Overview of the US ALPS Program

presented by

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on behalf of US ALPS Program Members:

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1st NIFS-CRC Int. Symposium

JAPAN, May, 2007

ALPS

- The US Advanced Limiter-divertor Plasma-facing Systems (ALPS) program continues to develop the science of liquid metal surface divertors for near and long term tokamaks.
- These systems may help solve the demanding **heat removal**, **particle removal**, **radiation damage** and **erosion issues** of fusion plasma/surface interactions.
- ALPS combines **tokamak experiments**, and supportive **laboratory experiments**, and **modeling**.
- Liquid-lithium divertor and wall experiments are underway on the the National Spherical Torus Experiment (NSTX) and Lithium Tokamac Experiment (LTX) at Princeton.
- Alternative liquid metal options tin, gallium, and tin-lithium systems are under evaluation at the lab level.

Why Liq. metal? Why Lithium?

- Reactor engineering:
  - A flowing liquid metal first wall eliminates erosion - the wall is continuously renewed
  - Unlimited lifetime in high neutron flux environment
  - Capable of dissipating very high power densities
    - >50 MW/m^2 demonstrated in PPPL experiments
- Physics (w.r.t. Li):
  - Access to new confinement regimes with very low recycling walls
    - Proposed by S. Krasheninnikov, L. Zakharov
    - Broad/flat T_e, T_i profiles with no or small conduction losses
      - Very long confinement times possible

ALPS Experiments

Facility	**Type**	**Experiments**
NSTX (PPPL)	spherical tokamak	Under upgrade to full Li divertor
LTX (CDX-U) PPPL)	small spherical tokamak	Li full toroidal limiter (under upgrade to full Liq. Li wall)
PISCES (UCSD)	arc-discharge	Liquid metal Plasma Surface Interactions (PSI)*
ARIES (SNL)	**ion spectrometer**	**Liquid metal PSI***
IIAX / SLIDE (UIUC)	**flow + beam/ colutron**	**Liquid metal PSI***
MTOR (UCLA)	**jet-film-magnet**	**MHD testing**
LIMITS (SNL)	**jet-magnet**	**MHD testing**
IMPACT (ANL)	**ion gun + in-situ spectroscopy**	**Liquid metal PSI***

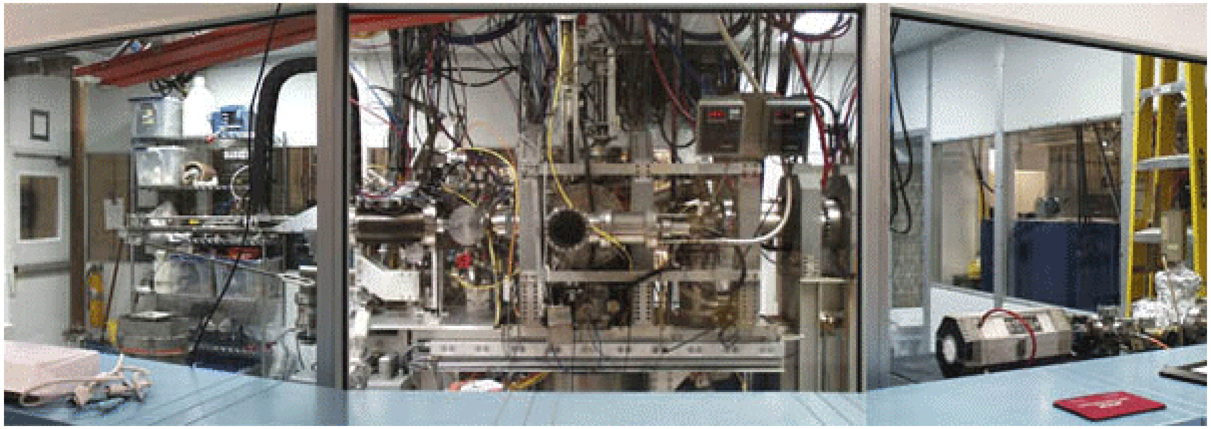
*PSI partially or totally including surface characteristics, D, He, O, metal—retention and sputter yields.

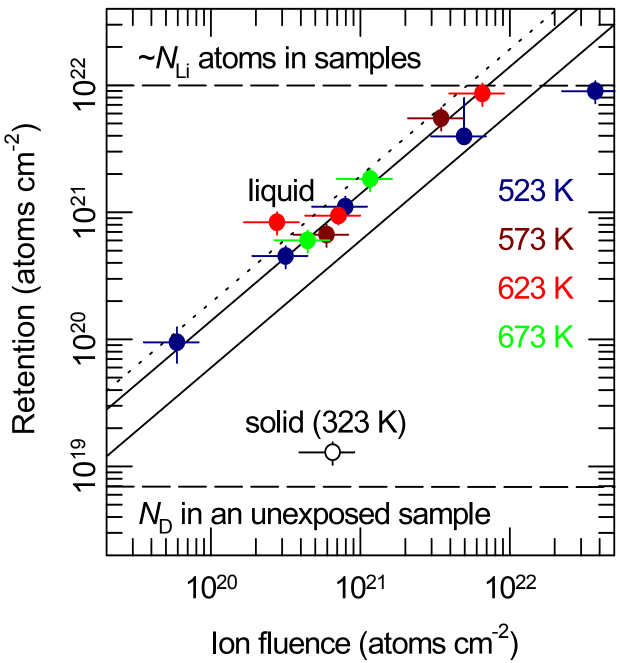
Results to date are extensive and generally encouraging

- Good tokamak (CDX-U) performance with a liquid Li limiters.
- High D pumping in Li and non-zero He/Li pumping.
- Well-characterized data on temperature-dependent liquid metal surface composition and sputter yield.
- **Predicted stable, low-recycling, improved-plasma, lithium divertor performance in NSTX.**
- High temperature capability (~1100 °C) Sn or Ga potential with reduced ELM & disruption response concerns.
- MHD analysis predicts good NSTX static Li performance.

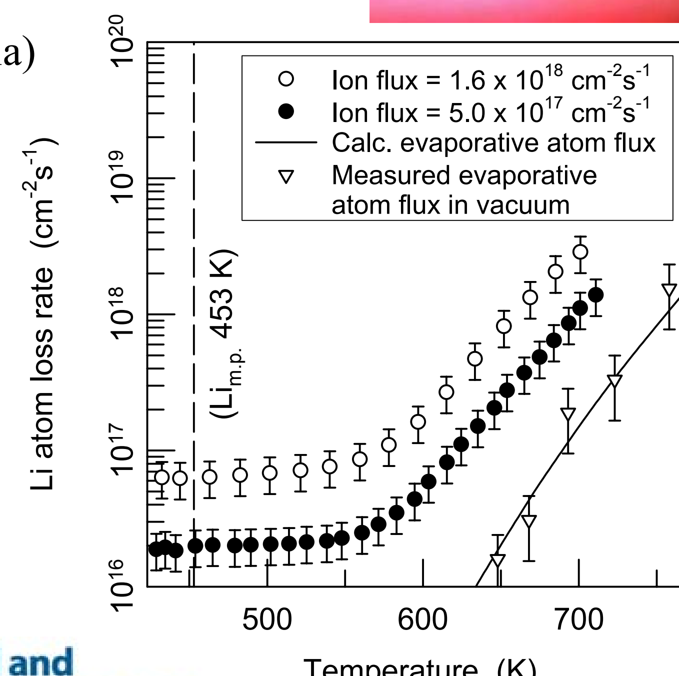
Support Laboratory Experiments

PISCES-B liquid Li PMI Experiments.





Li Sample (25 mm dia)

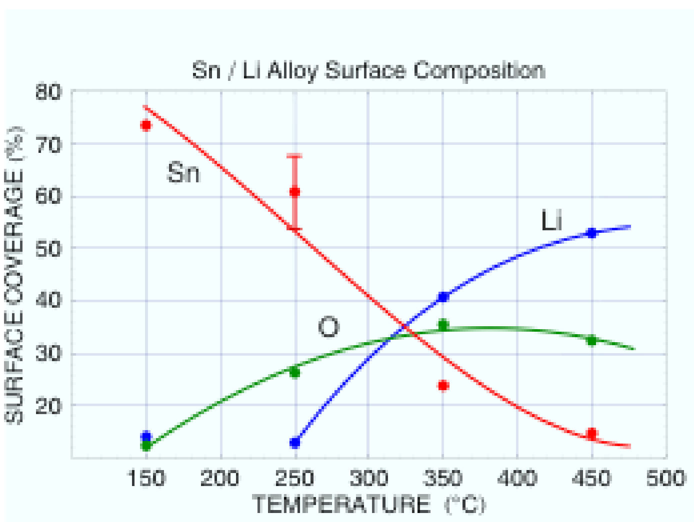


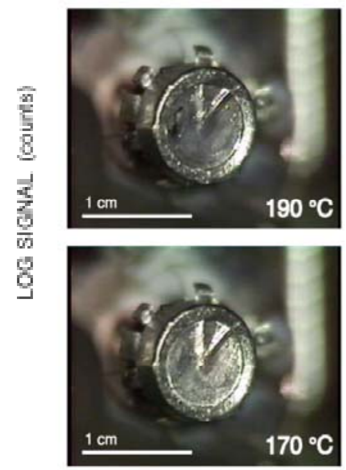
ALPS lab studies of liquid surfaces at SNL/CA

- For the ALPS program, we examined liquid Li, Ga, Sn, and a Sn-Li alloy over a wide temperature range.

