NSTX Lithium Technologies and Their Impact on Boundary Control, Core Plasma Performance, and Operations

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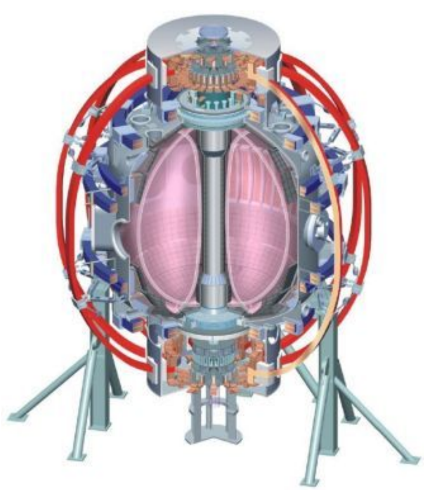
and the NSTX Research Team

23rd IAEA Fusion Energy Conference
Daejeon, Republic of Korea
11-16 October, 2010



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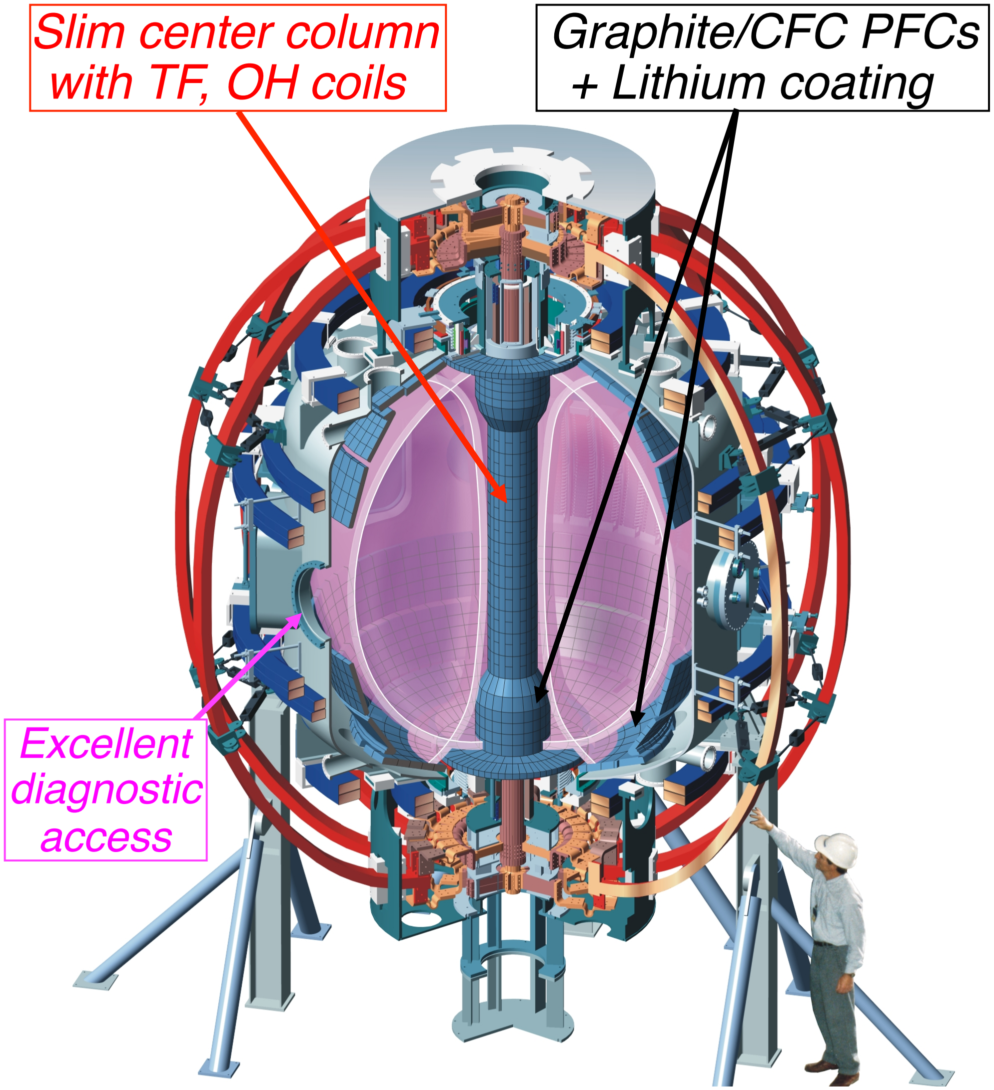
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius	0.85 m
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	0.7 – 1.5MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20} m^{-3}$
Toroidal beta β_T	10 – 40 %

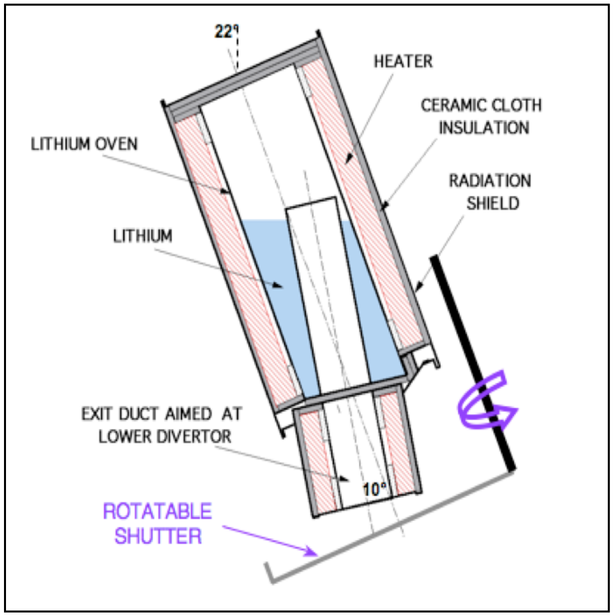
Liquid Lithium Shows Promise for Providing a Self-healing Plasma Facing Surface for DT Reactors

- **NSTX lithium program on *diverted H-mode plasmas* grew from experience with TFTR limiter plasmas, and is aimed towards using liquid lithium to control density, edge recycling, impurity influxes, and eventually power handling.**
  - **Edge fueling is reduced as plasma D efflux incident on Li forms LiD**
    - ***Solid lithium provides short pulse capability but has limited LiD capacity***
    - ***Liquid lithium has much higher LiD capacity, and has potential for power handling and self healing***

- **Over the longer term, NSTX will investigate if liquid lithium can help integrate 4 important potential benefits for fusion**
  - **Divertor pumping over large surface area compatible with high flux expansion solutions for power exhaust and low collisionality**
  - **Improved confinement**
  - **ELM reduction and elimination**
  - **High-heat flux handling (e.g., via capillary-porous flow,…)**

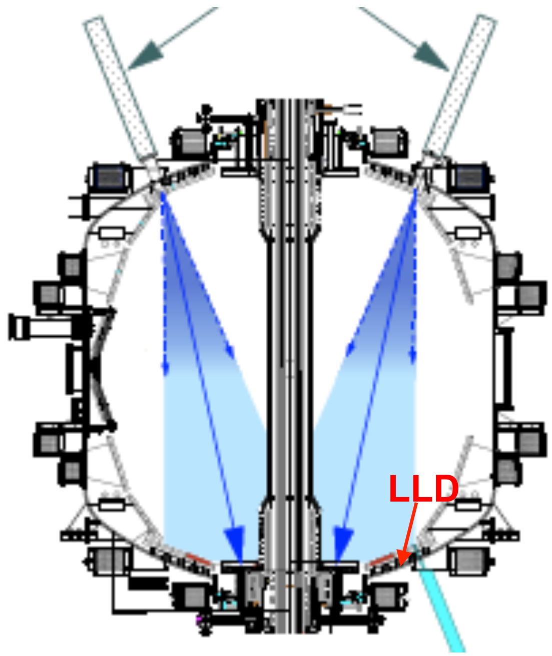
Dual Lithium Evaporators (LITERs) Are Now Routinely Used To Deposit Lithium Coatings On NSTX Lower Divertor Between Discharges

