



NSTX

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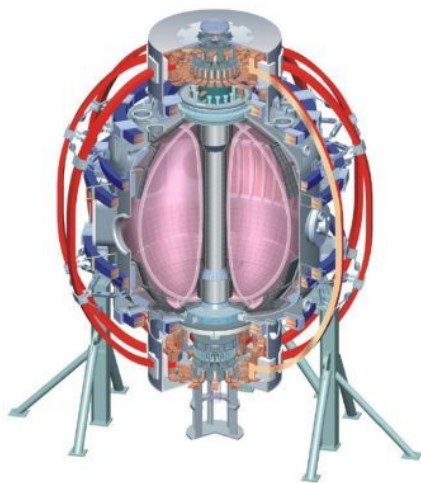
Overview of NSTX Liquid Lithium Divertor Performance and Divertor Upgrade Plans

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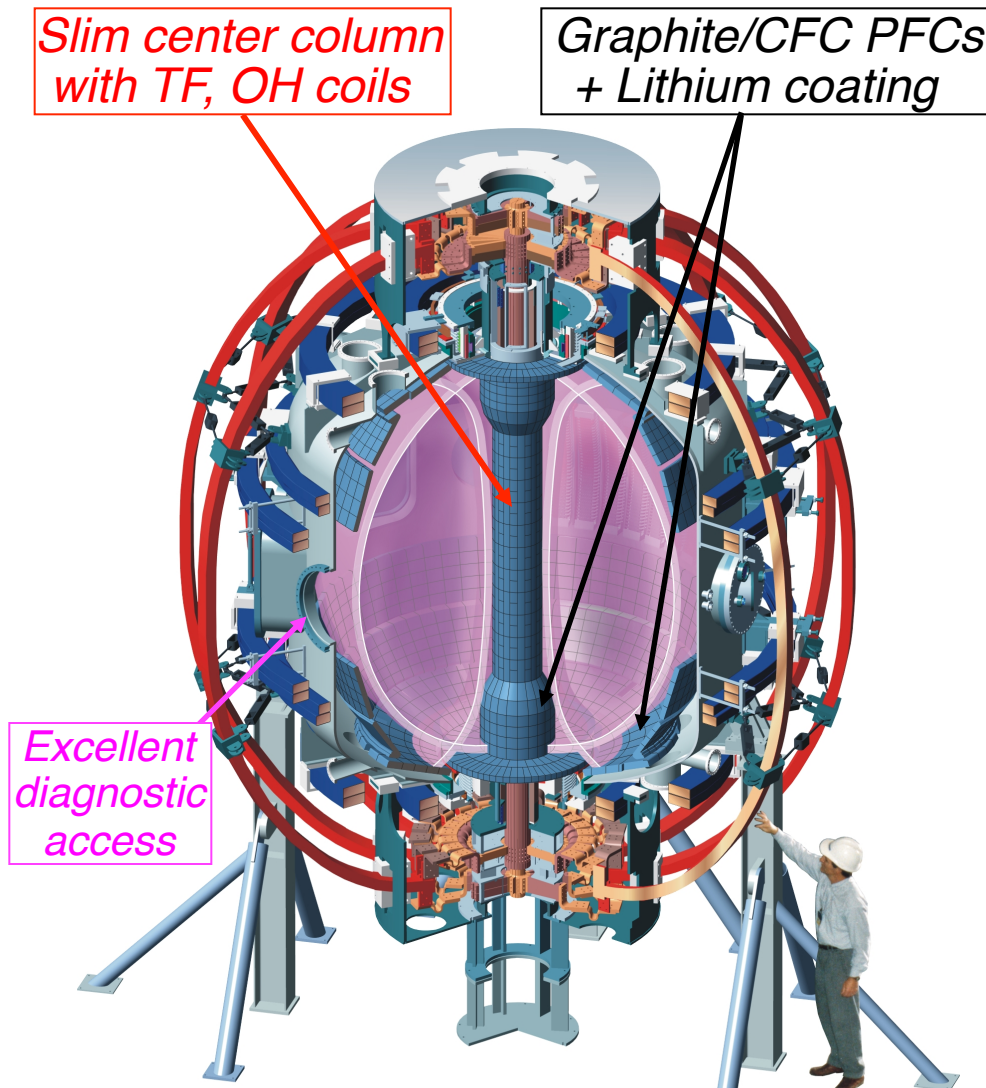
**American Physical Society,
Division of Plasma Physics Meeting,
Chicago, IL, 7-12 November, 2010**

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



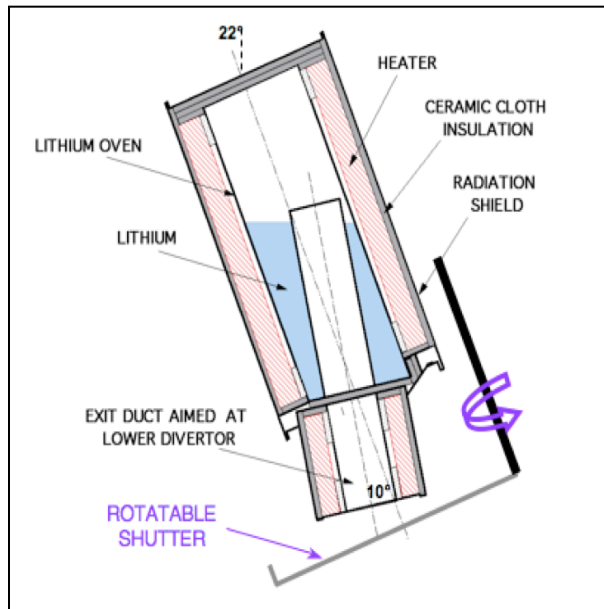
Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius	0.85 m
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	0.7 – 1.5 MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2 \times 10^{20} \text{m}^{-3}$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

Liquid has Been Proposed 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,...)

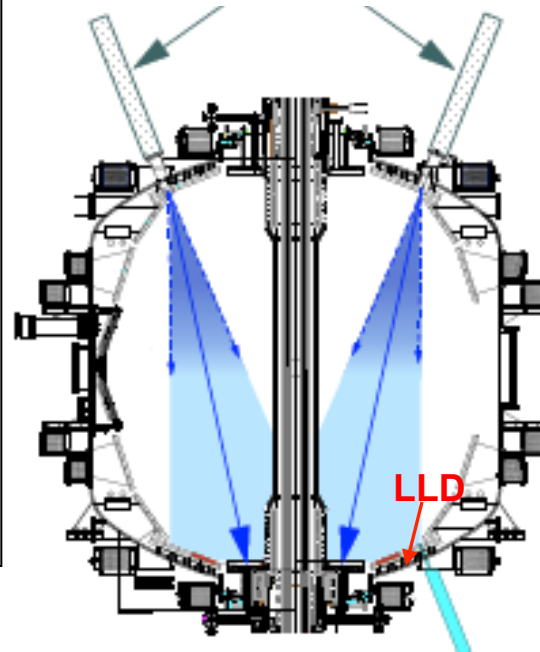
Dual Lithium Evaporators (LITERs) Are Now Routinely Used To Deposit Lithium Coatings On NSTX Lower Divertor Between Discharges

LITER Oven



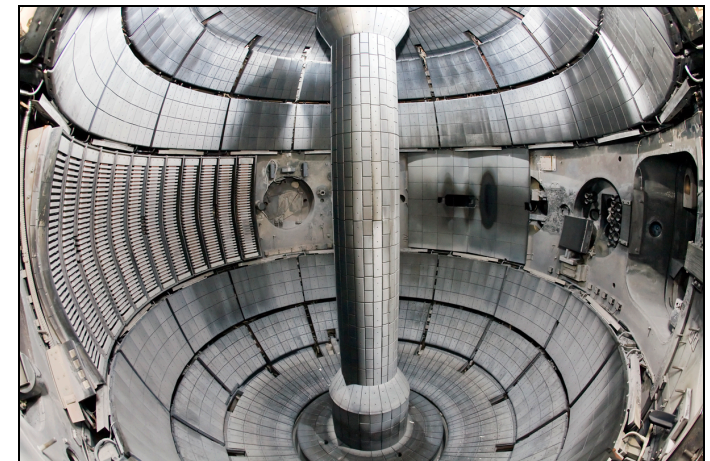
- Rotatable shutter stops lithium when diagnostic window shutters are open.