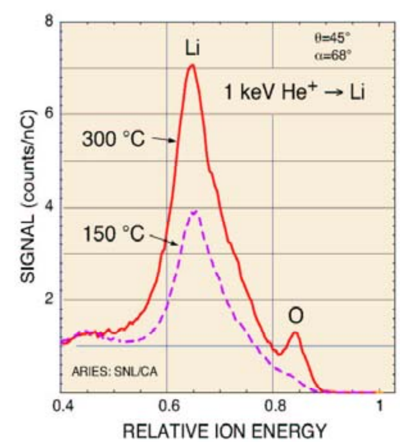
  We found that:
  - > oxygen segregation to the Li surface can be a transient source of plasma impurities.
  - > hydrogen isotopes bind strongly to Li, weakly to Ga, and not at all on Sn surfaces.
  - > lithium segregation in Sn-Li alloy produces a low-Z, low-recyling surface on a low T inventory liquid.

  These findings provide guidelines for selecting a suitable liquid plasma-facing material.



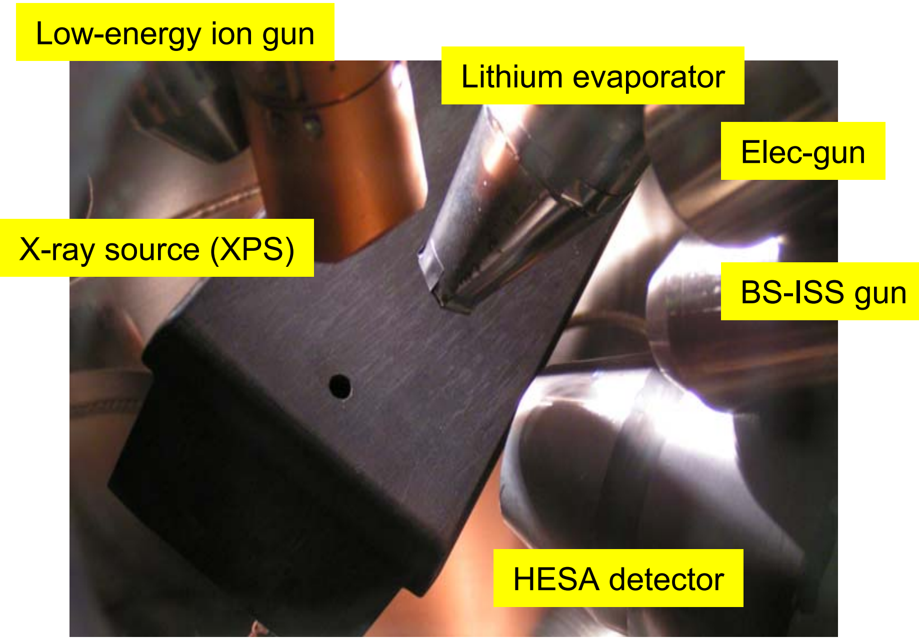


Lithium

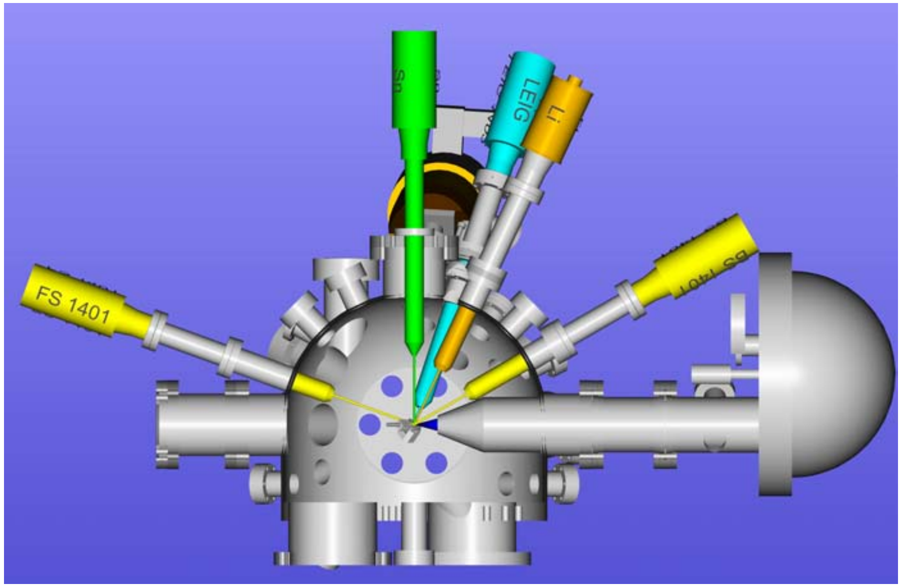


Materials & Engineering Sciences Center
Atoms to Continuum

IMPACT In-situ Surface Analysis at Argonne



J.P. Allain, et al.

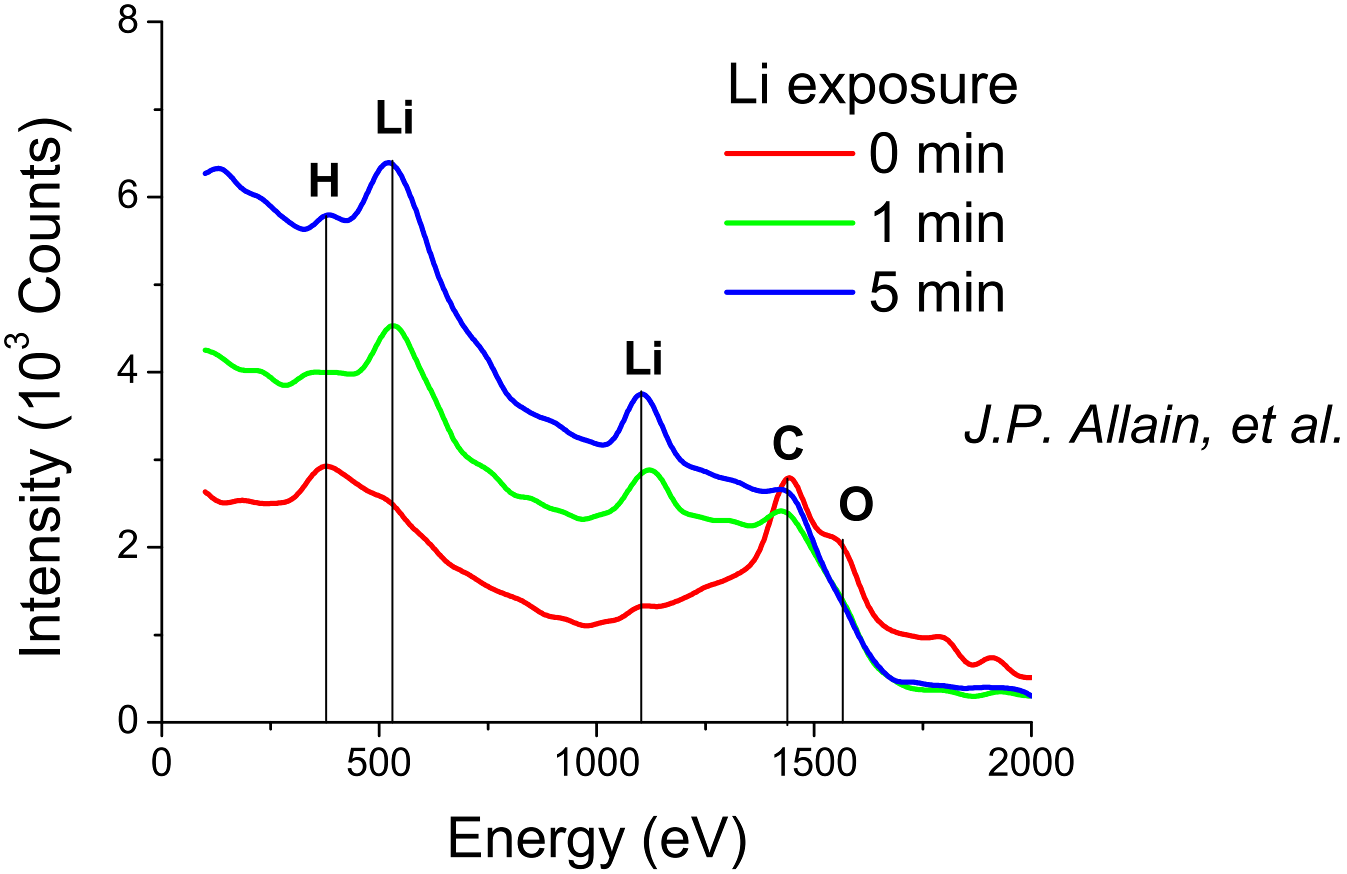


Ion spectroscopies are complemented by several electron and X-ray spectroscopies for surface chemical analysis: XPS, EUPS, AXRF and AES

