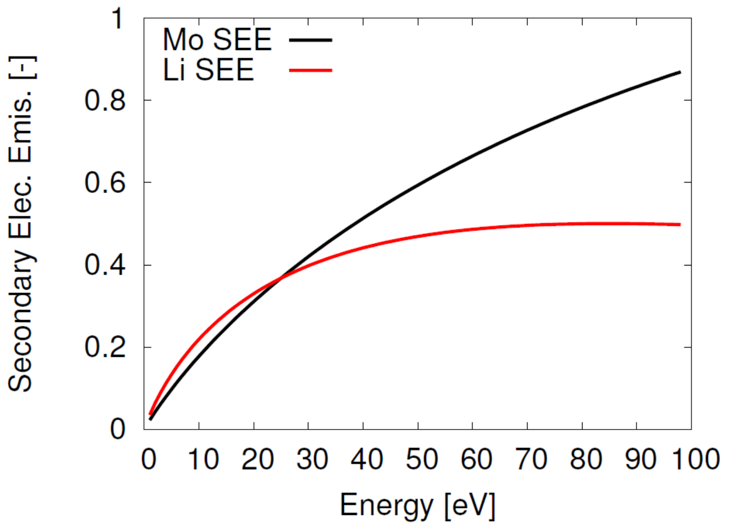
$$\frac{J_{Li}}{J_D} \approx \frac{4 \times 10^{20}}{3 \times 10^{20}} \sqrt{\frac{2.014}{6.941}} = 0.72$$

- Current density to target depends on ion sound-speed
- Measured Thomson values indicate increased density, but…
- Mass ratio still results in ~25% decreased current *assuming 100% lithium fraction at the target*

Particle reflection is very different for high-Z vs. low-Z targets

- Ballistic reflection coefficients depend on reduced mass and energy
  - **5x** more particles reflected from Mo
  - **17x** more energy reflected from Mo
- Electron emission negligible from both materials
  - Negative biasing eliminates secondary emission
  - Thermionic emission negligible (7 orders of magnitude smaller than ion current)
  - Photo-electric emission negligible (2 orders of magnitude smaller)