LITERs



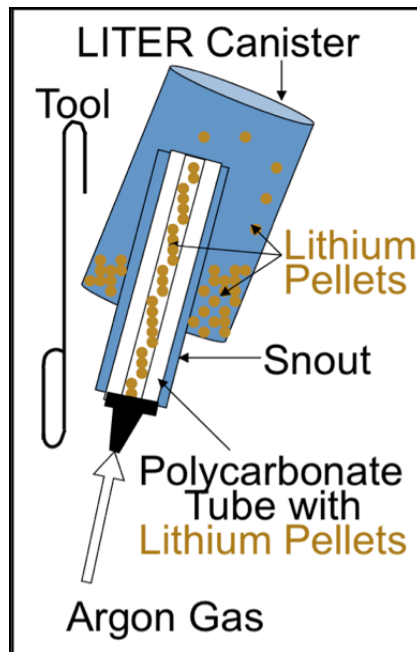
- LITERs aimed toward the graphite divertor. Shown are 1/e widths of the emitted distribution.

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

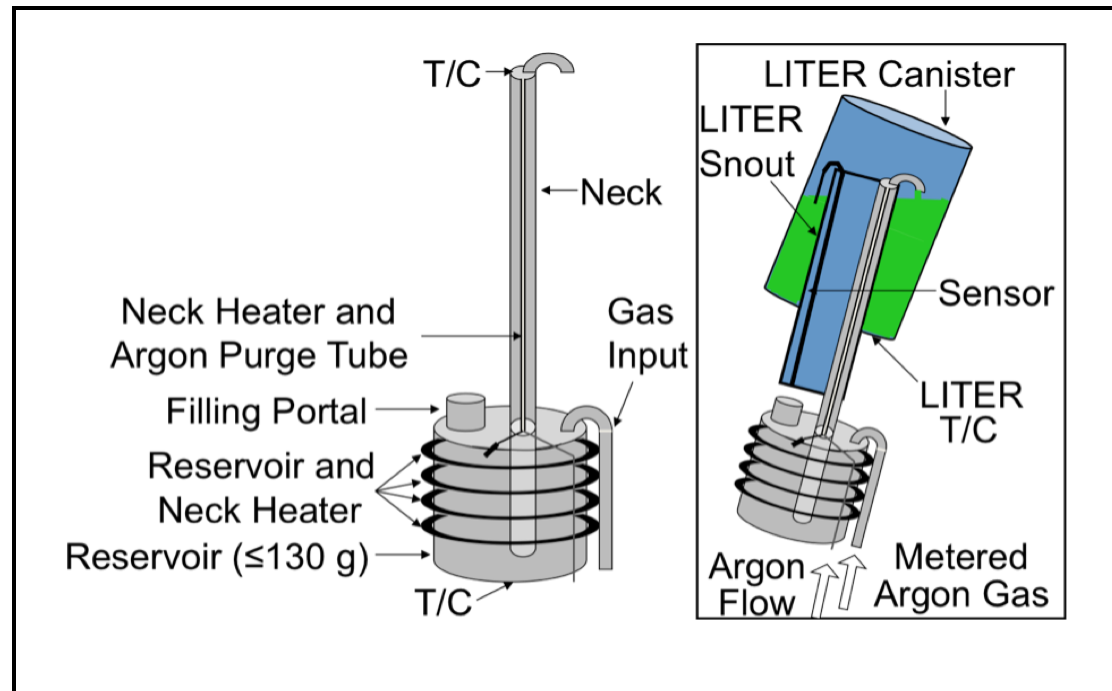


- After exposure to air (2009), 600g Li deposition converts to white lithium carbonate (Li_2CO_3).

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



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

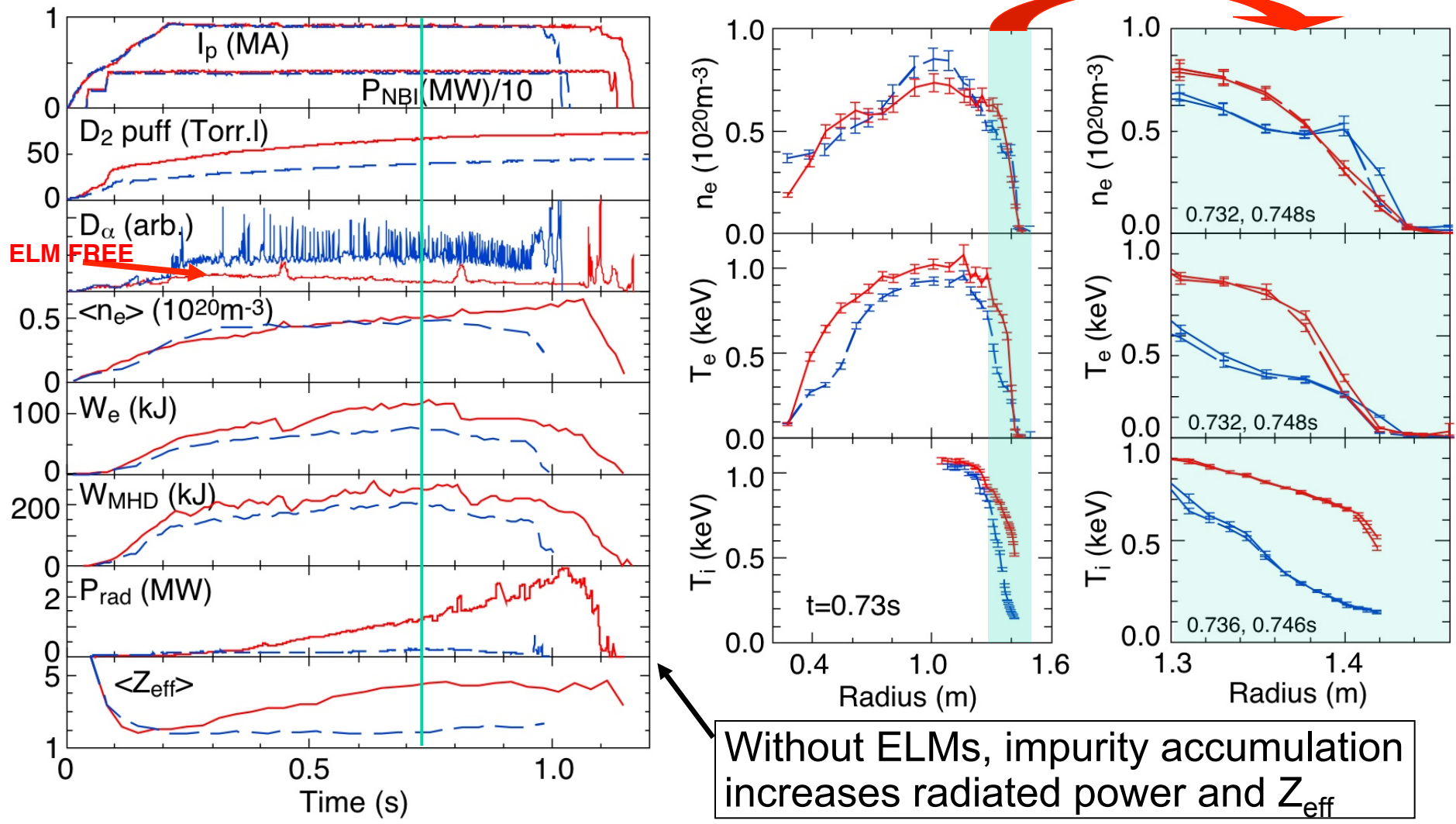


- Recently, LITERs filled using liquid lithium injected with argon (100% packing fraction, for liquid, 80g max).

- 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.

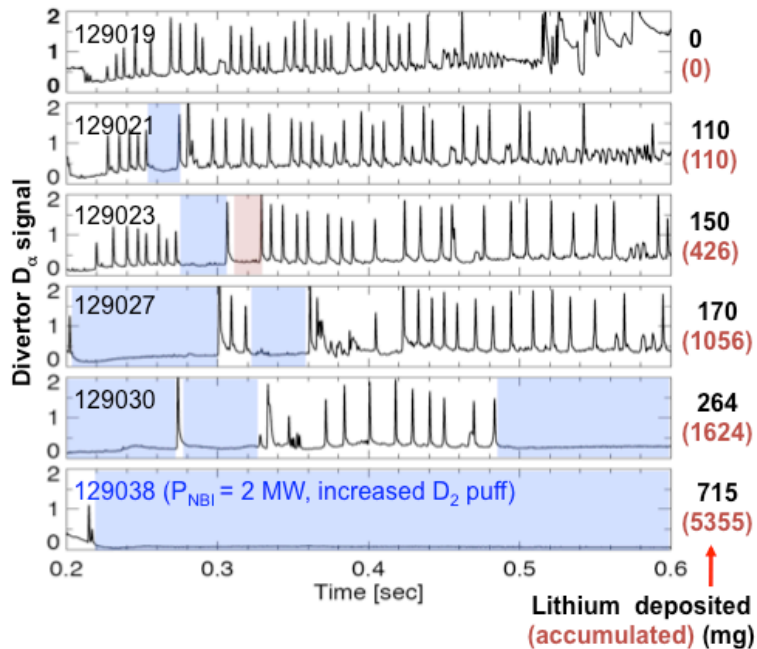
Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Increases Stored Energy, Improves Confinement