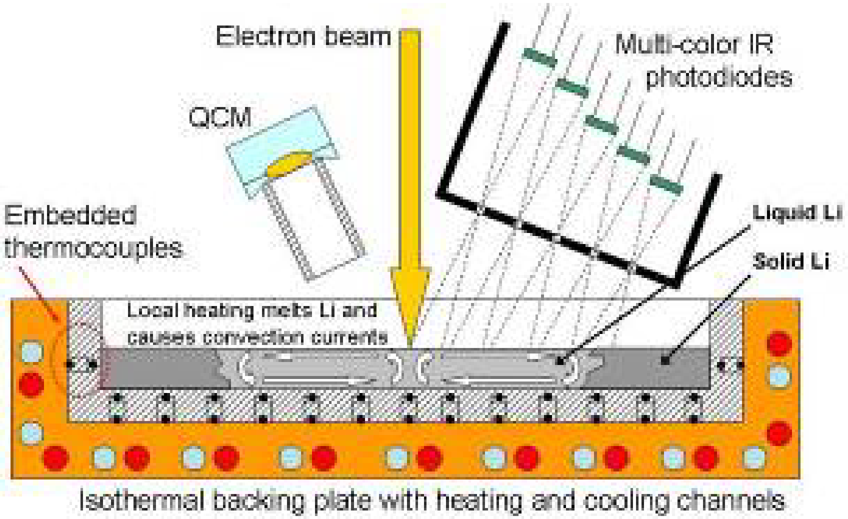
- NSTX ATJ graphite tiles exposed to evap. Li shots analyzed with XPS taking high resolution scans along relevant regions: O, C, Li, B.
- Top left: NSTX tile installed on manipulator with tilt and length adjustment
- BS-ISS not used for these measurements

RT Li coating of ATJ graphite sample

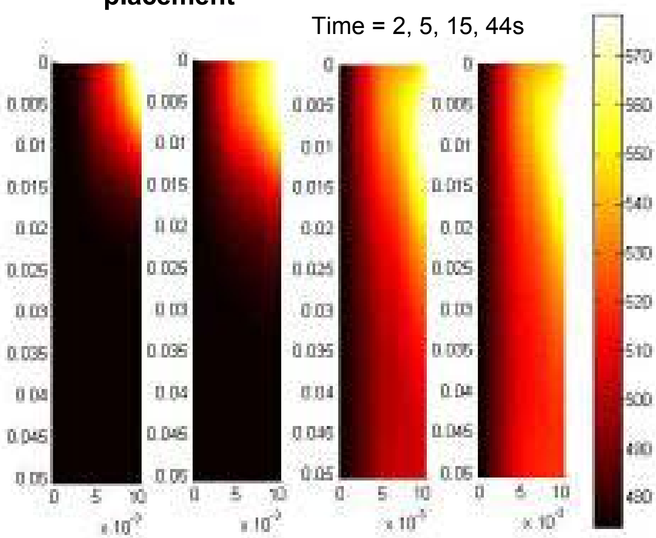
- Red line: uncoated carbon
- Peaks at ~ 550 eV and ~ 1100 eV correspond to Li recoil and scattered, respectively, and become dominant after ~ 5 min of Li exposure



Solid-Liquid Lithium Divertor Exp. (SLiDE)



Temperature distribution through tray and liquid lithium modeled to determine optimal thermocouple placement



- **Facility for studying surface tension driven flows with MHD effects**
  - Temperature gradients induce passive flowing of liquid metal
  - Effectively redistributes heat away from local heating
  - May enable lithium to redistribute larger power fluxes before evaporating into a fusion machine
- **Experimental capabilities**
  - 15 kW beam power for local heating of lithium
  - Adjustable beam shape to explore power flux profile effects
  - Magnetic fields up to 0.2T ($0 < Ha < 400$)
  - Transient and steady state measurement of operation

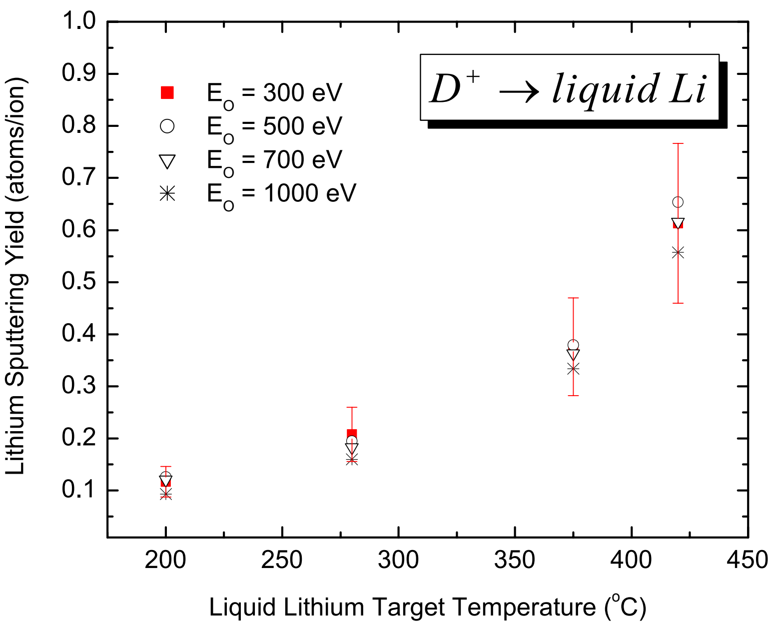
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

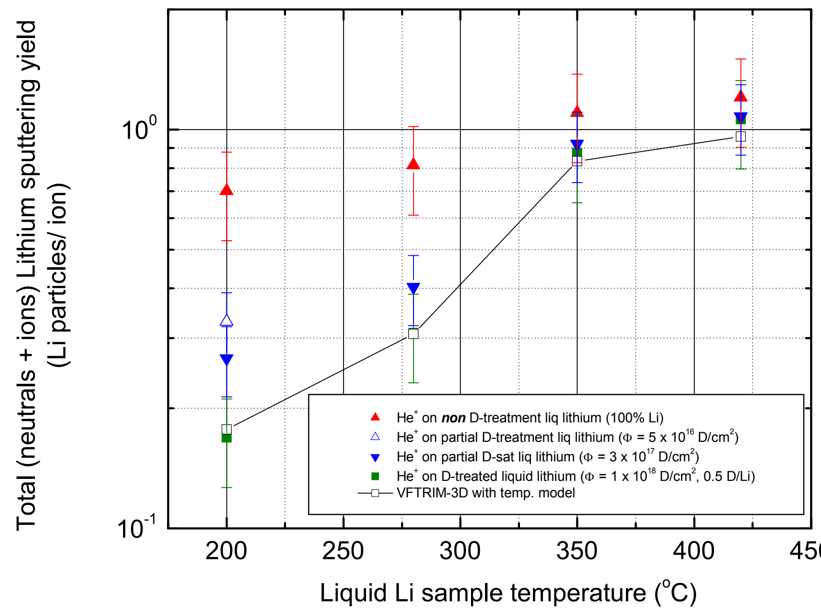
Ion-surface **I**nter**A**ction e**X**periment **IIAX**

- Uses a mass–filtered ion beam to bombard samples. Ejected mass monitored with quartz-crystal microbalances to determine sputtering yields of solid or liquid surfaces.