LITER Oven



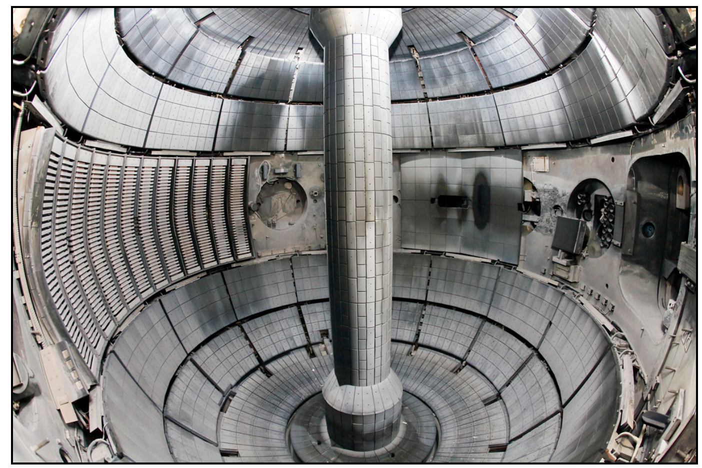
- **Rotatable shutter stops lithium when diagnostic window shutters are open.**

LITERs



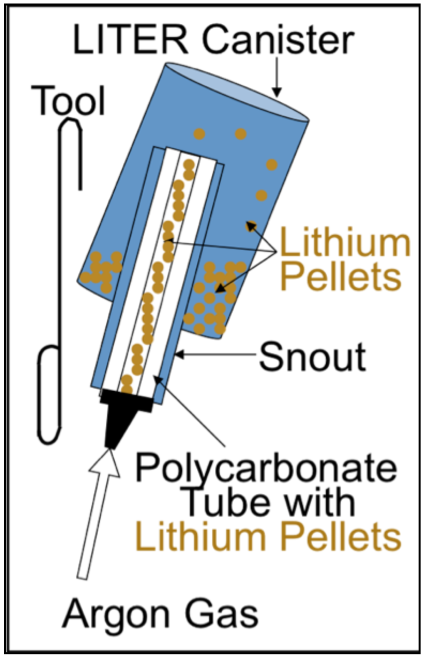
- **LITERs aimed toward the graphite divertor. Shown are 1/e widths of the emitted distribution.**

- **Lithium transported over broad area by wings of LITER distribution and plasma migration.**

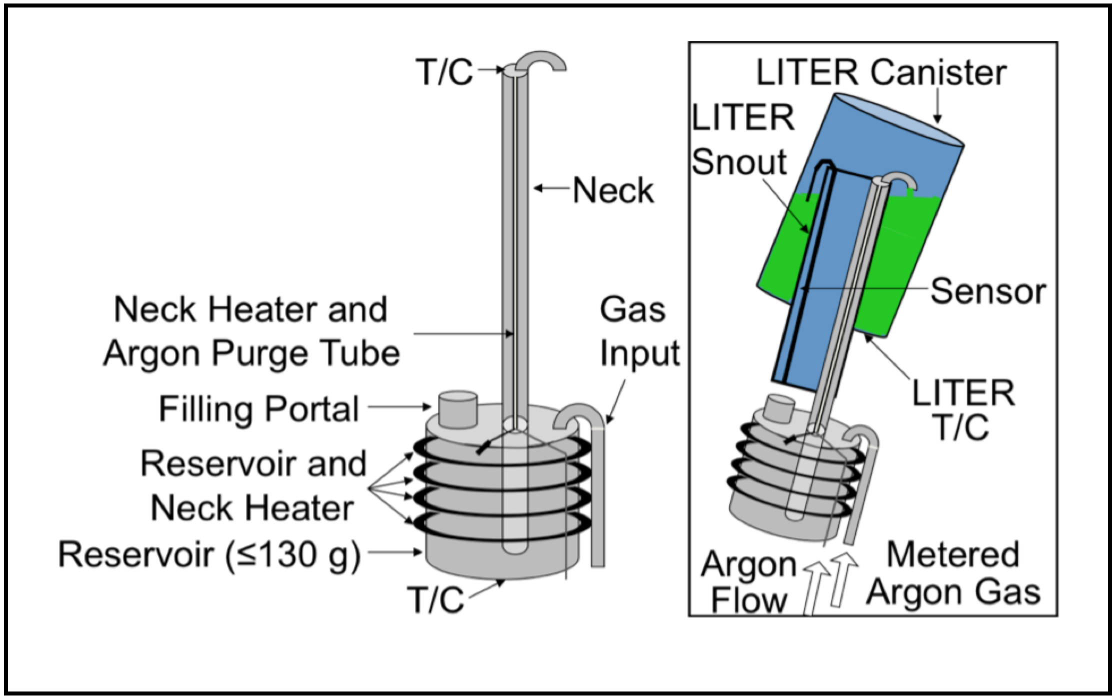


- **After exposure to air (2009), 600g Li deposition converts to white lithium carbonate (Li_2CO_3).**

LITERs Filled Using Liquid Fill System for Improved Loading Efficiency and Reduced Lithium Impurities



- **Initially, LITERs filled using solid Li pellets (50% packing fraction for pellets, 40g max).**

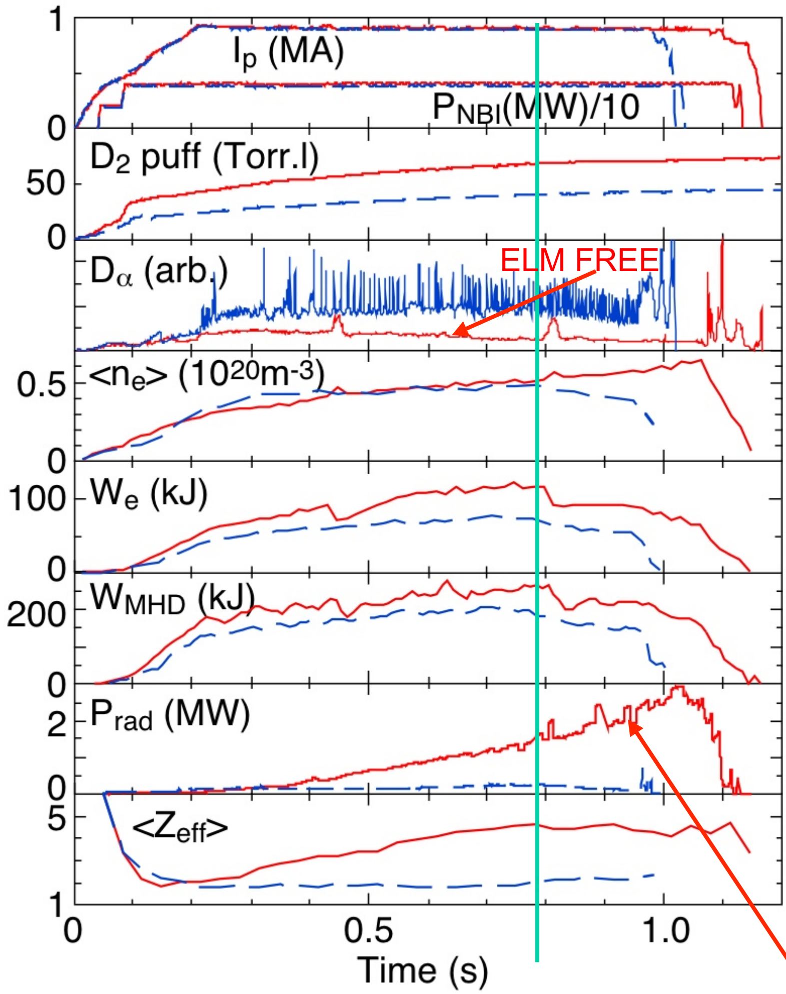


- **Recently, LITERs filled using liquid lithium injected with argon (100% packing fraction, for liquid, 80g max).**