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

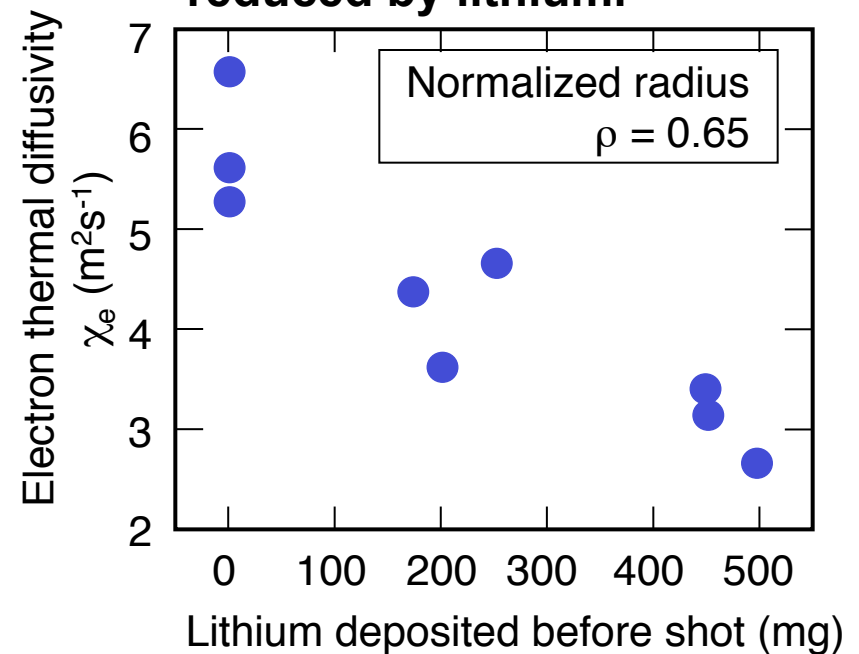


Lithium Evaporated on Divertor Suppresses ELMs and Improves Confinement

- ELMS Reduced as Lithium Increases

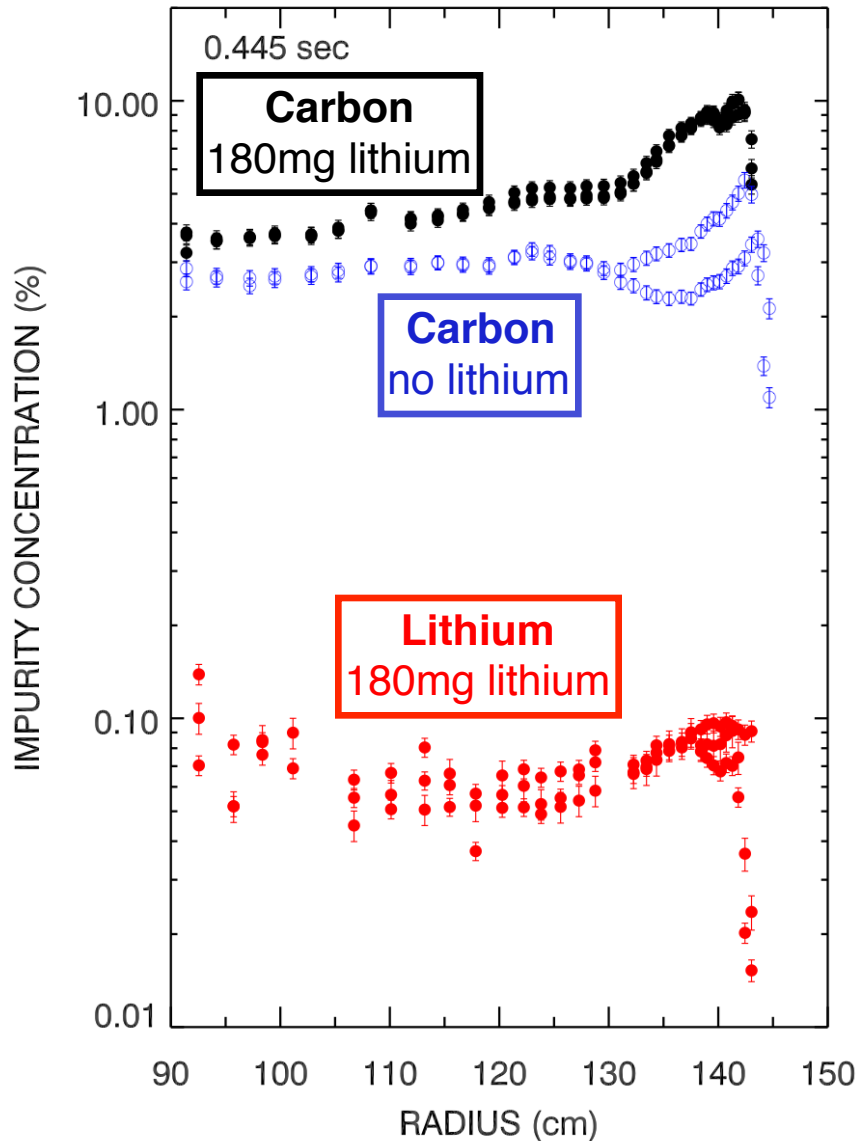


- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium.



- H-mode threshold reduced by lithium coating by up to factor 4
- Fast-ion contribution to total energy ($\propto T_e^{3/2}/n_e$) also increases

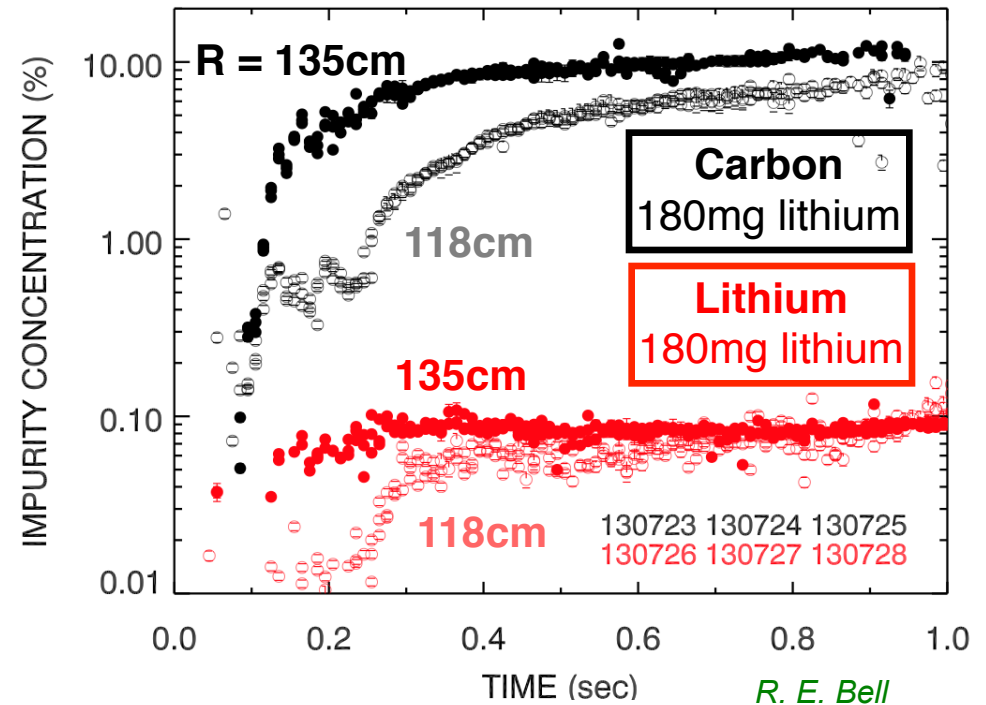
Lithium Concentration in Plasmas Remains Low but Carbon Concentration Rises with Lithium Coating



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

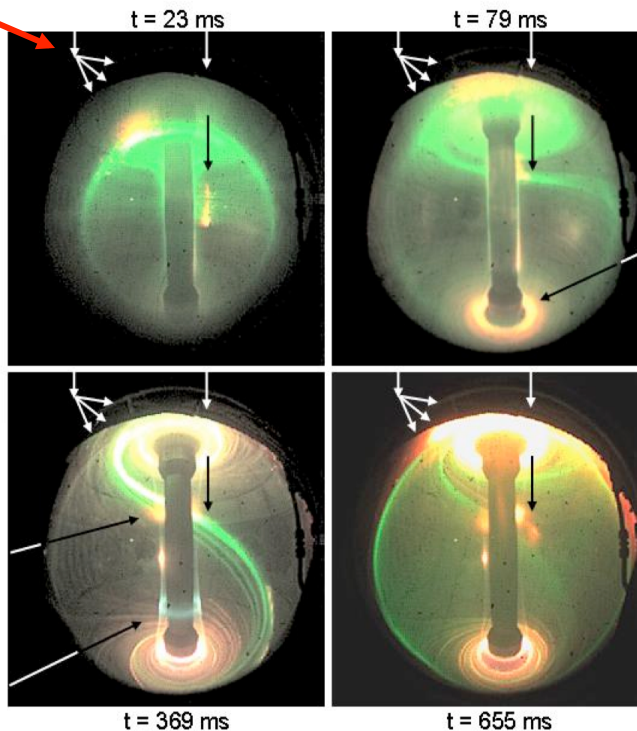
$$n_C/n_{Li} = 30 - 100$$

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



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

44 mm Li spheres enter SOL



ELM filaments strike lithium in SOL flow.