- **Early work focused on temperature-dependent low energy ion sputtering of liquid Li**

  Allain, J.P., M.D. Coventry, and D.N. Ruzic,. J. Nucl. Mater., 2003. **313-316**: p. 641-645





- **Recent work focuses on temperature-dependent low energy ion sputtering of liquid Sn**

  M. D. Coventry, J. P. Allain and D. N. Ruzic, J. Nucl. Mater., 313-316, (2003) 636-640

  M. D. Coventry, J. P. Allain and D. N. Ruzic, J. Nucl. Mater. 335, (2004) 115-120

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CDX-U & (LTX)

- CDX-U tokamak dedicated to ALPS studies.
- Lower toroidal belt limiter
- Gain experience using Li in-vessel
- Establish safety procedures
- Study influence of Li surface on performance
- Test bed for concepts to be used in larger devices, e.g., NSTX

Total of three lithium, two gas fueling systems employed for the CDX-U experiments

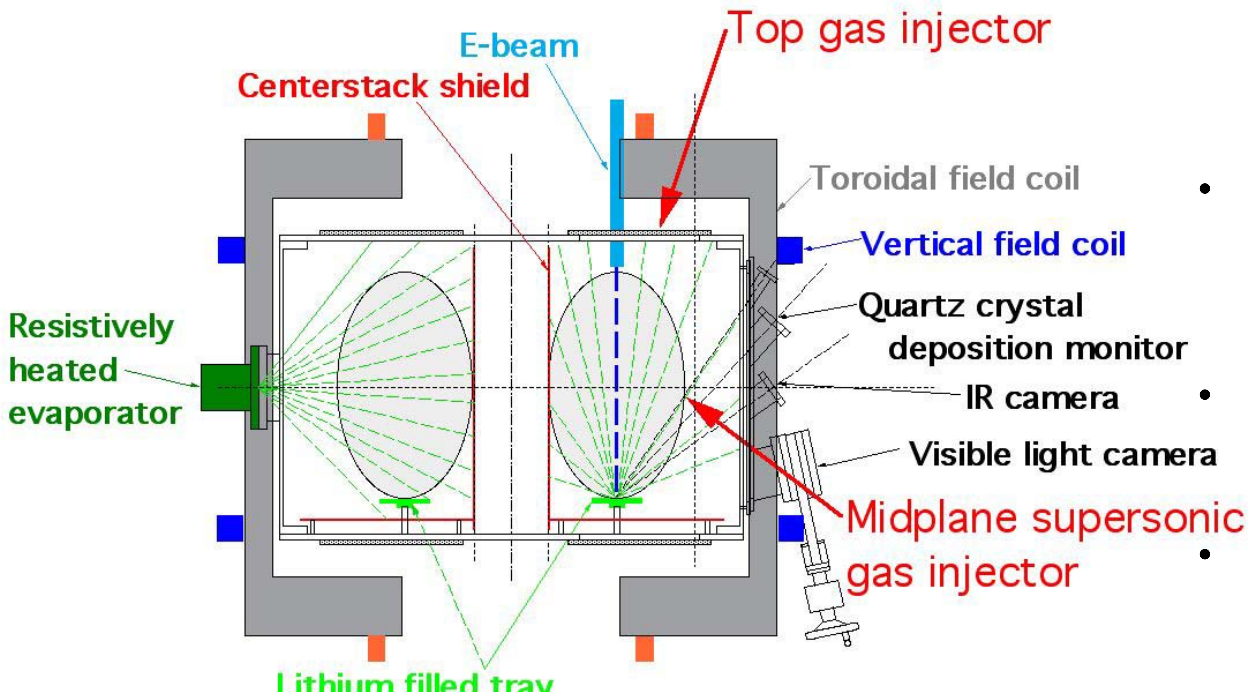
CDX-U

LTX

CDX-U:

R_0=34 cm	κ≤1.6	$I_P \leq$ 80 kA	$T_e(0)$~100 eV
a = 22 cm	$B_T(0) \leq$2.1 kG	τ_{disch}<25 msec	$n_e(0)<6 \times 10^{19}$ m^{-3}

>No carbon limiters used in CDX-U



R_0= 34 cm, width = 10 cm
6 mm deep

- Lithium tray limiter
  - 300 g of lithium in a toroidal tray
  - Half Li inventory liquid
- New electron beam lithium coating system
  - Used lithium in tray as source
- New resistively heated lithium evaporator
  - NSTX prototype
- Gas injection systems
  - Wall mounted piezo valve
  - Supersonic gas injector

⇒Up to 1000Å of lithium coatings between discharges

⇒600 cm² of liquid lithium forms lower limiter

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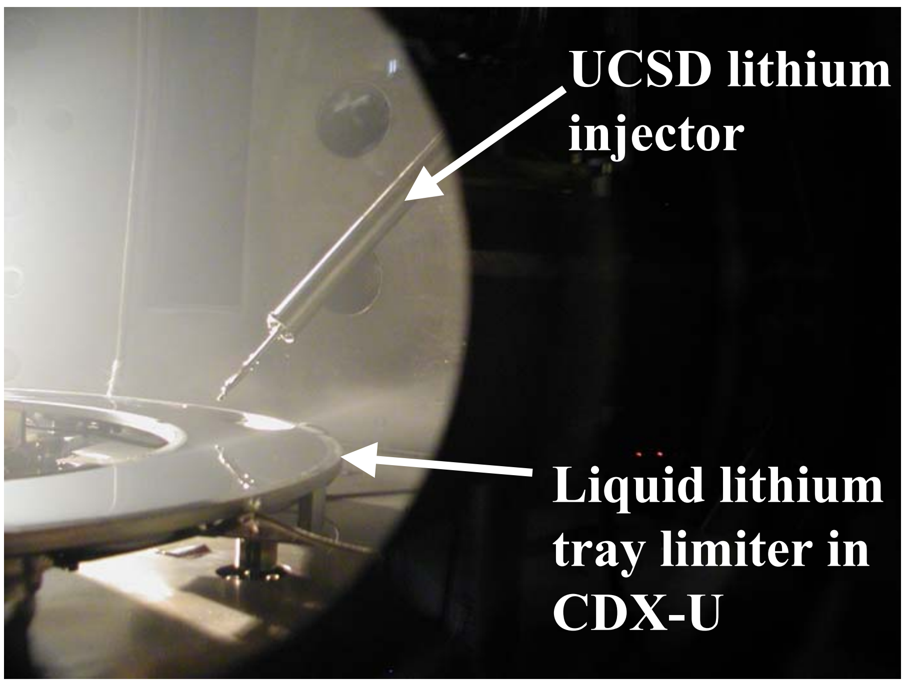
PRINCETON PLASMA PHYSICS LABORATORY

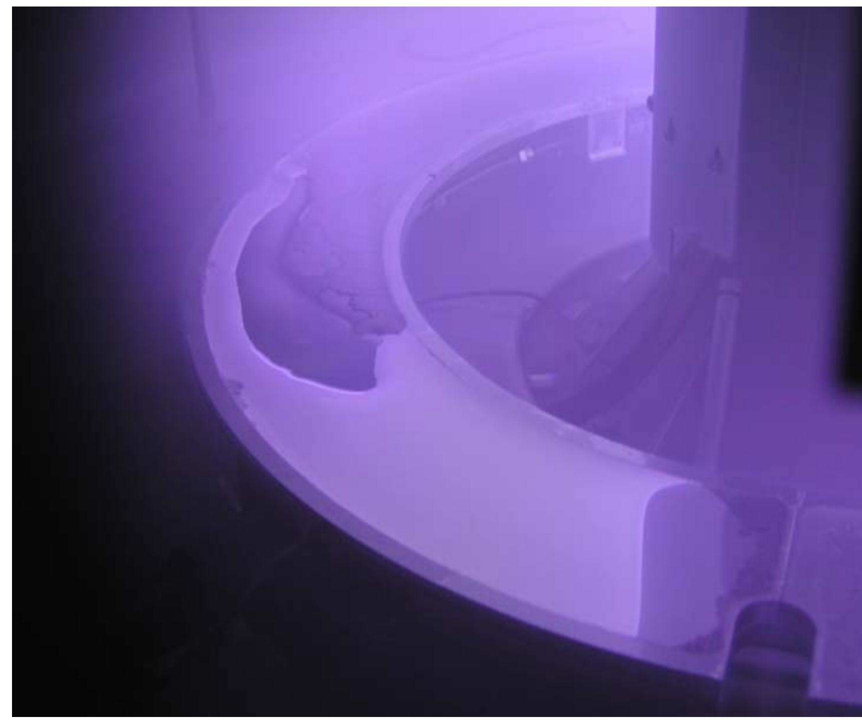
Tray filled with *liquid* lithium under argon (1.01 atm)

CDX-U

- Filling technique developed with UCSD
  - Load liquid lithium onto 500^{o}C tray
  - High temperature promotes wetting
  - "Injection" of liquid lithium eliminates solid contaminants
- Thin coatings appear between runs
  - Removed/dissolved by GDC, heating
- One fill active for up to ~ 1 year
  - Pumped for hundreds of discharges