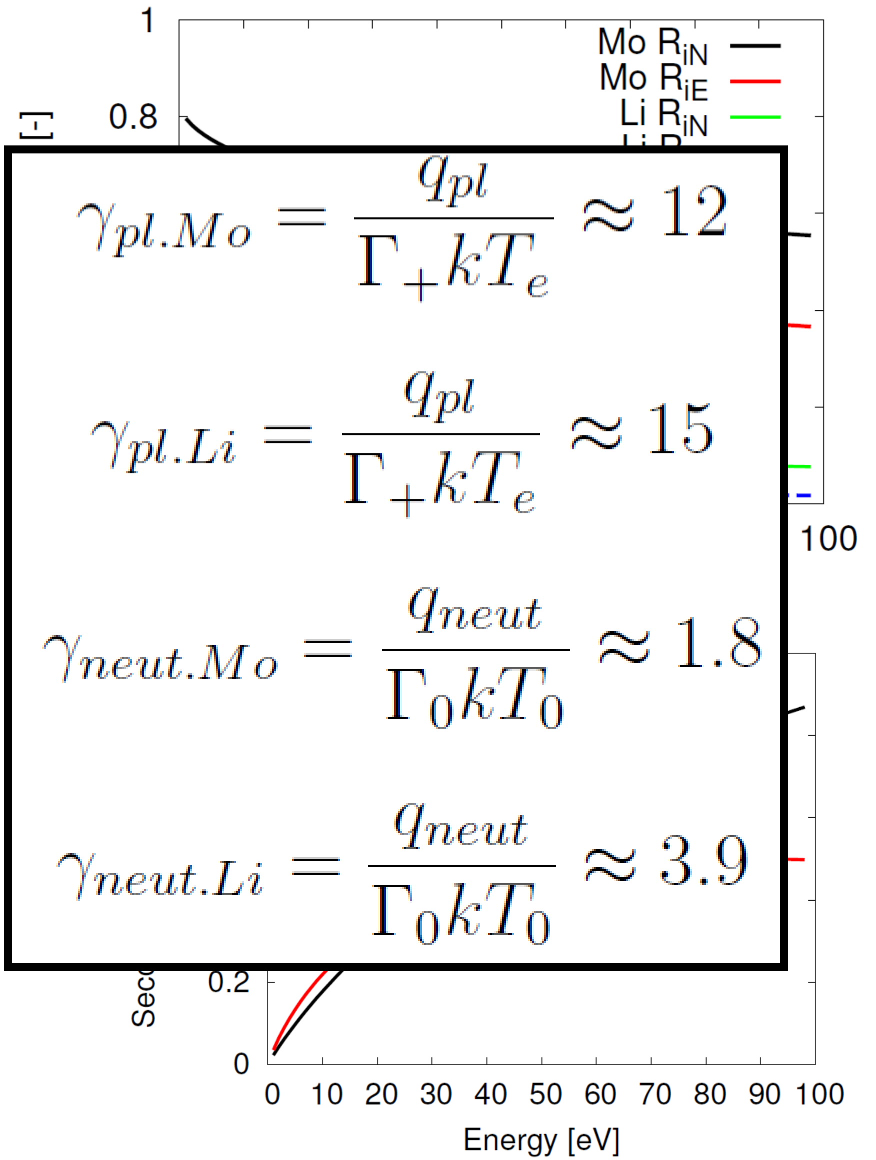




Thomas, 1991 IAEA Report, INDC(NDS)-249

Particle reflection is very different for high-Z vs. low-Z targets

- Ballistic reflection coefficients depend on reduced mass and energy
  - **5x** more particles reflected from Mo
  - **17x** more energy reflected from Mo
- Electron emission negligible from both materials
  - Negative biasing eliminates secondary emission
  - Thermionic emission negligible (7 orders of magnitude smaller than ion current)
  - Photo-electric emission negligible (2 orders of magnitude smaller)



$$\gamma_{pl.Mo} = \frac{q_{pl}}{\Gamma_+ kT_e} \approx 12$$

$$\gamma_{pl.Li} = \frac{q_{pl}}{\Gamma_+ kT_e} \approx 15$$

$$\gamma_{neut.Mo} = \frac{q_{neut}}{\Gamma_0 kT_0} \approx 1.8$$

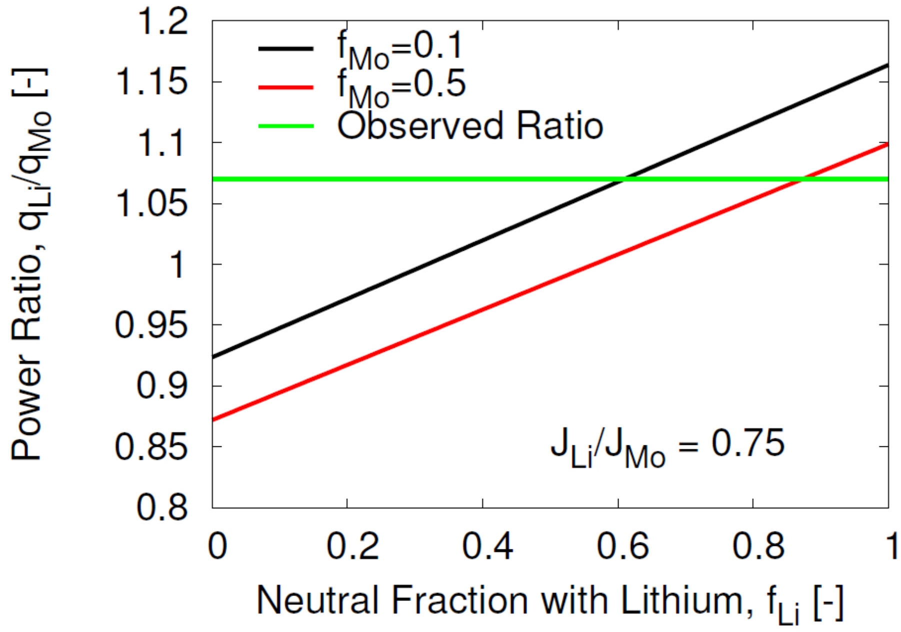
$$\gamma_{neut.Li} = \frac{q_{neut}}{\Gamma_0 kT_0} \approx 3.9$$