Diffuse plasma edge and MARFE (blue).

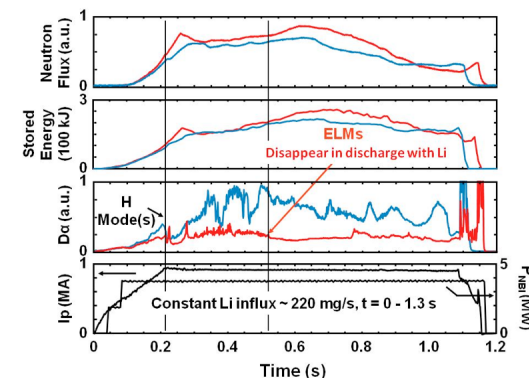
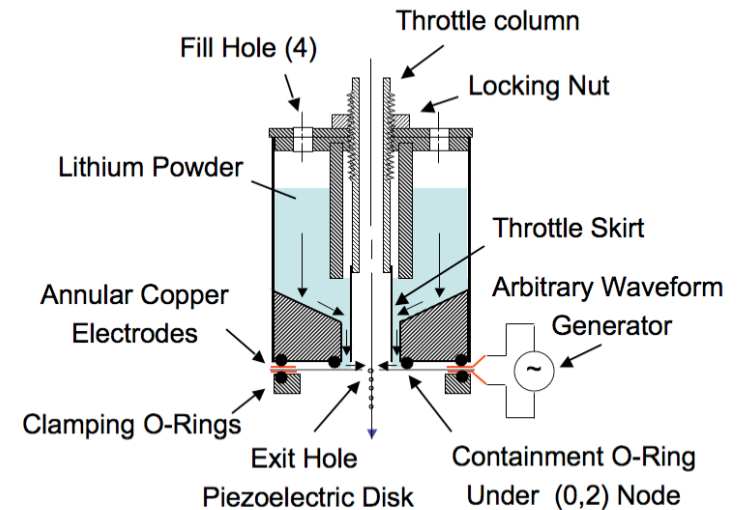
- Lithium particles delivered before and during discharges.
- Particle delivery rates up to 80 mg/s (LITER ~10-20 mg/min per unit)

As NBI starts, lithium is swept toroidally in SOL flow

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

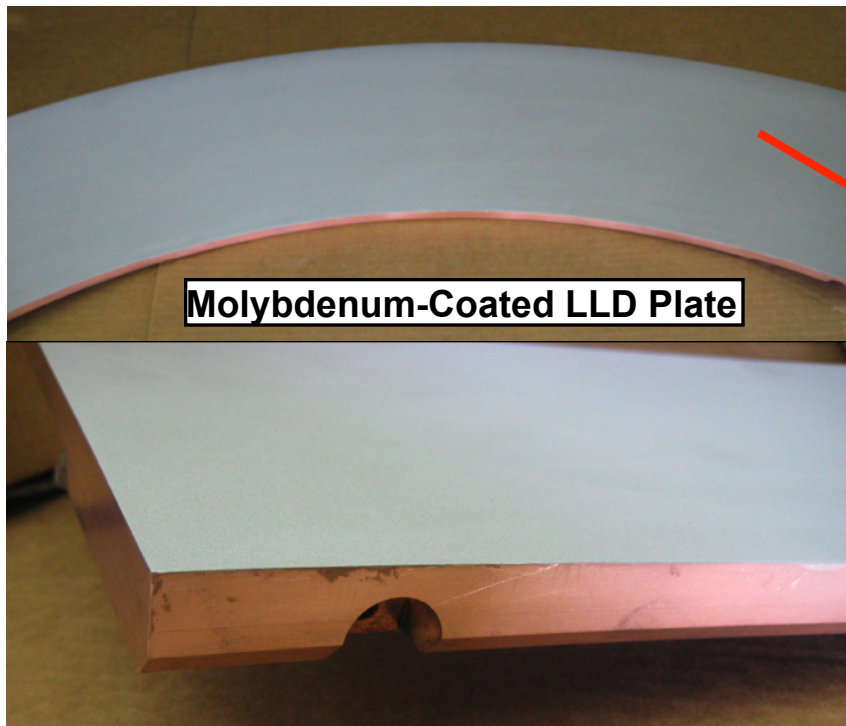
ELMS and MARFES vanish by t~500ms. Sharp plasma edge and Li radiative mantle

Schematic of Lithium Powder Piezoelectric Acoustic Injector

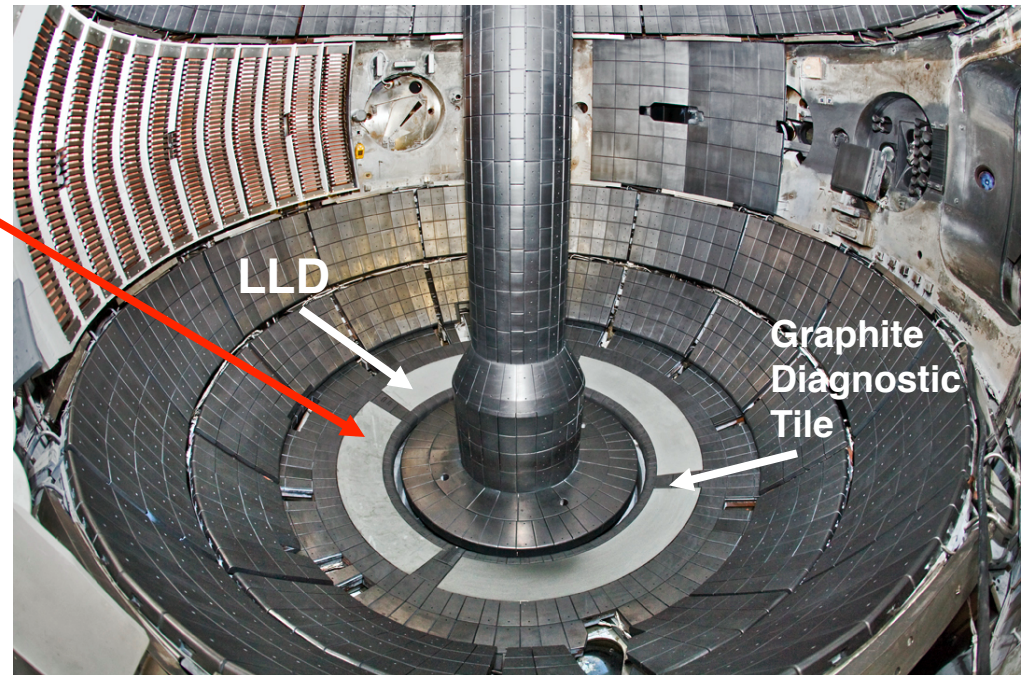


- Initial results dramatic but not yet reproducible

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.