Tray during fill


Tray after plasma operations, during hot argon glow

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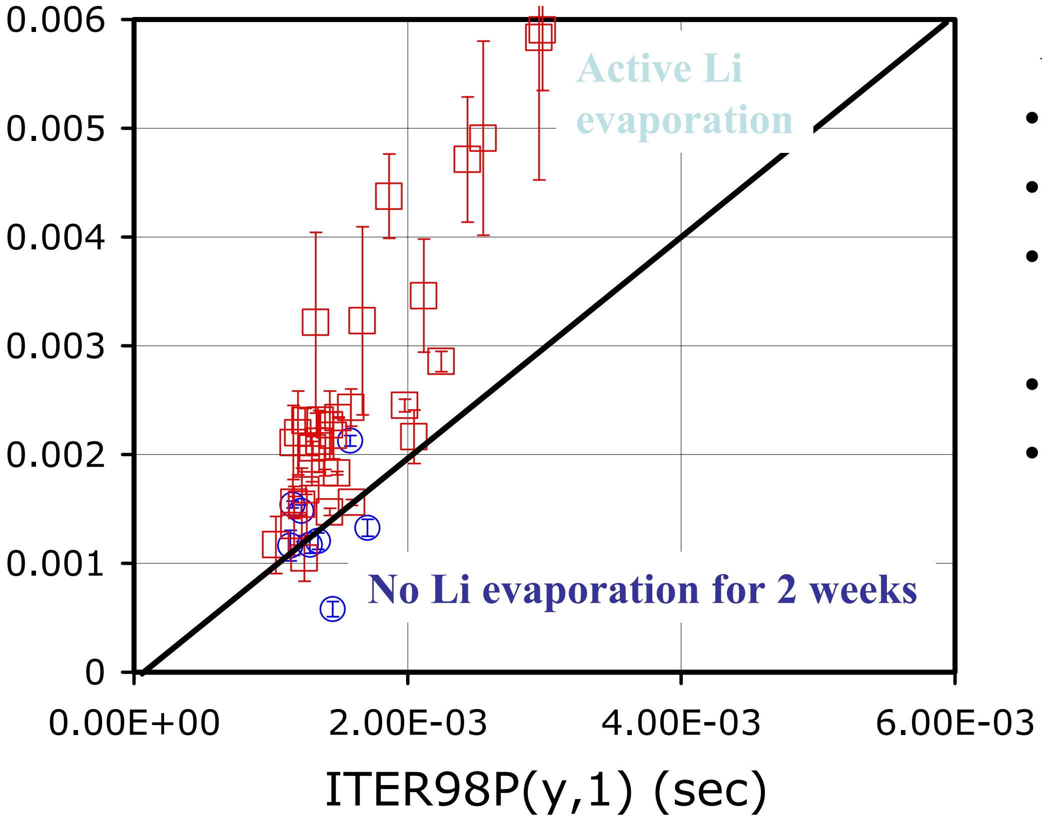
Confinement times exceed ELMy H-mode scalings

CDX-U LTX



All discharges:

- 61kA $< I_p <$ 78kA
- 2.1 kG
- Identical loop voltage waveforms
- $0.5 < n_e < 1 \times 10^{19}\ m^{-3}$
- Gas puffing terminated several msec before peak in plasma current

R. Majeski, Phys Rev. Lett. 97, 075002 (2006)

- Confinement in CDX improved by 6× or more with lithium wall coatings, partial liquid lithium limiter
- Exceeds scaling by 2-3×
- **Largest increase in ohmic tokamak confinement ever observed**

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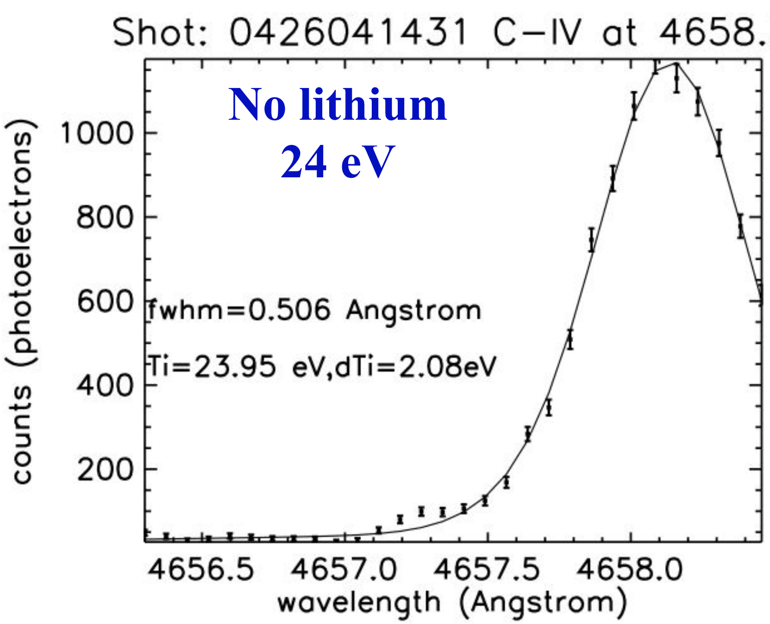
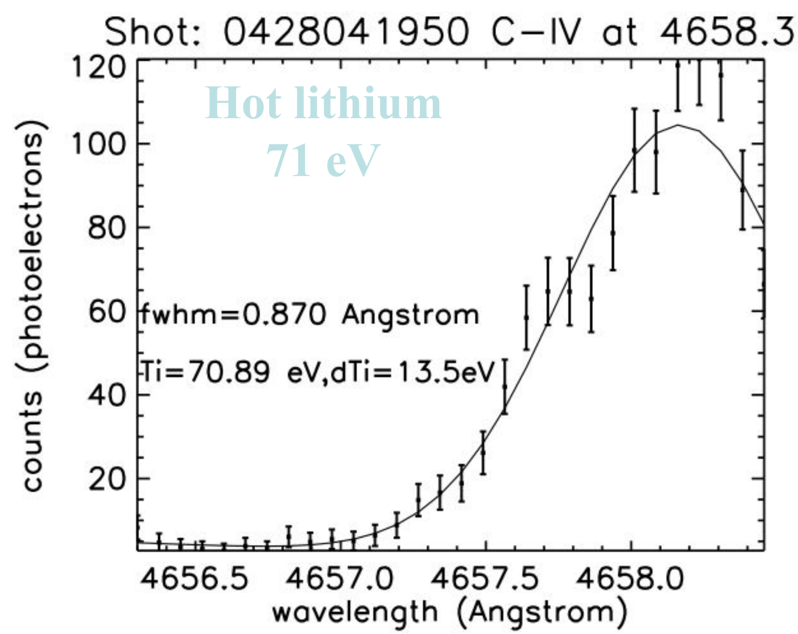
Impurity ion temperature increases with lithium

- Carbon impurity level (signal magnitude) drops by over an order of magnitude
- No profile information (no radial localization)

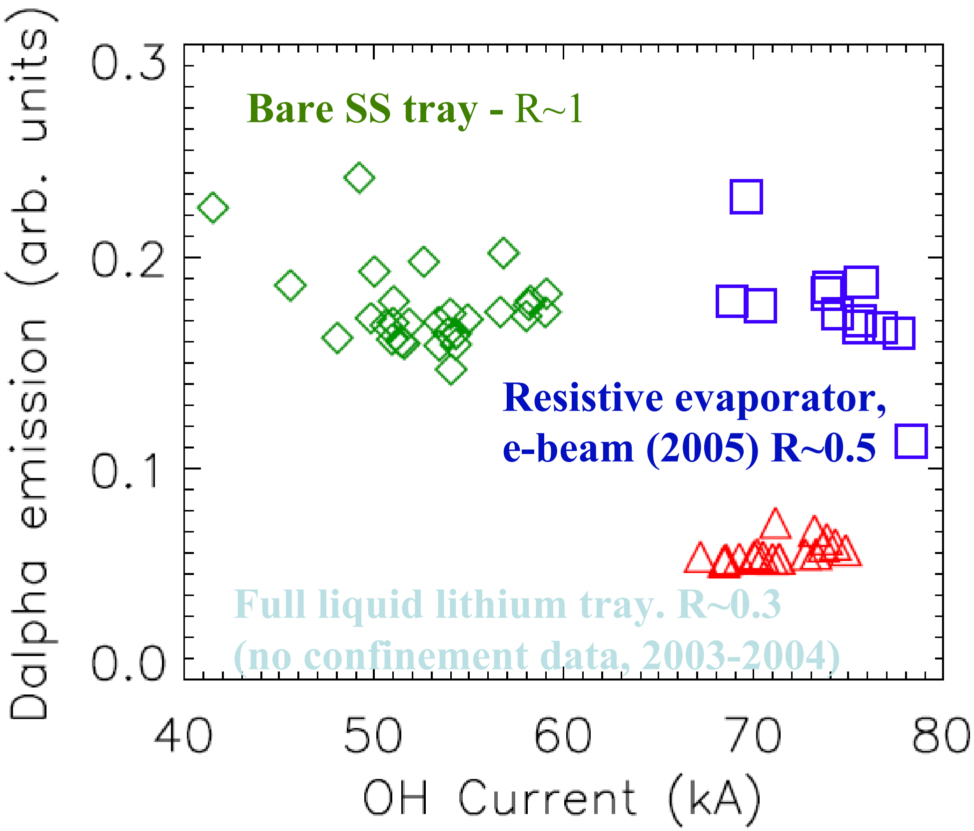




Lowest recycling obtained with full tray - Evaporative coatings less effective

CDX-U

- D_α emission at the centerstack
  - Lithium coated (solid)
  - Primary plasma contact



- ~3× reduction in D_α for full-tray liquid lithium operation (2000 cm^2)
- Bare tray: deuterium prefill only
- Lithium operation required up to **~20×** increase in gas fueling
- **Lithium reduces recycling coefficient R from ~1 to ~0.3**
  - Overestimate (background light)
- Lowest global R ever obtained for a magnetically confined plasma