Closer accounting of PMI processes still implies larger neutral flux with Li on the surface

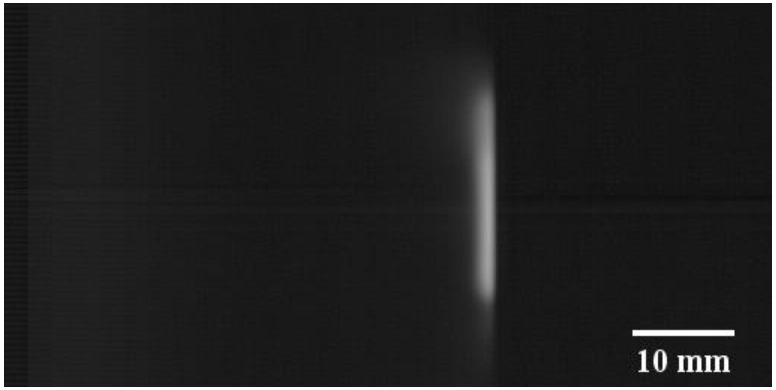
- Power deficit persists despite reflection coefficient accounting
  - Increasing neutral flux fraction can *increase* power deposition…
  - Due to decreased energy reflection with Li

$$q_{part.} = \Gamma_+ \left(\gamma_{pl} + \gamma_{neut.} f \right)$$

$$\frac{q_{part.Li}}{q_{part.Mo}} = \frac{J_{Li}}{J_{Mo}} \frac{\gamma_{pl.Li} + \gamma_{neut.Li} f_{Li}}{\gamma_{pl.Mo} + \gamma_{neut.Mo} f_{Mo}}$$



Picture of vapor-cloud PMI already showing rich physics



- Observation of reduced current to target consistent with
  - Increased effective ion mass due to large lithium fraction
  - Increased neutral particle bombardment
- Increased heating to the target consistent with
  - Increased plasma and neutral energy deposition due to replacement of high-Z target with low-Z lithium surface
  - Requires increased neutral particle flux due to decreased ion bombardment

“Rich Physics” means there’s still a lot to do

- Confirming neutral hydrogen and lithium fractions should be feasible with existing data set
  - OES data through Thomson measurement locations
  - See also T. Abrams for beginnings of this process
- Modeling of the near-surface plasma commencing to describe mass, momentum and energy balance
  - Why is the cloud so effectively confined? Is flow friction sufficient?
  - Can the results be extended to a tokamak divertor?
- Results imply that momentum loss alone will not be sufficient to reduce incident heat loads
  - Power could be transmitted to neutral gas and still impinge target
  - However, no Li-II emission observed in these experiments due to low T_e in Magnum-PSI
- Long-life of the vapor cloud provides initial feasibility study of vapor-shielding experiments in NSTX-U
  - Thin-coatings can be used prior to developing fully-flowing lithium divertor targets
  - Initial experiments in NSTX-U can be planned after high-Z divertor upgrades

Summary

- Liquid metals are renewable surfaces and this is a key advantage over solid PFCs

- The NSTX-U research program has made development of liquid metal PFCs a priority to compare high-Z and low-Z, liquid PFCs

- Inertially-cooled and actively-cooled divertor targets with 10 MW/m^2 incident heat flux will quickly reach temperatures above 600C

- Preliminary results are revealing rich physics in vapor-shielded targets and provide the first indications that this is a viable line of research prior to developing fully-flowing modules

Thank you!

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