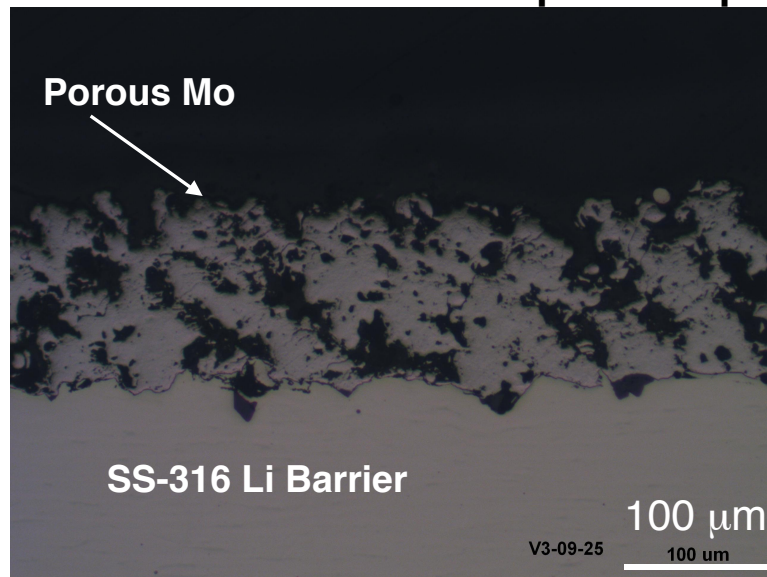
LLD Lithium-bearing Surface is Thin Porous Molybdenum

Key properties of an acceptable LLD lithium surface

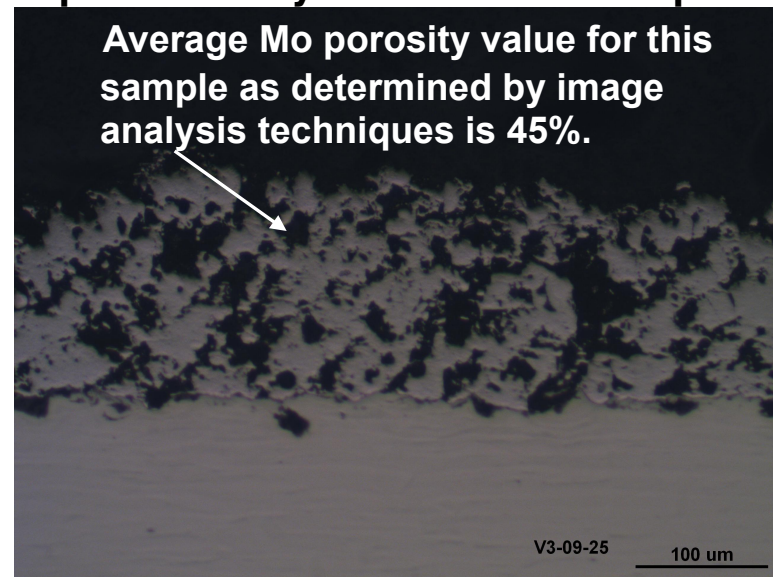
- sufficient surface tension to hold Li in presence of JxB forces
- ability of liquid Li to flow across metal surface (wetting capability)
- minimize temperature rate of rise of Li --> rapid heat transfer from Li to base

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

Discharges Run With Outer Strike Point on Liquid Lithium Divertor

- **Discharge**

$$I_p = 0.8\text{MA},$$

$$P_{\text{NB}} = 4.0\text{MW}$$

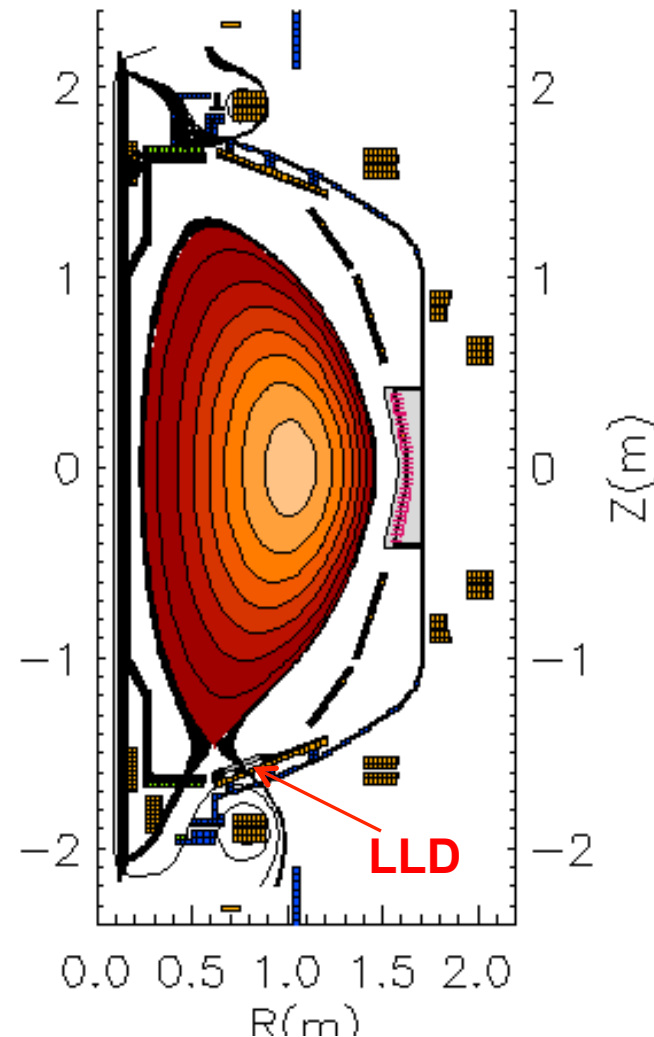
$$B_T = 0.48\text{T}$$

$$R_{\text{OSP}} = 0.78\text{m}$$

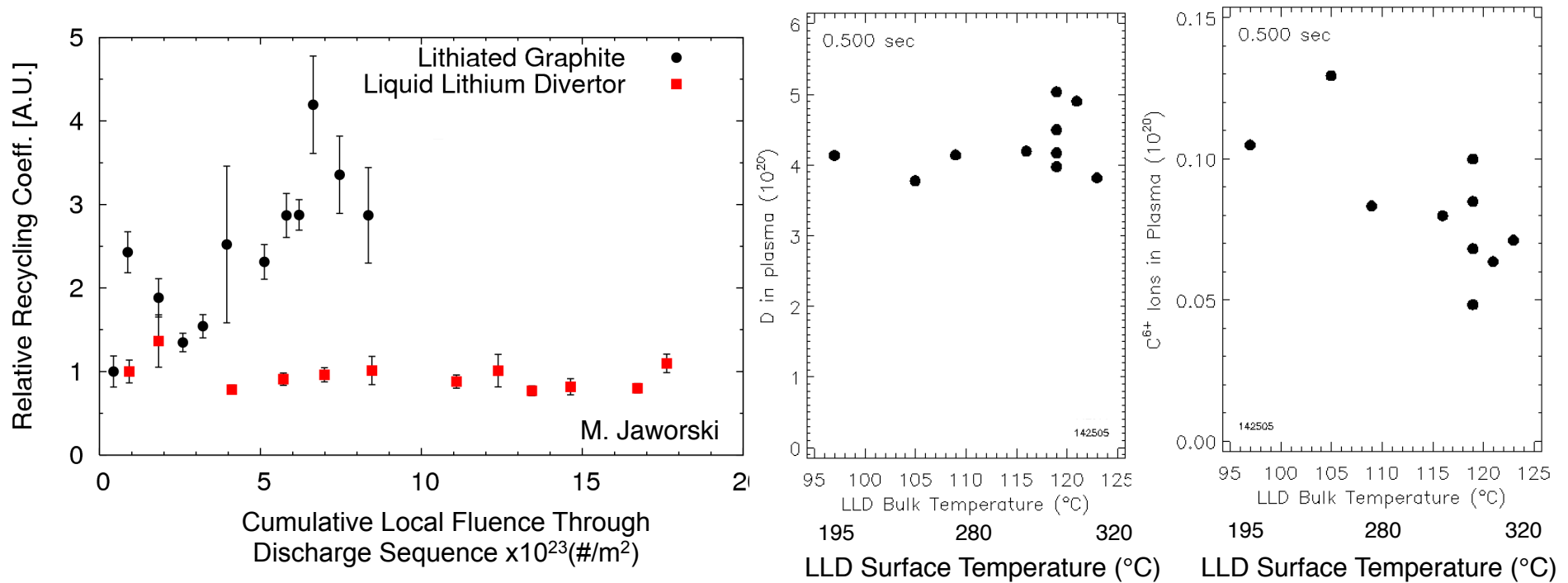
- **LLD Lithium Content**

- LLD loaded using one LITER (2.5% eff. at LLD radius)
- 7.5g evaporated from one LITER preceding the exp.
- Estimated fresh Li coating on LLD $0.025 \times 7.5\text{g} = 0.188\text{g}$.
- Fresh Li thickness $\sim 0.35\mu\text{m}$.