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Lithium Tokamak Experiment (LTX)

CDX-U

LTX

- Lithium wall technology: molten thin films
  - Heated (300° C), conformal wall
    - 304 SS liner explosively bonded to 3/8” copper
  - Recoated with lithium (1000Å) between discharges
  - Initial operation will use CDX-style “pool” in lower shell
  - Replaceable
    - Second wall with plasma-sprayed porous molybdenum inner coating
  - Designed for argon glow discharge cleaning of lithium, at temperature
- Complete rebuild of CDX-U for larger, longer duration, higher current plasmas
  - R=40 cm, a=26 cm, κ=1.55, B_T=3 kG, $I_p < 400$ kA
- Poloidal field, control system upgraded
- Core fueling
  - Gas jets
  - NBI

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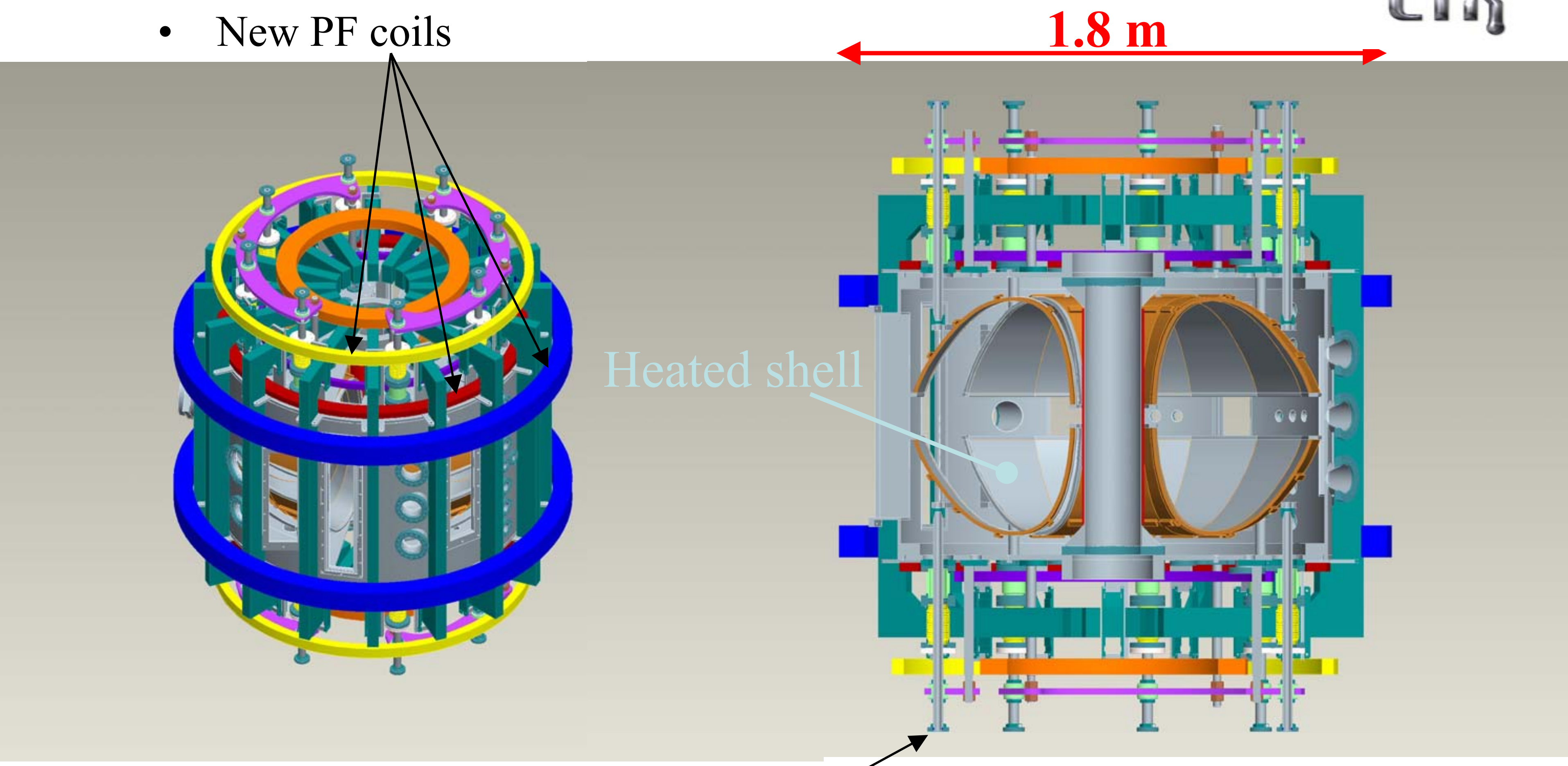
New
LTX configuration