- **After lithium filling, *prior to installation on NSTX*, LITERs are outgassed in vacuum chamber by raising temperature slowly to 600°C to remove any argon and dissolved gases.**

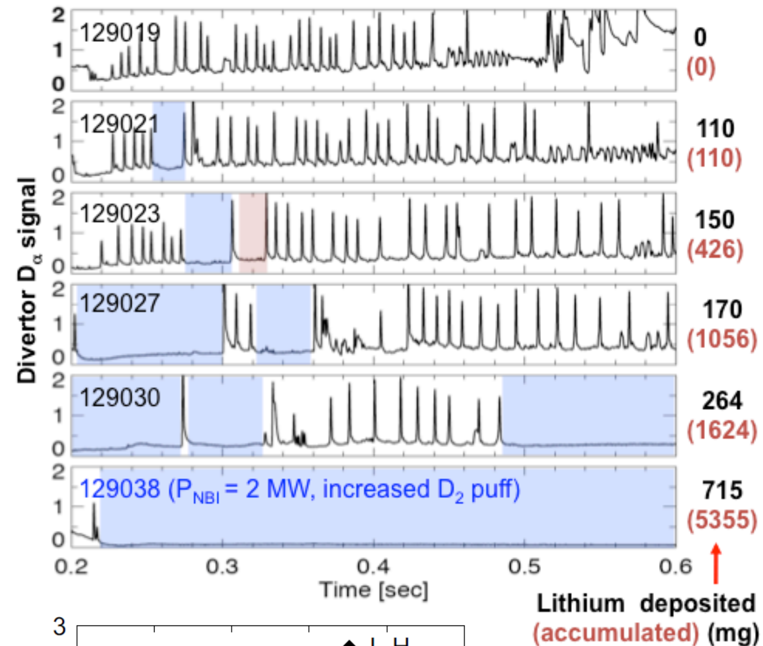
Lithium Coating Reduces Deuterium Recycling, Reduces $P_{L\text{-}H}$, Suppresses ELMs, Improves Confinement

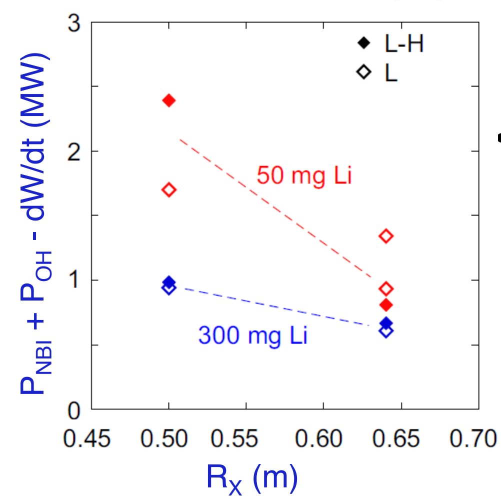
No lithium (129239); **260mg lithium** (129245)



Without ELMs, impurity accumulation increases radiated power and Z_{eff}

- ELMS reduced as lithium increases

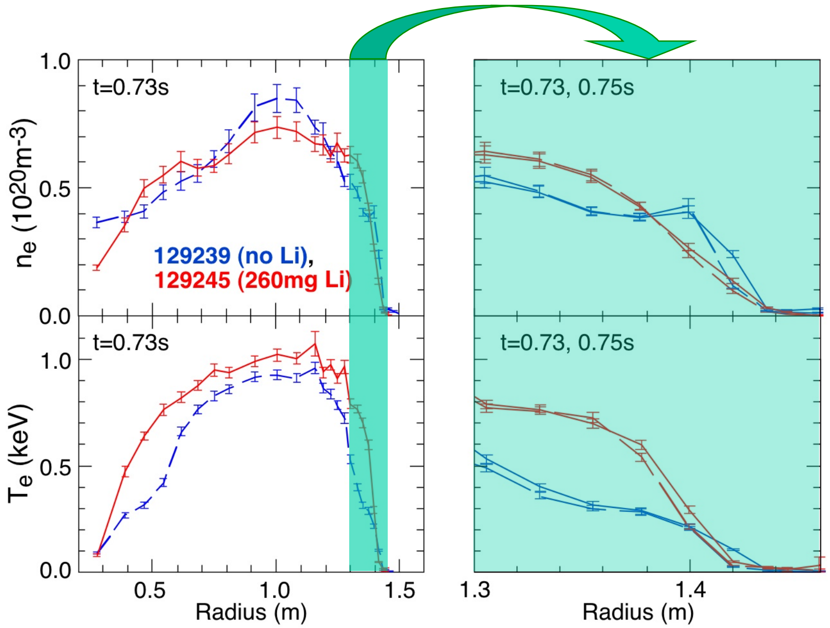




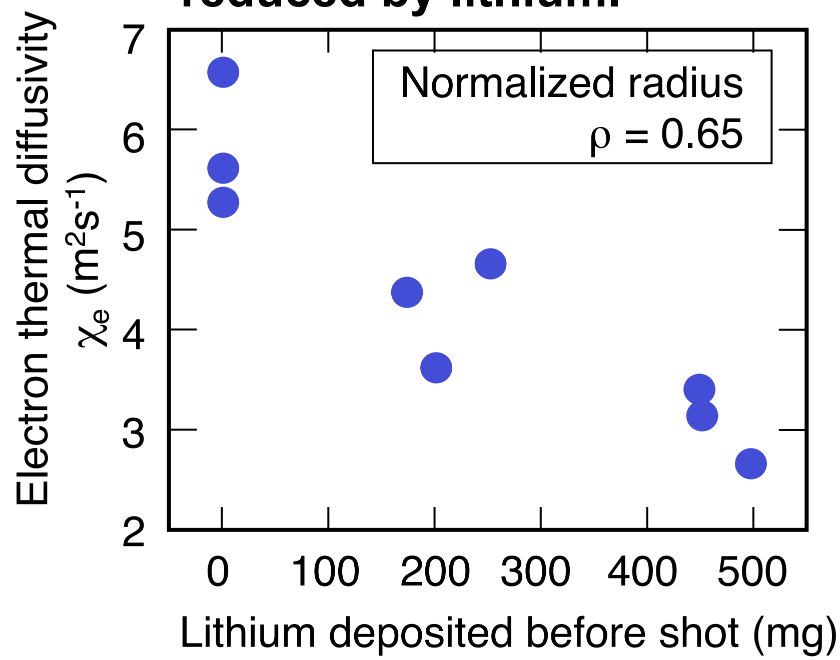
- **Lithium lowers H-mode threshold at both radii.**

Lithium Evaporated on Divertor Broadens Electron Temperature Profiles and Decreases Electron Thermal Diffusivity