\EFIT02, Shot 142512, time=547ms

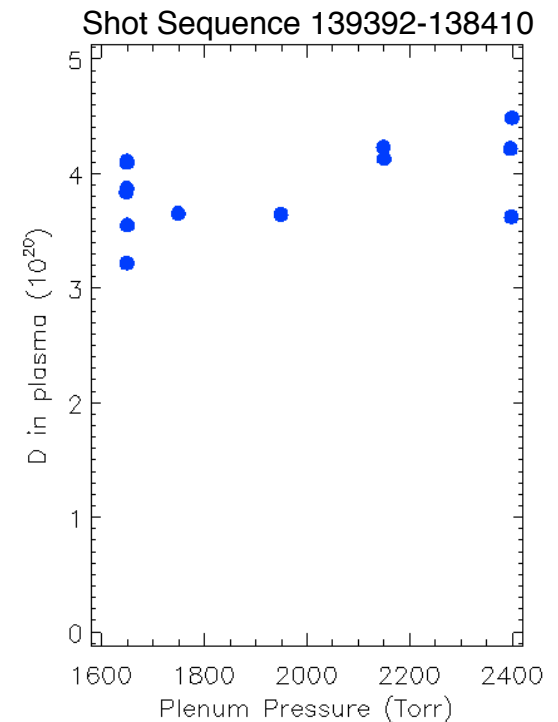
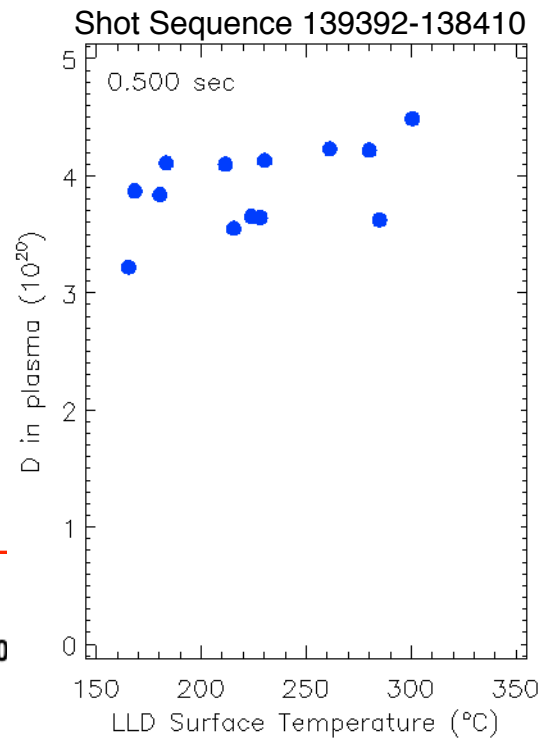
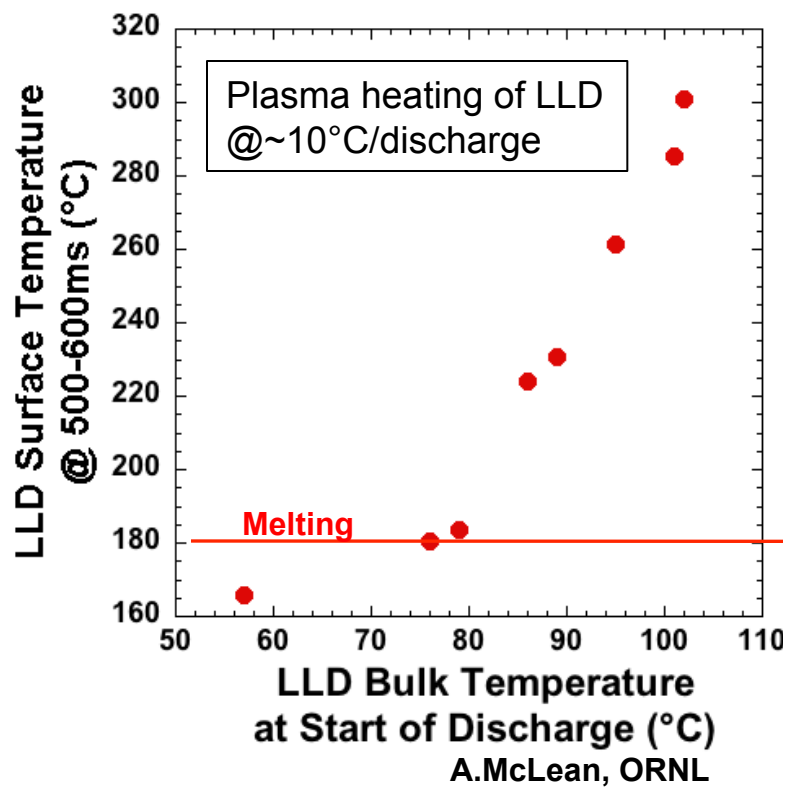


Constant Fueled Discharges With Outer Strike Point on LLD Exhibit Persistence of Recycling Behavior, Constant Core Particle Content, & Decrease in Core Carbon as LLD Liquefies

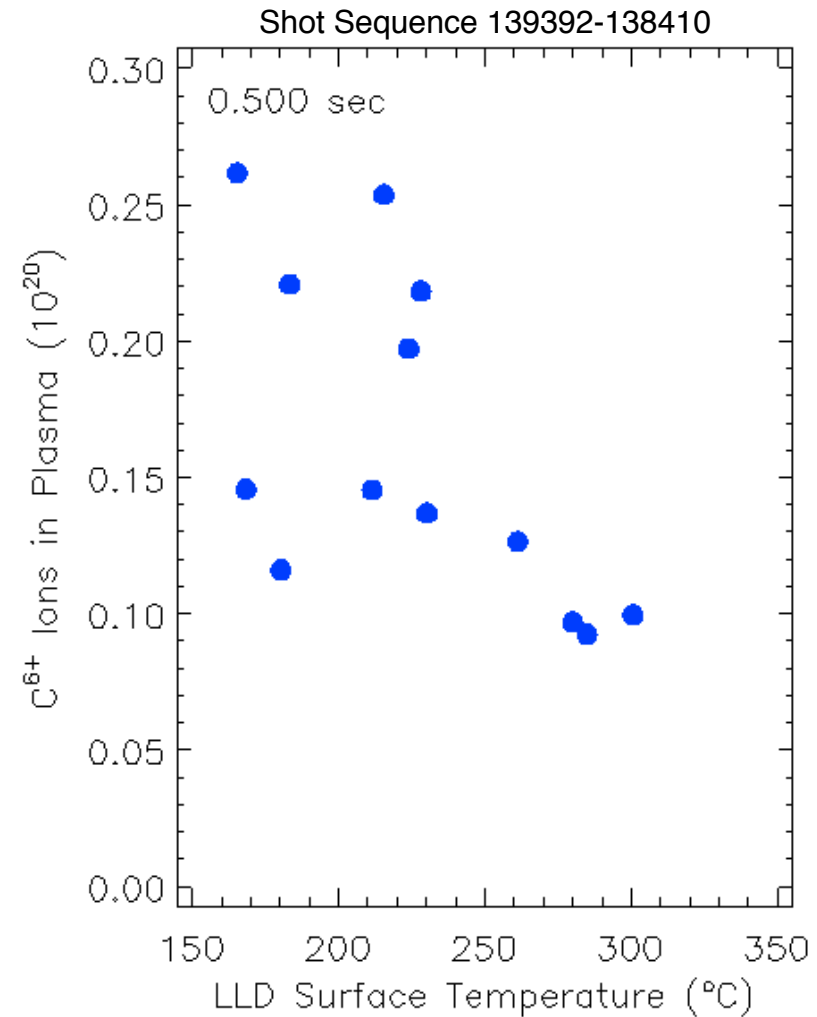
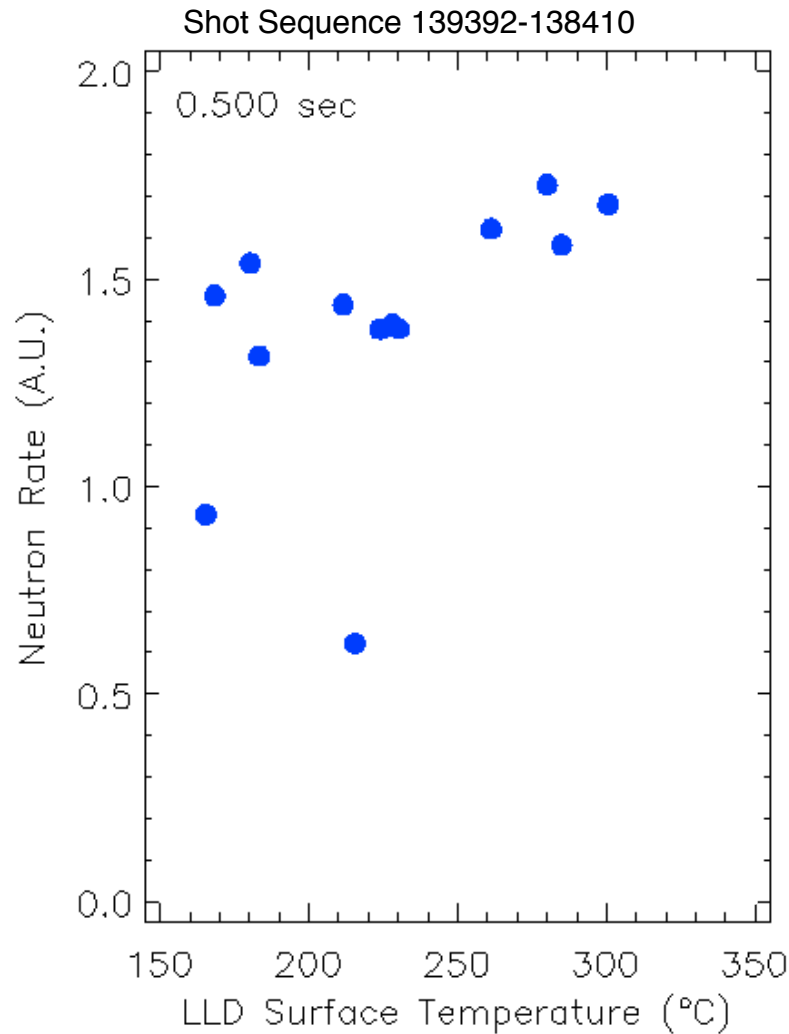