- New PF coils

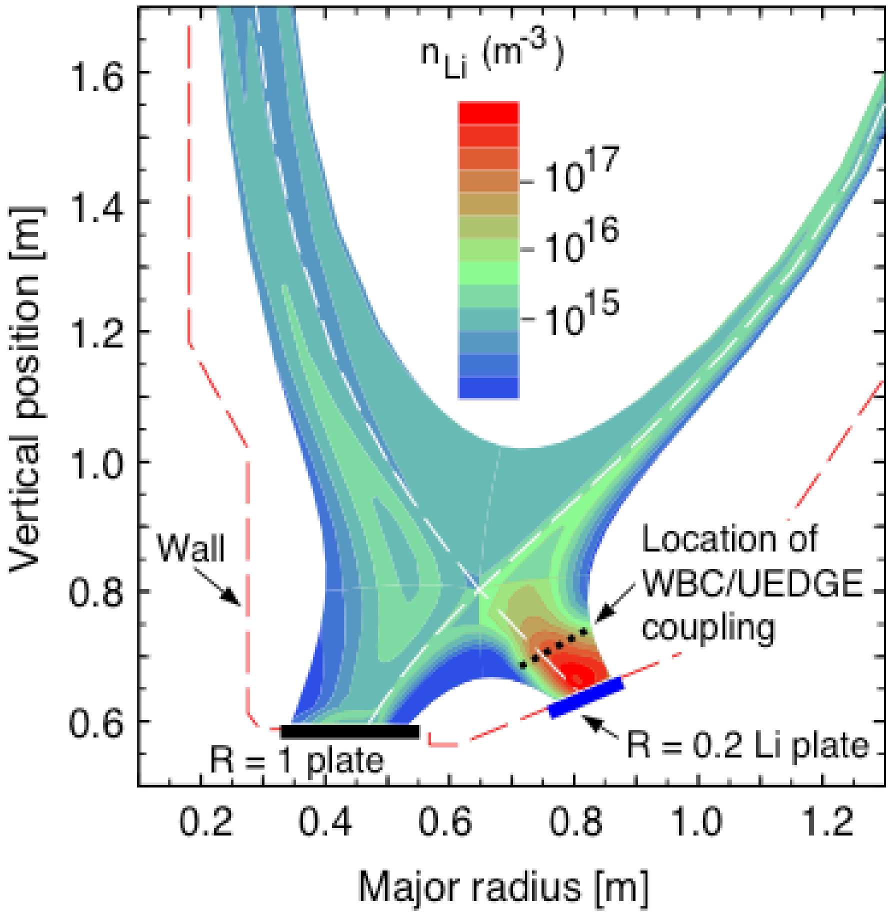


- Support structure for shell
  - Loads transferred to external supports

NSTX Experiments/Modeling

PSI Modeling of lithium coated NSTX divertor

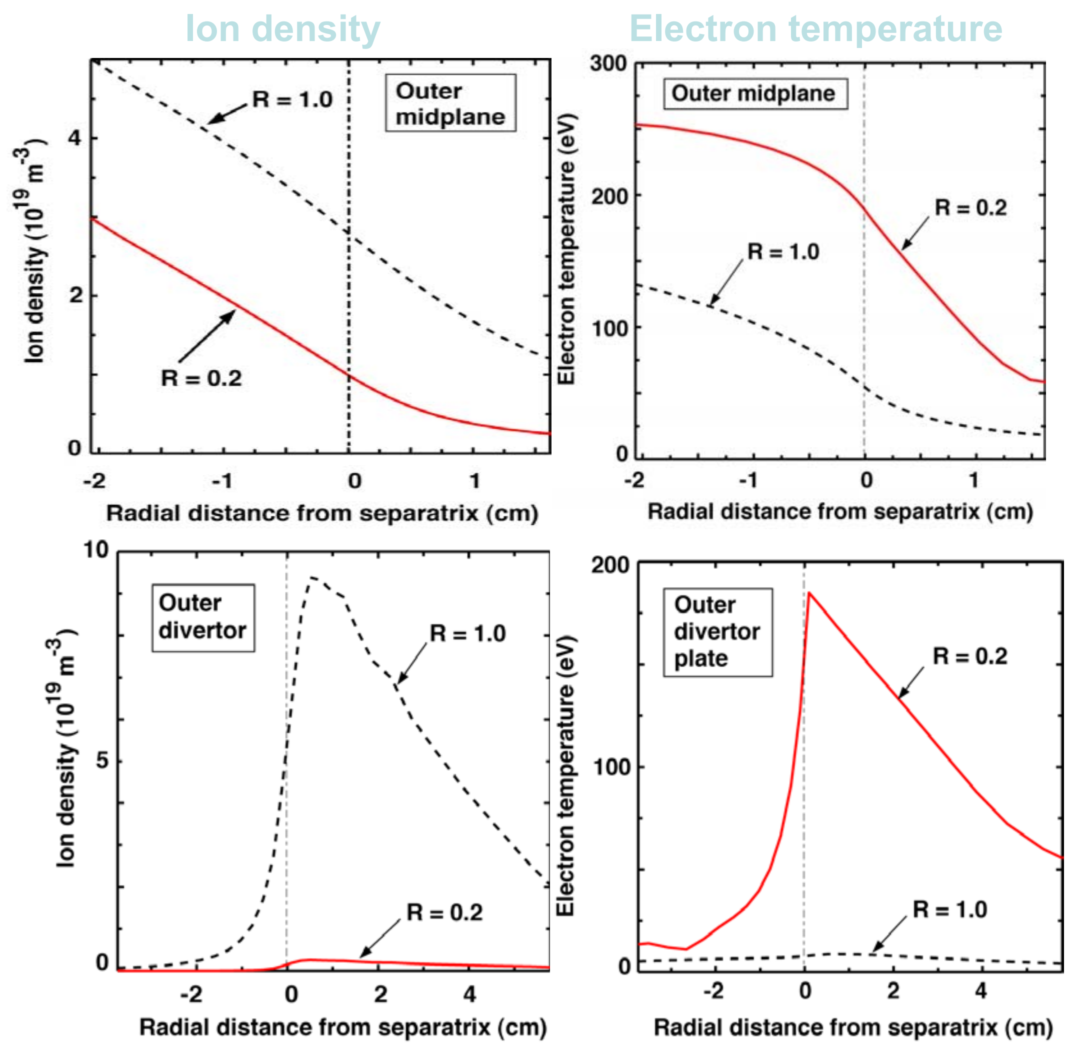
- Critical Plasma-Surface Interaction Issues:
  - D pumping by lithium
  - Low-recycling effect on operation
  - Power handling of Li
  - Erosion/redeposition of Li
- One coating of Li (~250-nm) can enable full 2-sec cycle shot
- Lithium is well entrained in divertor region from friction with H and downward E-field (see fig.)



J.N. Brooks, J.P. Allain, T. Rognlien, R. Maingi, 337-339 (2005) 1053

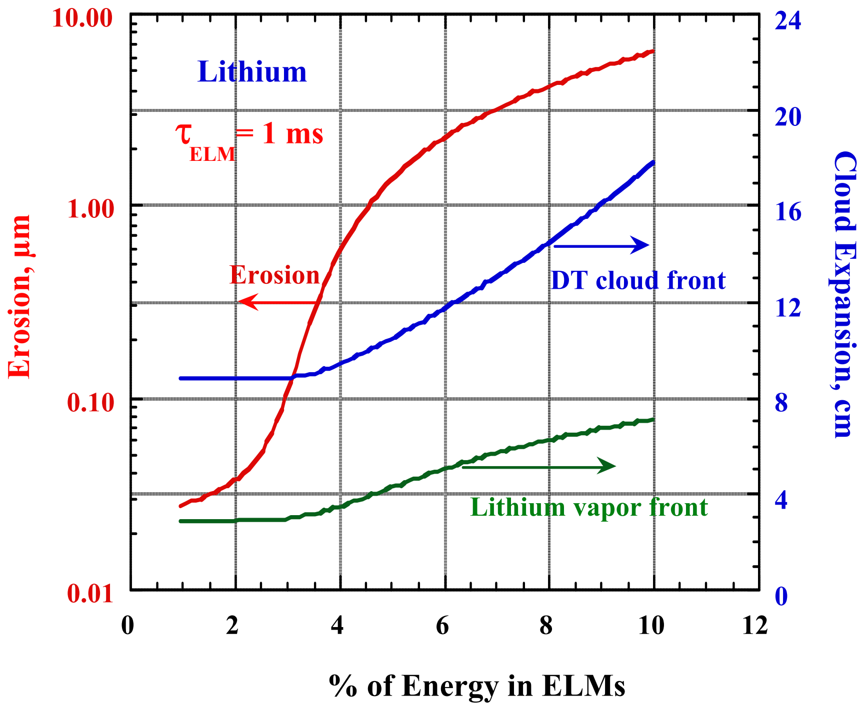
NSTX modeling: Low recycling increases midplane temperatures by factor of ~2

- D^+ recycling coeff., R=0.2 at lithium outer divertor used for analysis. (supported by PISCES et al. data).
- Low recycling decreases edge density for fixed source.
- Increased edge temperature may reduce core turbulence.



ELM Response Simulations—HEIGHTS (Hassanein et al.) Analysis

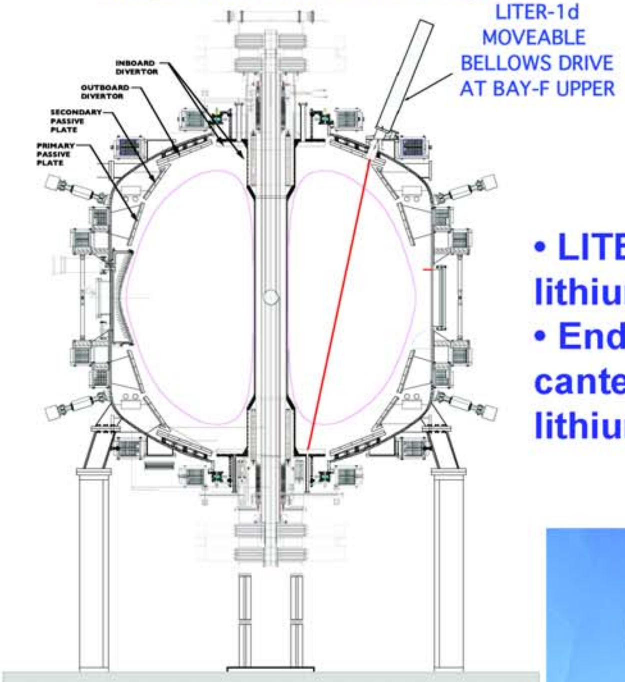
- Comprehensive Analysis.
- Vapor shielding is critical.
- Vaporization markedly increases with ELM energy.
- ELM's are a serious concern for all materials.
- Li advantage is that erosion, per se, is no problem.



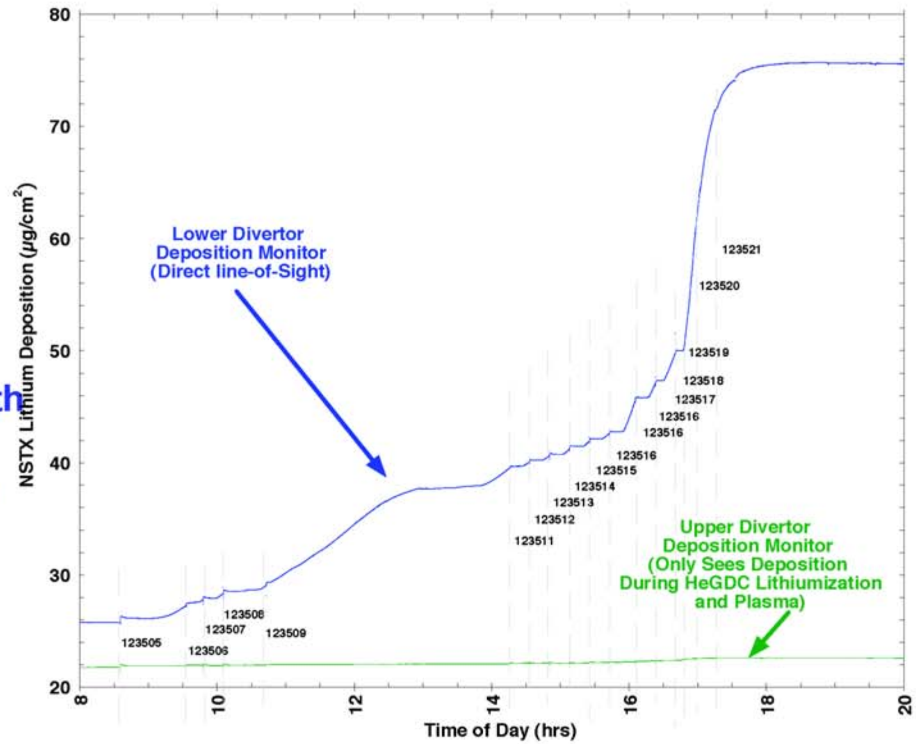
LITER LIThium EvaporatoR Evaporates Lithium on NSTX PFC's