- **Edge electron density decreases and electron temperature increases.**

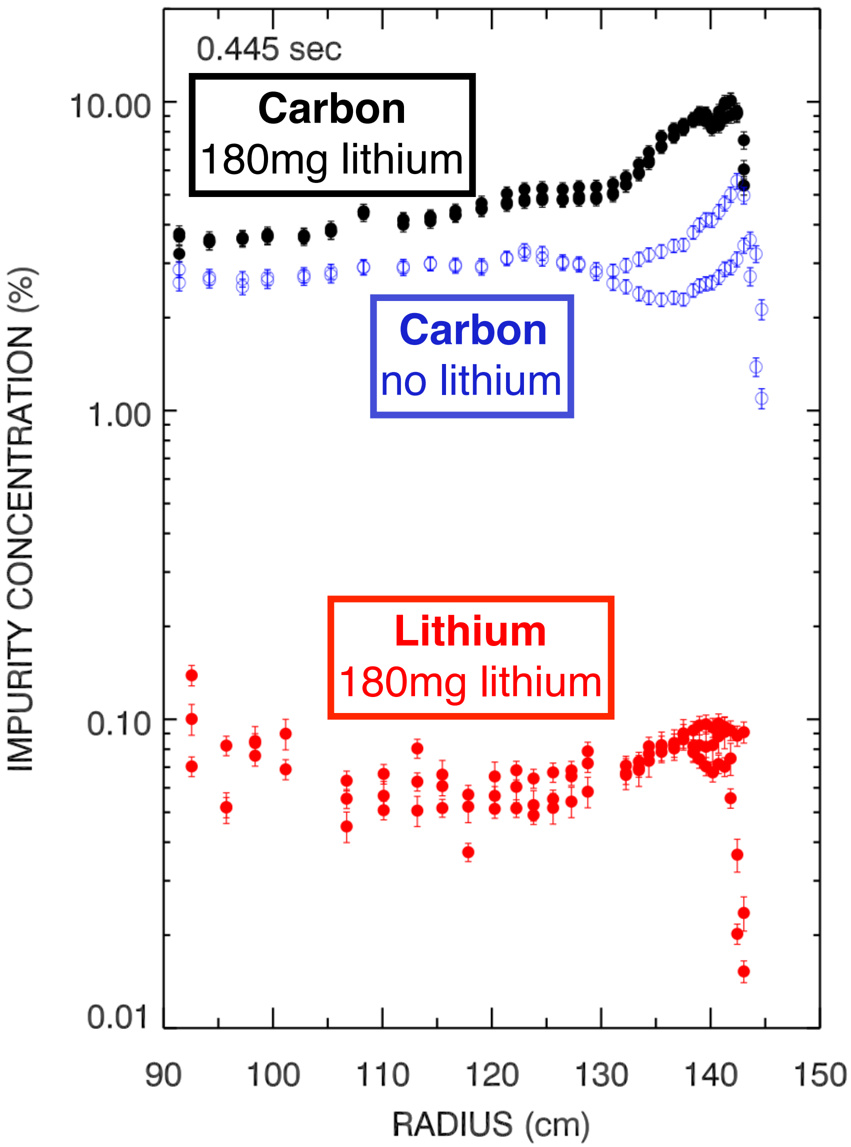


- **TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium.**



- **Fast-ion contribution to total energy ($\propto T_e^{3/2}/n_e$) also increases**

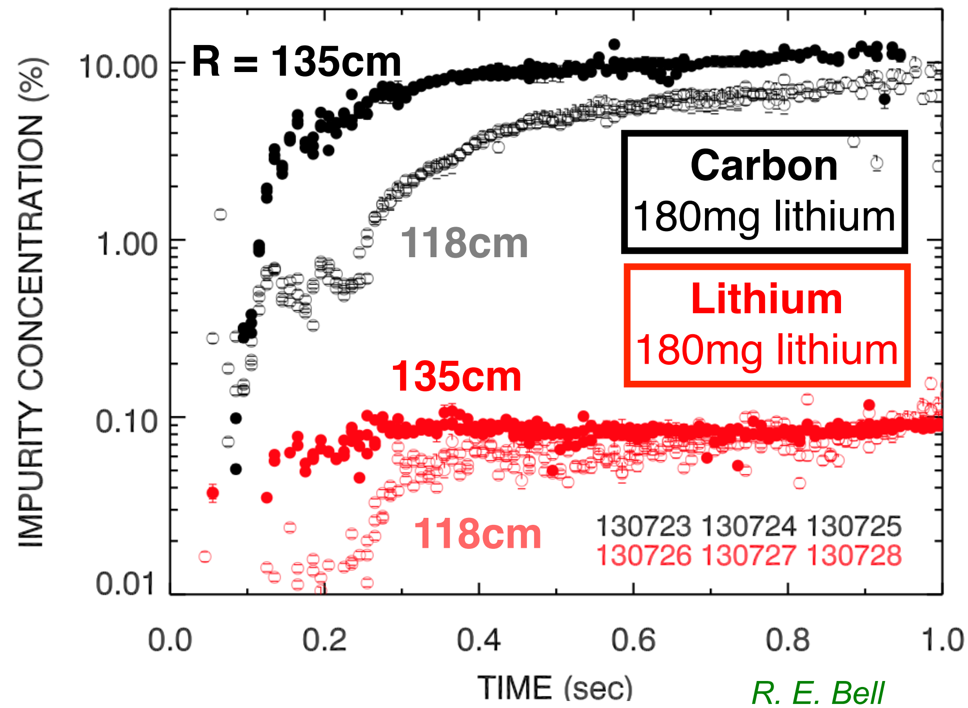
Lithium Concentration in Plasmas Remains Low but Carbon Concentration Rises with Lithium Coating



Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy

n_C/n_{Li} = 30 – 100

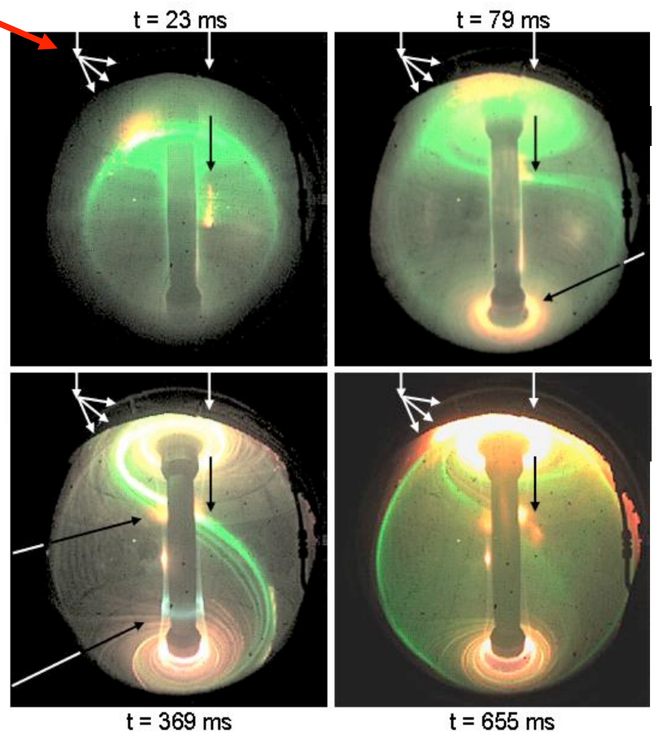
Hollow profiles early for both C and Li fill in as time progresses



R. E. Bell

Lithium Powder Injection in Progress to Test Increased Rate of Lithium Delivery to Plasma Wetted Areas

44 mm Li spheres enter SOL



As NBI starts, lithium is swept toroidally in SOL flow

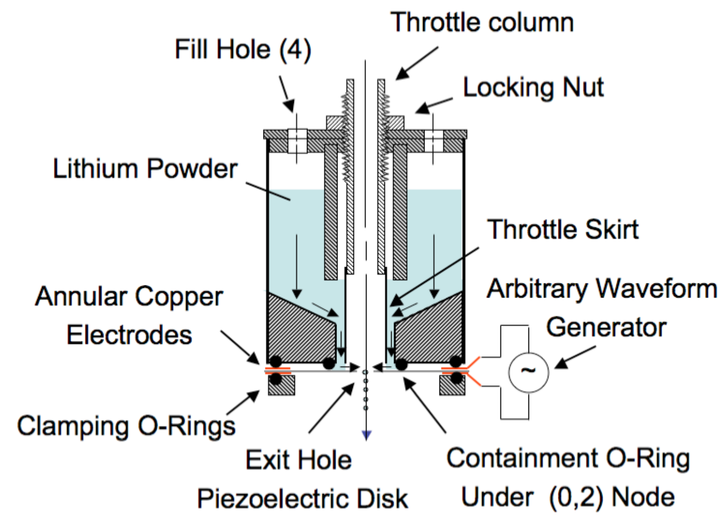
Lower single null strike points evaporate Li before t=0.