- Systematic rise in relative recycling coefficient on lithiated-graphite, but not on LLD. Indicates difference between lithiated-graphite and LLD.
- Multi-shot ion fluence indicates LLD has “reservoir” effect compared to Li-graphite.
- Liquid lithium decreases core carbon.

Discharges With Outer Strike Point on LLD and Increasing Fueling Exhibit Constant Core Particle Content, as LLD Liquefies



Discharges With Outer Strike Point on LLD and Increasing Fueling Exhibit Decreasing Carbon and Increasing Neutrons as LLD Liquefies



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

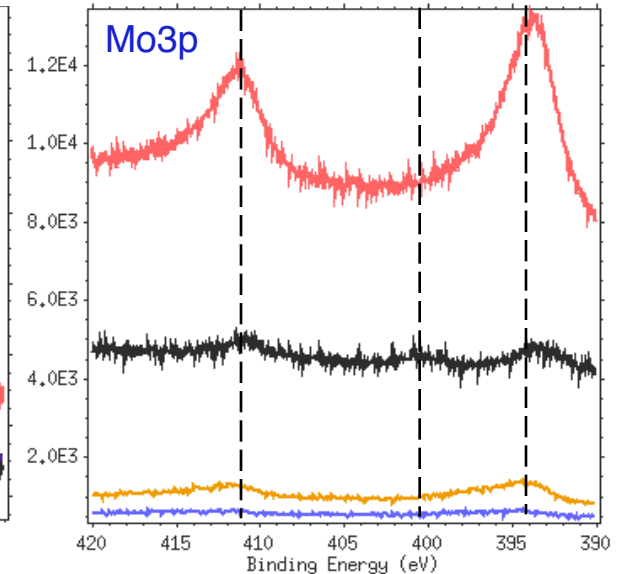
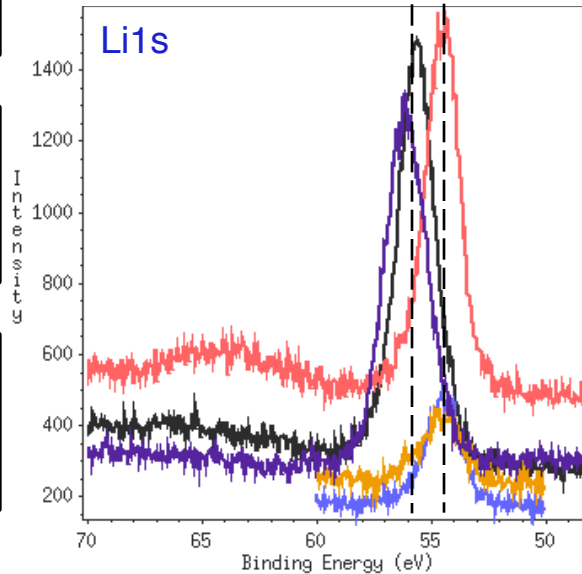
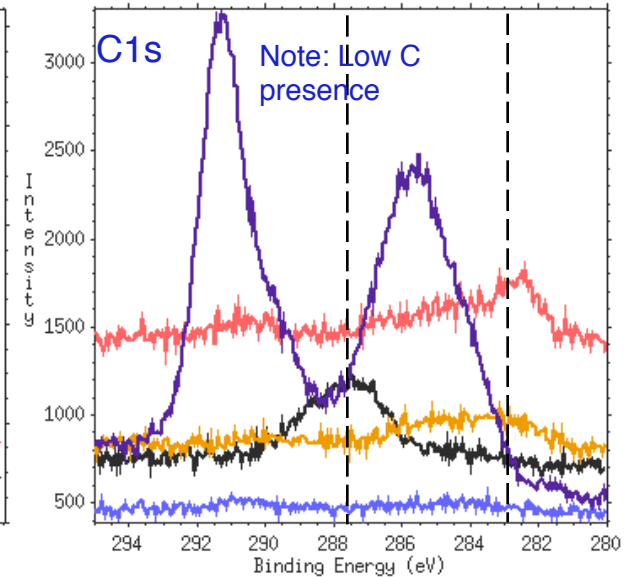
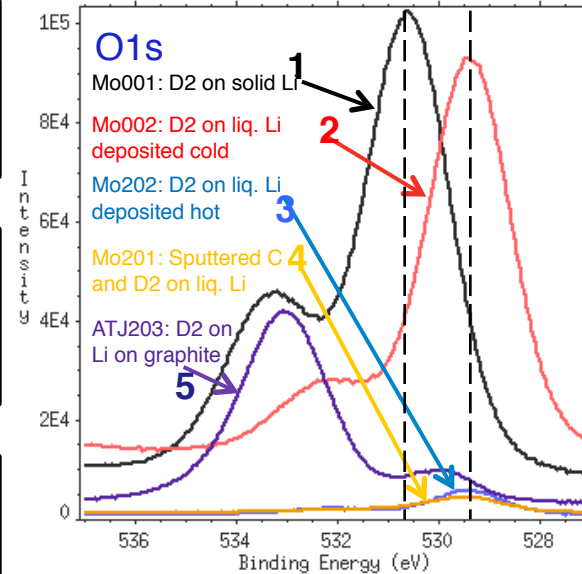
1) Mo001: 30 min D₂ irradiation on 2μm Li deposited on cold Mo.

2) Mo002: 30 min D₂ irradiation on 2μm Li at 255° C. Li deposited on cold Mo.

3) Mo202: 30 min D₂ 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 D₂ irradiation at 200° C.

5) ATJ203: 30 min D₂ 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

← Li-2 μ m, T_{room} →

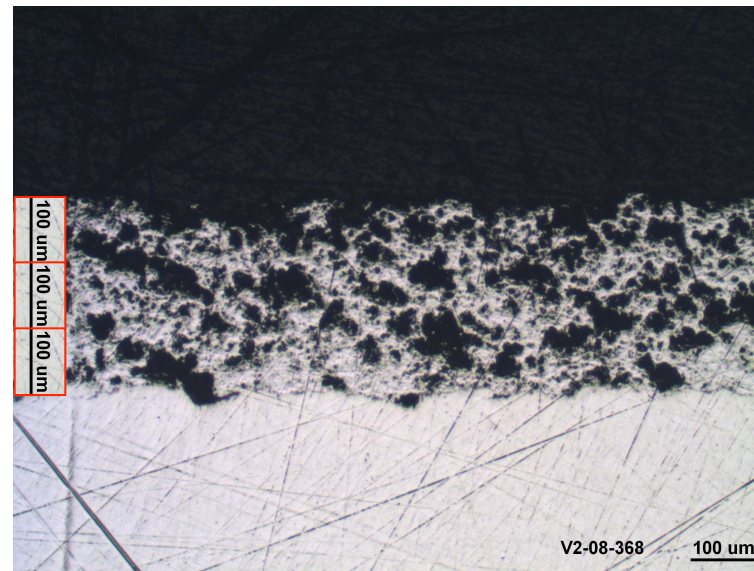
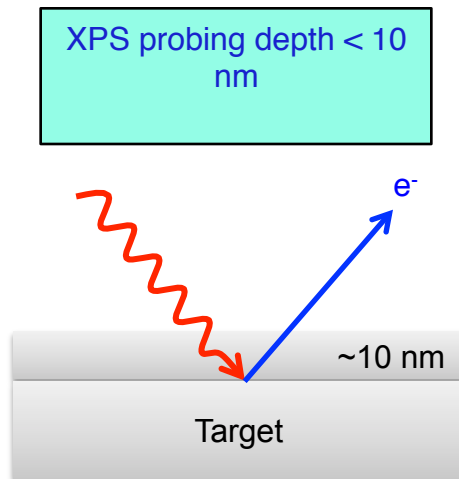
← Li-2 μ m, T_{room} →