NSTX

- **LITER-1d Aimed at Lower Inner Divertor**
- **Routine Use For NSTX Experiments Has Begun**



- **LITER-1d loaded with lithium on probe**
- **Endpiece ("snout") canted to direct lithium vapor**



- **Divertor Region Quartz Deposition Monitors Shows Increasing Lithium Thickness with Shot Number**
- **Reliable Lithium Coating of PFC's Demonstrated**

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Deposition of Li and D in NSTX after lithium injection experiments

NSTX

Results from Li Evaporation Coatings in NSTX

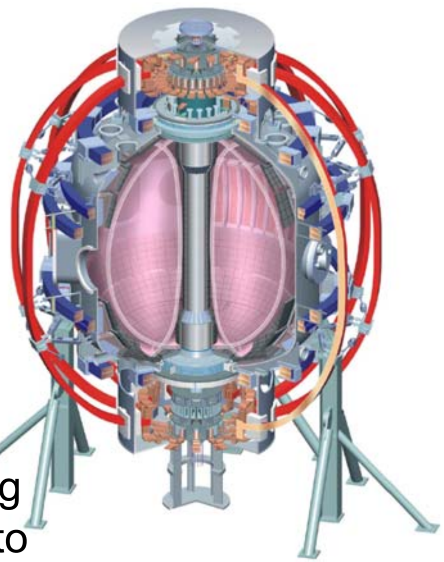
Maingi, Kugel, Kaita, Majeski, NSTX Team,

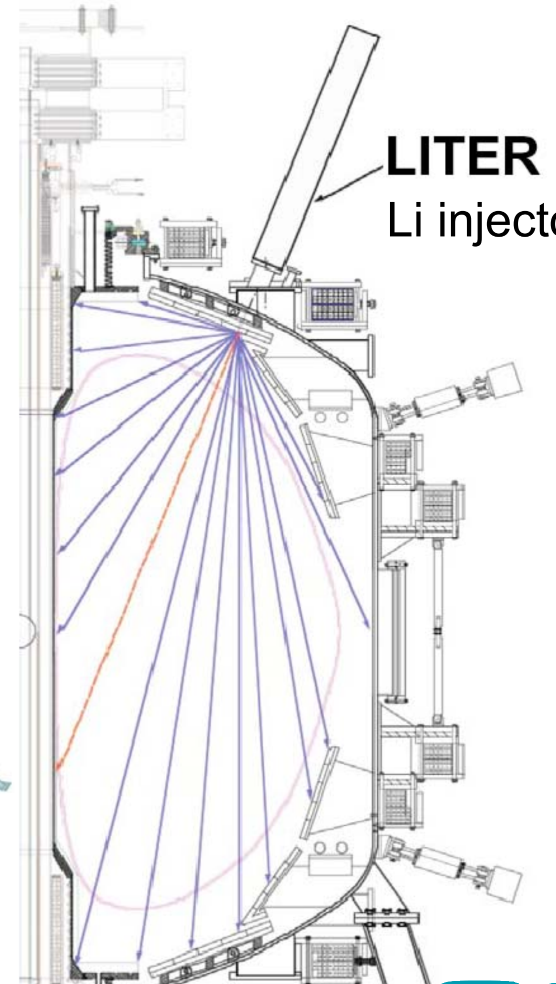
Short term changes in discharge following evaporation:

- Line-average n_e decreased by 15%
  - $Z_{eff}0$ decreased by 30%
  - T_e0 increased by 15%
  - T_i0 increased by 40%
  - $v_{tor}0$ increased by 50%
  - τ_E [relative to H98y2 scaling] increased by 15%

Longer term changes:

- Li-I recycling light increased with a 5 discharge e-folding
- Core oxygen light decreased to below levels directly following boronization





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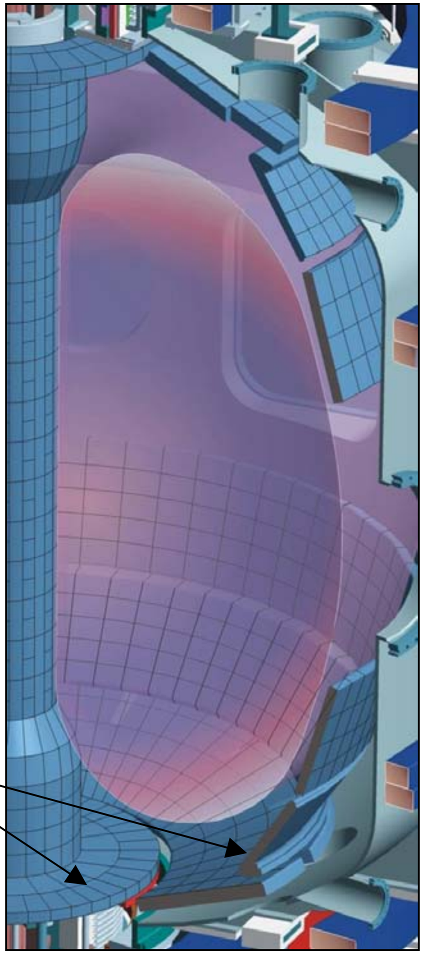
Sandia National Laboratories

NSTX LLD

Liquid Lithium Divertor

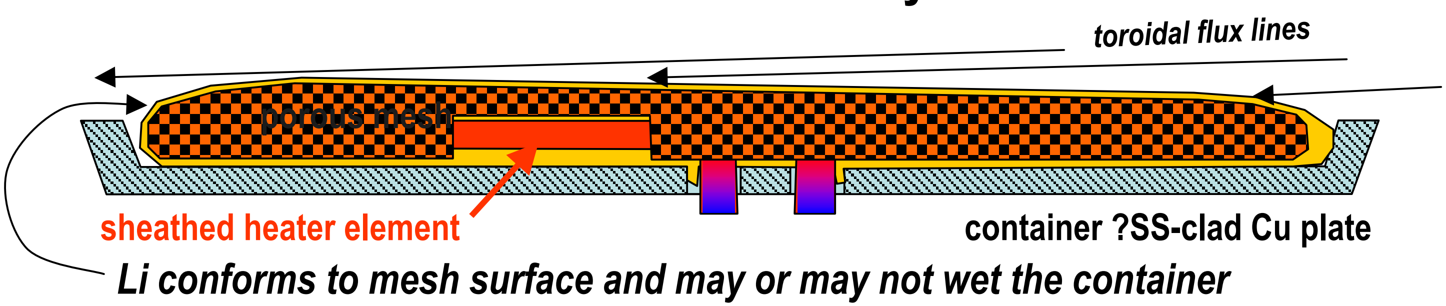
- **Joint effort by Sandia, UCSD and PPPL**
- **Funding by DOE/OFES**
  Award to Sandia in FY2007 NSTX-DOE Lab Collaboration
- **Principals:**
  - **Henry Kugel, Bob Kiata, Dick Majeski** (PPPL)
  - **Richard Nygren, Dennis Youchison, Tom Lutz, Jimmie McDonald** (Sandia), **Tre Shelton** (K-Tech)
- **Contractors:**
  - **UCSD (Russ Doerner) – Li injectors**
  - **Ultramet, Inc. – Mesh fabrication**
- **Basic scope: Toroidal LLD in bottom of NSTX**
  - **Location (inner/outer divertor begin decided)**
  - **PPPL - NSTX design and machine interfaces**
  - **Sandia - design, R&D on Li wetting, build LLD**
  - **UCSD – design, build, test Li injectors**



Basic Design Concept

Cartoon below shows basic features

- **Mesh holds Li surface above container to reduce heat at the sides.**
- **"Tiling" of LLD sections reduces heating at the ends.**
- **Embedded heaters in "deep" mesh improve thermal control because mesh and Li are heated directly. Container can be cooler.**



The surface temperature of Li will increase during a (5s) shot in NSTX. Initial design analyses on heat transfer is proceeding. For example, a denser mesh of Mo, which has higher thermal conductivity than Li, would improve thermal diffusion, but an "open" mesh might allow thermally driven Li circulation to reduce the temperature at the surface.

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Sandia National Laboratories

Summary

- The U.S. ALPS program continues to develop the science of liquid metal divertors through a comprehensive, coordinated, experimental and modeling program.
- Lab experiments and modeling have provided critical data on liquid metal surface preparation, cleanliness, temperature dependent sputtering & D and He trapping, etc.
- CDX-U tokamak shows highly improved operation with a large area liquid lithium limiter. Reduced plasma oxygen, low D recycle, enhanced confinement time & loop voltage reduction, are observed.
- CDX-U is currently undergoing transformation into LTX, a new fully Liq. Li wall experiment to be operational in late 2007.
- NSTX experiments with Li coatings are also encouraging & Liq. Lithium divertor operation is marked for 2008.