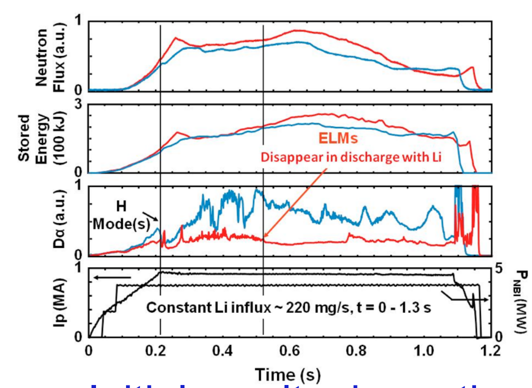
ELM filaments strike lithium in SOL flow.

Diffuse plasma edge and MARFE (blue).

ELMS and MARFES vanish by t~500ms. Sharp plasma edge and Li radiative mantle

Schematic of Lithium Powder Piezoelectric Acoustic Injector

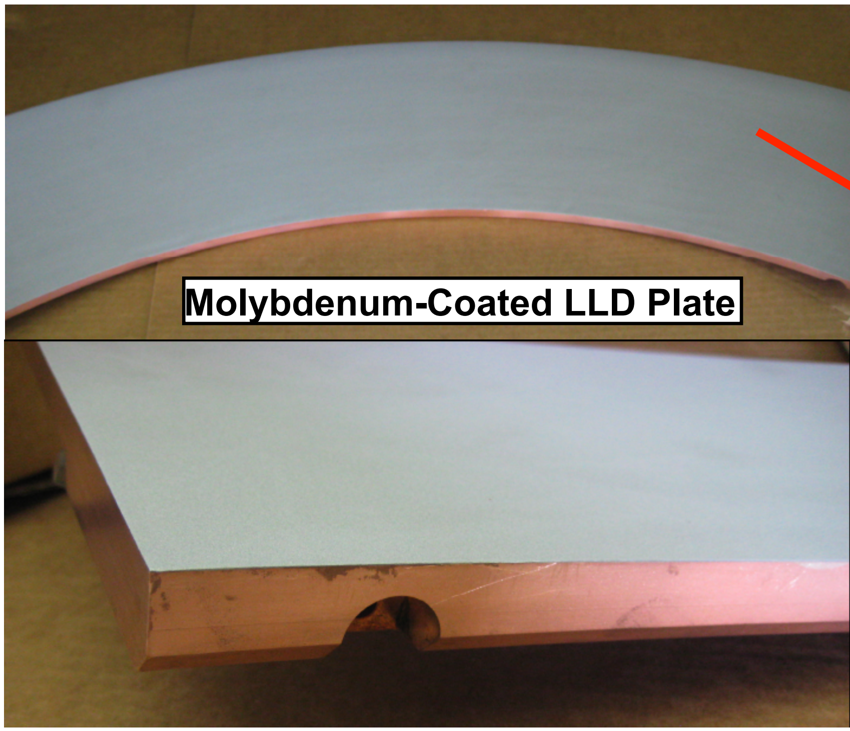




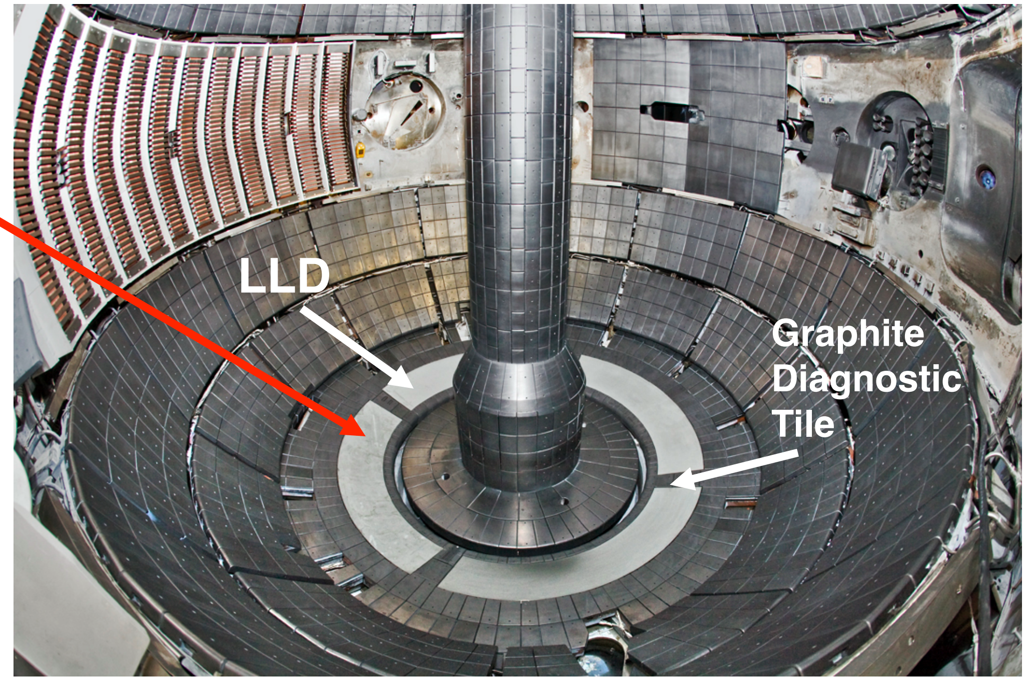
- **Lithium particles delivered before and during discharges.**
- **Particle delivery rates up to 80 mg/s (LITER ~10-20 mg/min per unit)**

- Initial results dramatic but not yet reproducible

Liquid Lithium Divertor (LLD) Installed in NSTX with Porous Molybdenum Face to Hold Lithium



- 0.165 mm Mo plasma sprayed with 45% porosity on a 0.25 mm SS barrier brazed to 22.2 mm Cu.



- 4 heated plates (80°each) separated by graphite diagnostic tiles.
- Each toroidal section electrically grounded to vessel at one mid-segment location to control eddy currents.

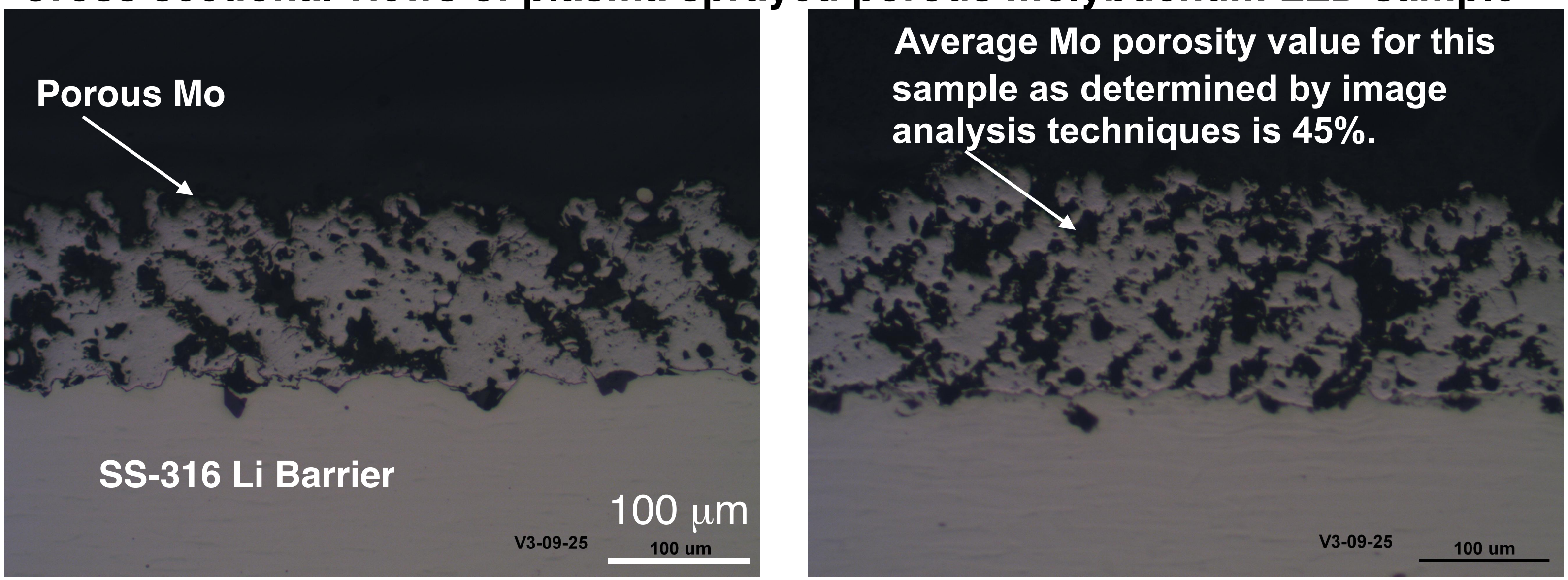
LLD Lithium-bearing Surface is Thin Porous Molybdenum