← Li-2 μ m, 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

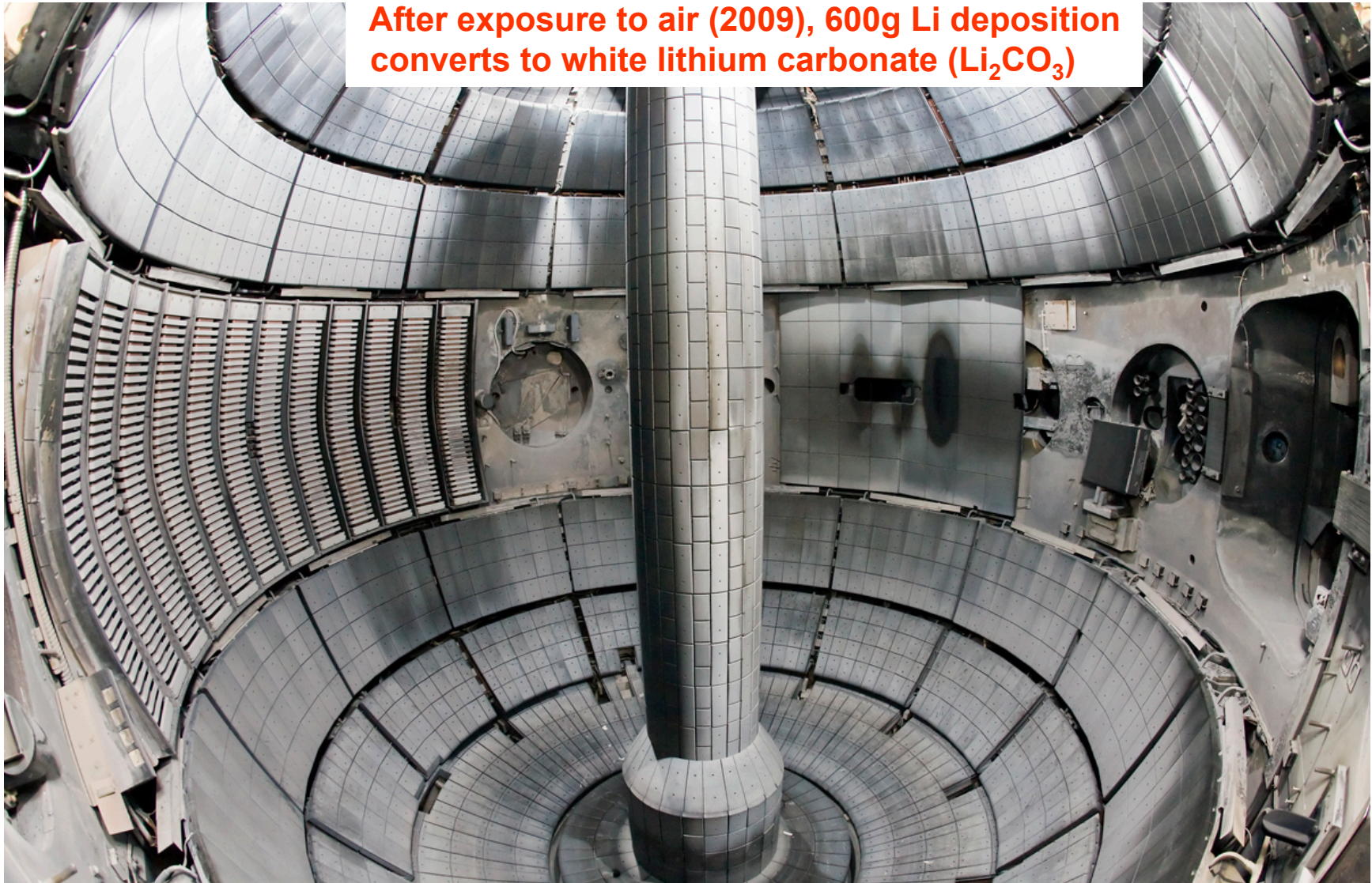


Surface lithium is plentiful and dominant after heating.

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)

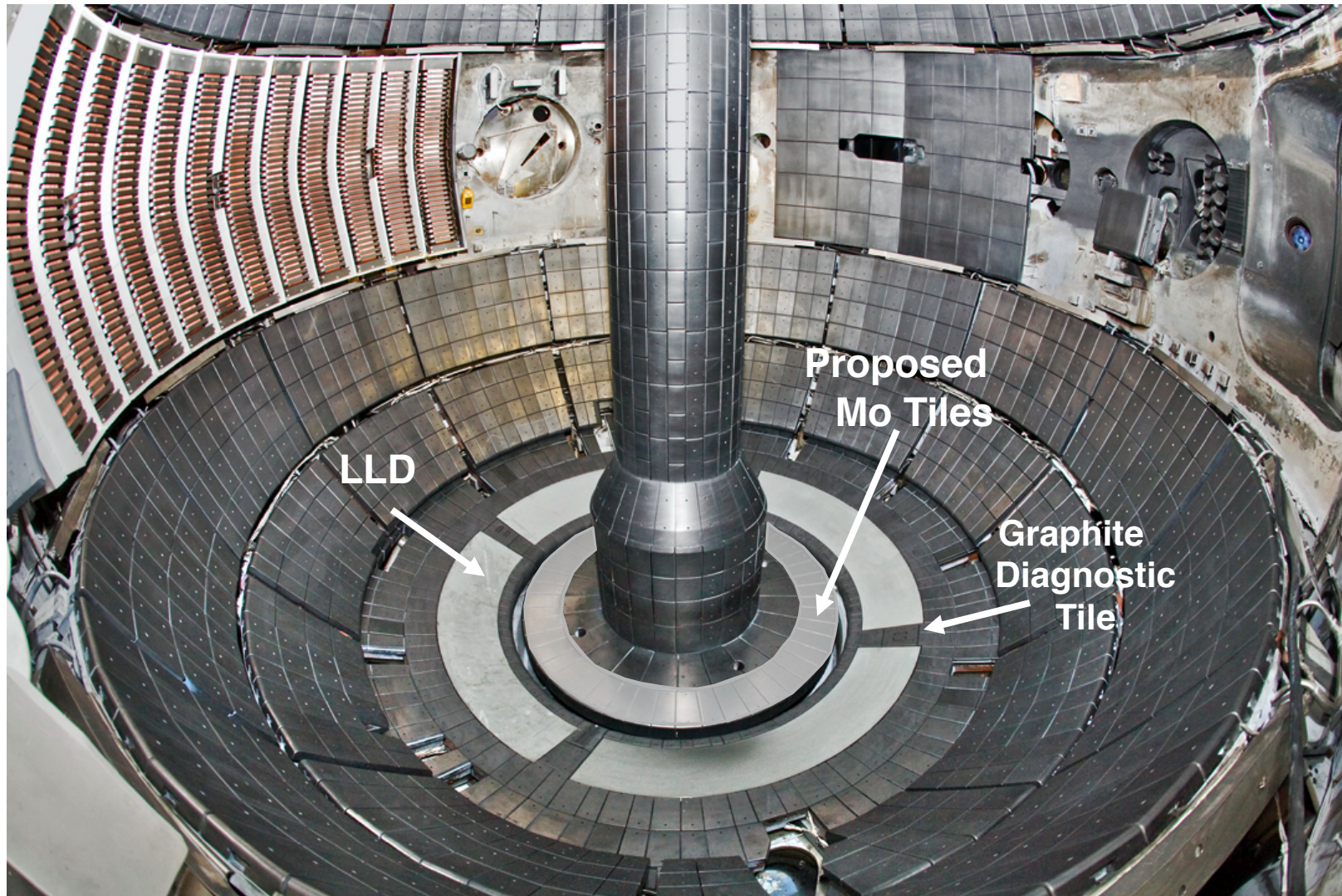


Li_2CO_3 coatings must be removed prior to evacuation to reduce plasma oxygen levels

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 ($\text{LiC}_2\text{H}_3\text{O}_2$) and removal with wet lint-free cloth.

Location of Molybdenum Tiles Proposed to be Installed on Inner Divertor in 2011



- Allows both Strike Points to be positioned on Mo to test reduction in divertor carbon source term

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
- Constant fueled discharges with outer strike point on LLD exhibit constant core particle content, decrease in recycling, and decrease in core carbon as LLD liquefies.
- Discharges with outer strike point on LLD and increasing fueling exhibit constant particle content, increasing neutrons, decreasing carbon as LLD liquefies.
- Liquid lithium surface impurities and the complex surface morphology can reduce the formation of LLD 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 for long duration discharges.