Key properties of an acceptable LLD lithium surface

- sufficient surface tension to hold Li in presence of JxB forces
- ability of liquid Li to flow across metal surface (wetting capability)
- minimize temperature rate of rise of Li --> rapid heat transfer from Li to base

Thin plasma sprayed porous Mo, on a thin SS-316 Li barrier, on thick Cu baseplate thermal sink, is highest confidence initial approach

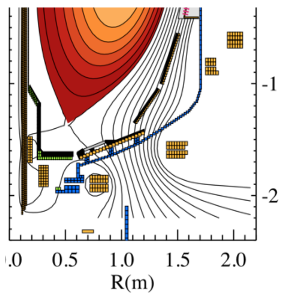
Cross sectional views of plasma sprayed porous molybdenum LLD sample



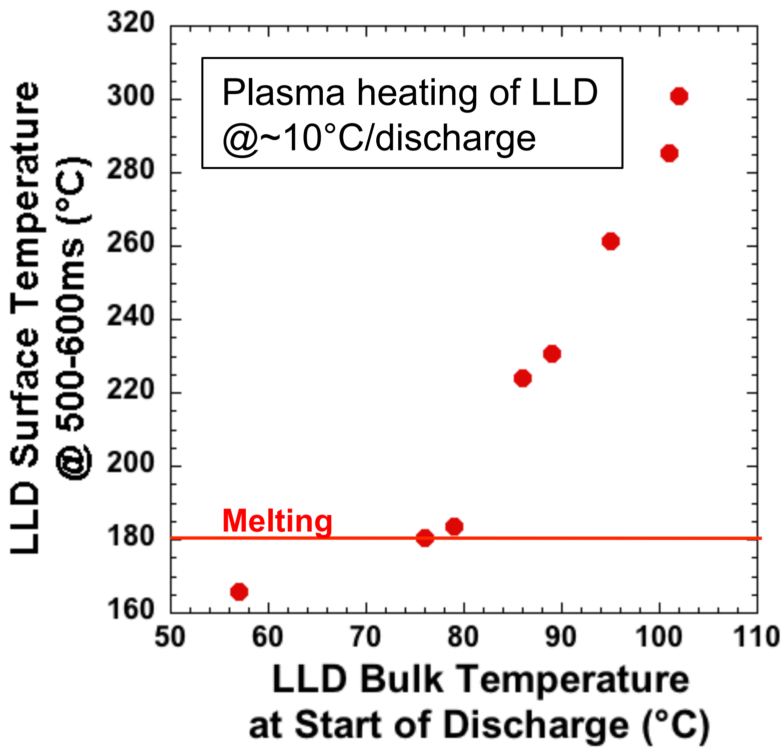
Longitudinal   Transverse

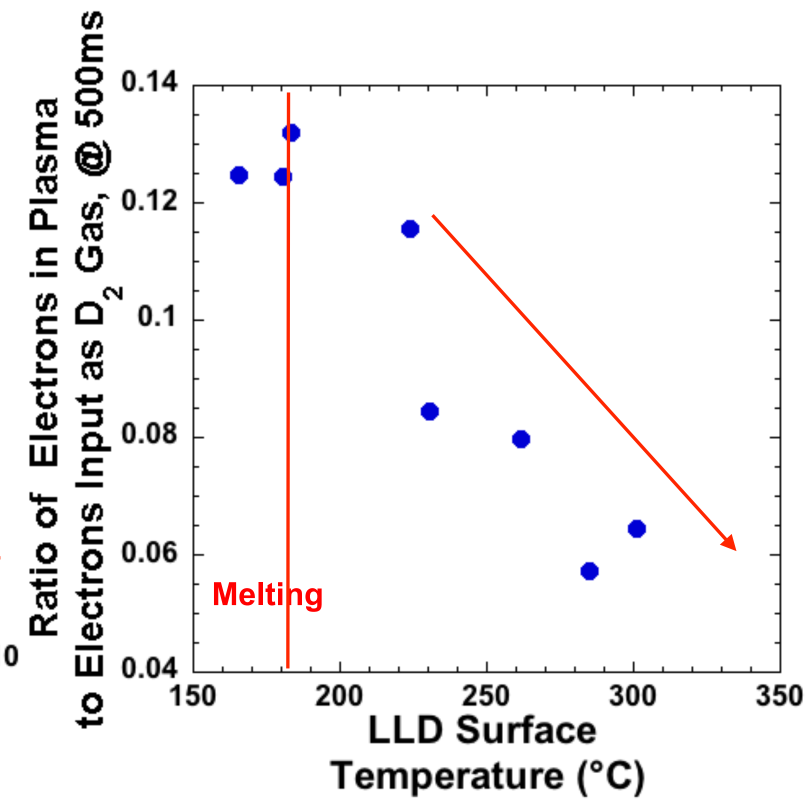
- The average thickness of the deposit on this sample was 0.152 mm

An Observed Plasma Density Decrease Despite Deuterium Fueling Increase as Lithium Surface of LLD Liquefied



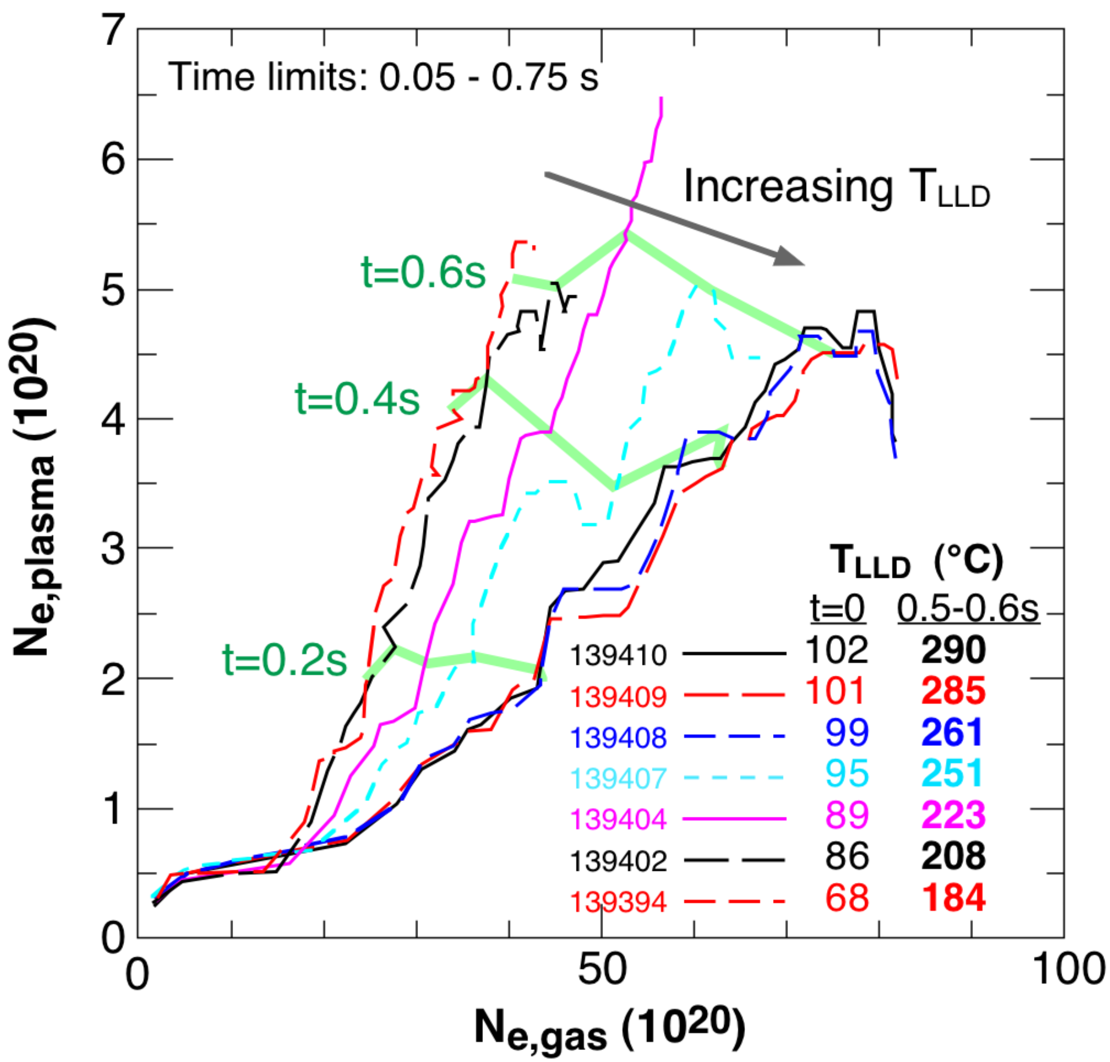
I_p = 0.8MA,
P_{NB} = 4.0MW
B_T = 0.48T
R_{OSP} = 0.73m
LLD ~%5 full
(~0.5μm)





- In other LLD tests, the amount of required fueling was similar to that for solid lithium coatings. Work is in progress to investigate these differences, e.g.,
  - liquid lithium can pump impurities and effect density
  - * liquid lithium surface impurities (C,O,…) from sputtering and gettering can reduce the formation of LiD and decrease pumping.

The Observed Plasma Density Decreased as the Deuterium Fueling Increased and the Lithium Surface of LLD Liquefied Due to Plasma FLux



LLD Porous Molybdenum Samples Analyzed 5 Laboratory Irradiation Scenarios to Test Various Possible NSTX Conditions

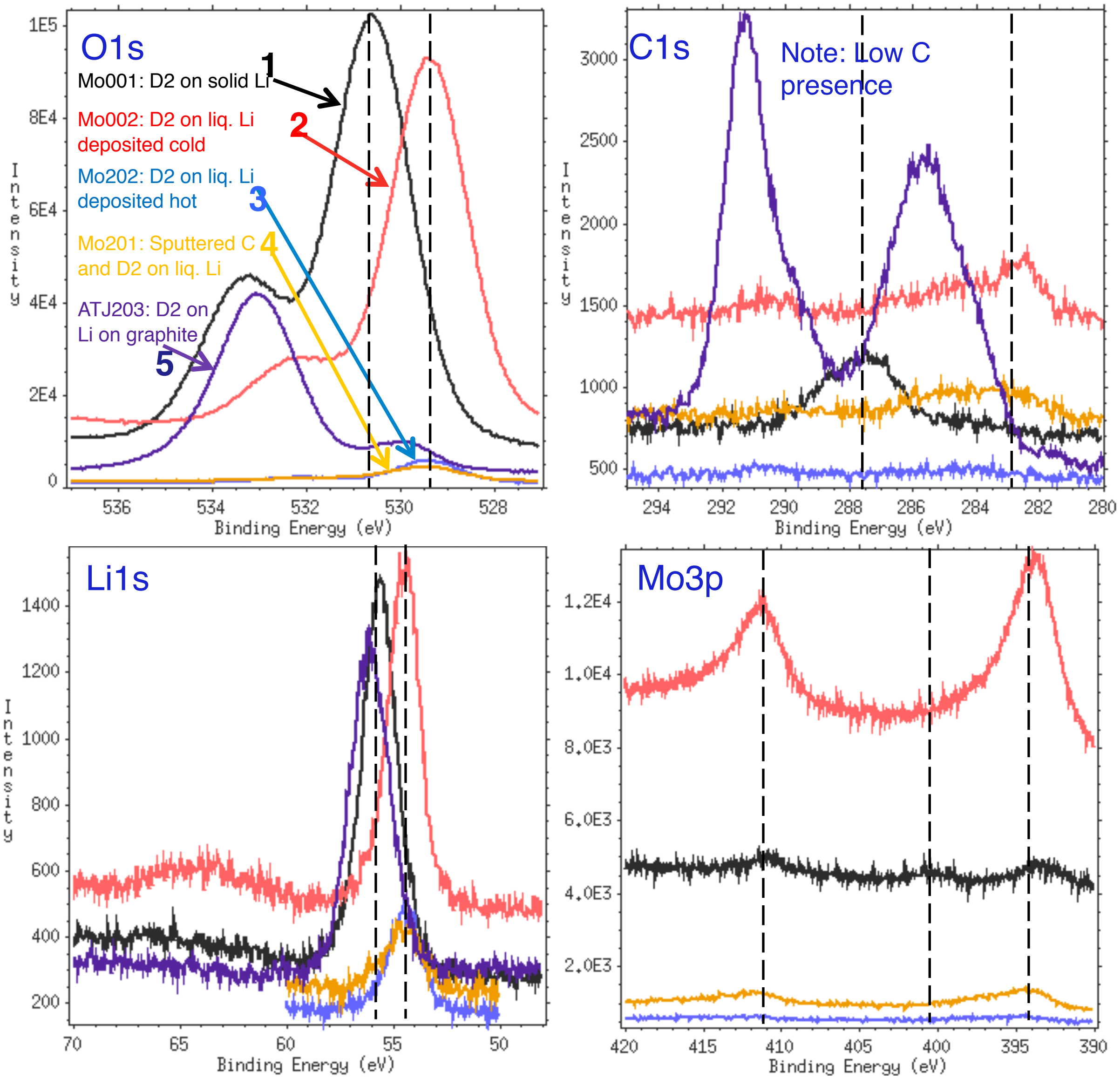
1) Mo001: 30 min D_2 irradiation on 2μm Li deposited on cold Mo.

2) Mo002: 30 min D_2 irradiation on 2μm Li at 255° C. Li deposited on cold Mo.

3) Mo202: 30 min D_2 irradiation on 3μm Li at 200° C. Li deposited on Mo at 250° C.

4) Mo203C: Carbon sputtered (via Ar) onto Li-coated Mo. 30 min D_2 irradiation at 200° C.

5) ATJ203: 30 min D_2 irradiation on ATJ graphite with 2μm Li dose.



LLD Porous Molybdenum Samples Analyzed to test Various Possible NSTX Conditions – % Concentrations

- Metal concentrations (neglecting impurities)

	% Li	% Mo
Mo001	**99.033**	**0.967**
Mo002	**98.766**	**1.234**
Mo101	**98.791**	**1.209**

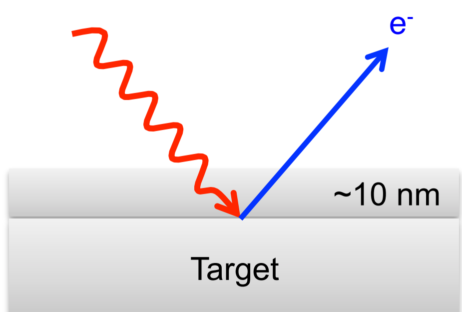
Mo001: ←Li-2μm, T_{room}→
Mo002: ←Li-2μm, T_{room}→
Mo101: ←Li-2μm, T_{melt}→

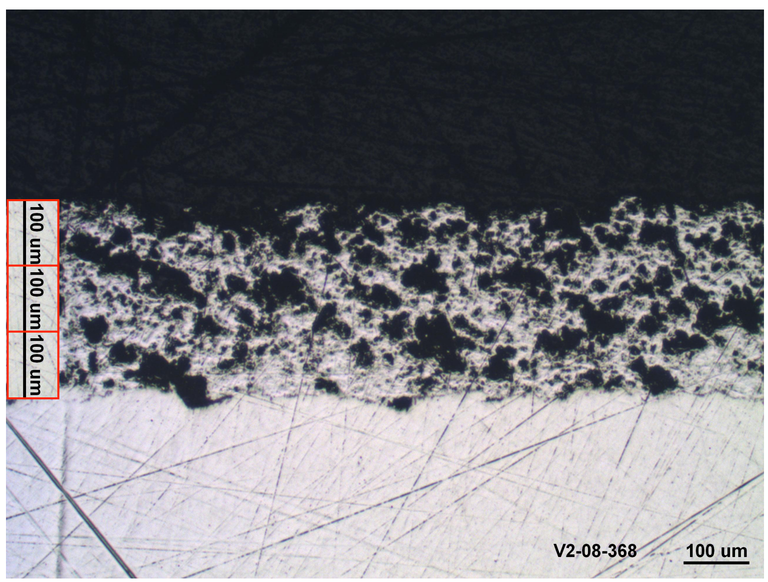
- Metal and impurity concentrations

	% Li	% Mo	%C	%O
Mo001	**85.023**	**0.830**	**2.866**	**11.281**
Mo002	**86.294**	**1.078**	**5.089**	**7.539**
Mo101	**71.669**	**0.877**	**4.593**	**22.860**

*Nominal Li thicknesses

XPS probing depth < 10 nm



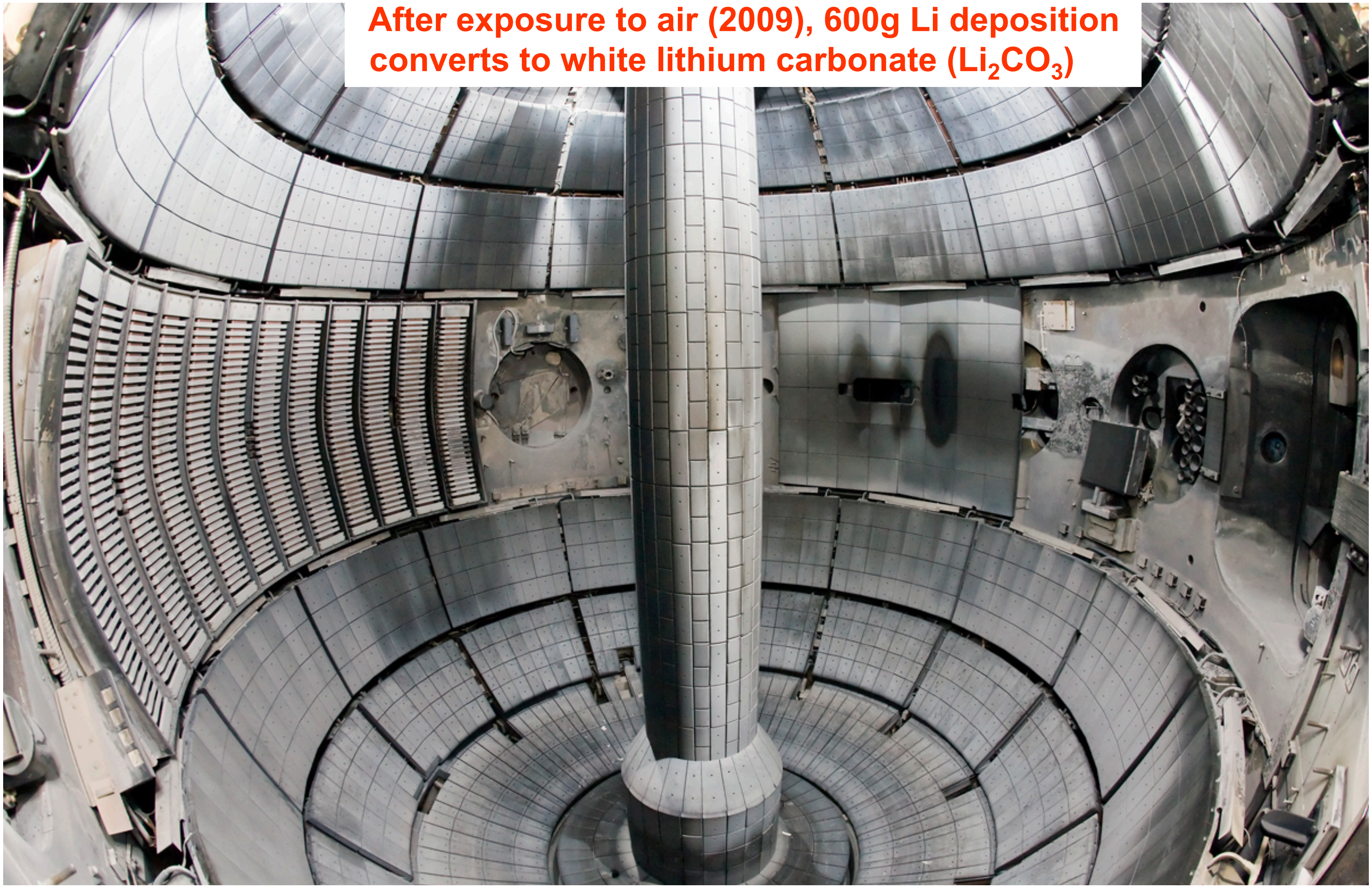


Surface lithium is plentiful and dominant after heating.

Implication: lithium wets rather than pools.

Lithium Transported Over Broad Area By Wings of LITER Distribution and Plasma Migration

After exposure to air (2009), 600g Li deposition converts to white lithium carbonate (Li_2CO_3)



Li_2CO_3 coatings must be removed prior to evacuation to reduce plasma oxygen levels

Vessel Clean Up After Lithium Deposition

- **Under NSTX vacuum conditions, Li reacts with the vacuum residual gases (predominantly H_2O, CO, CO_2) to form LiOH, Li_2O, Li_2CO_3**
- **NSTX is vented with atmosphere and purged with humidified atmosphere for 1 week prior to first personnel entry.**
- **After inspection, sample collection, and photography, all surfaces are washed with deionized water and a wet lint-free cloth.**
- **All graphite tiles are then abraded with Scotchbrite® to remove Li_2CO_3.**
- **All other metal surfaces are washed with a 5% solution of acetic acid (common vinegar, CH_3COOH) to convert hard ceramic Li_2CO_3 to water soluble lithium acetate ($LiC_2H_3O_2$) and removal with wet lint-free cloth.**

Summary and Conclusions

- **Significant improvements in the performance of NSTX NBI heated divertor discharges resulting from lithium depositions are observed.**
    - Lithium evaporated on divertor suppresses ELMs and improves confinement

- **Under higher power conditions, experiments with the liquid lithium divertor indicated a plasma density decrease despite deuterium fueling increase as lithium surface of LLD liquefied.**

- **In other LLD tests, the amount of required fueling was similar to that for solid lithium coatings. Work is in progress to investigate these differences, e.g.,**
    - **liquid lithium can pump impurities and effect density**

    *** liquid lithium surface impurities (C,O,…) from sputtering and gettering can reduce the formation of LiD and decrease pumping.**

- **NSTX Experiments with solid lithium coatings and a liquid lithium divertor plate contribute toward developing replenishable liquid lithium walls for providing a pumping, impurity flushing, low-Z, self-healing plasma facing surface.**