Effects of Evaporated Lithium Coatings on Plasma-Facing Surfaces in NSTX*

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Conditioning of Carbon Plasma Facing Components Important to Achieving NSTX Goals

- Control of impurities, particularly oxygen, crucial for achieving H-mode
  - Broad profiles of H-mode benefit quest for higher β, f_{BS}, reduced flux
- Boronization has provided a reliable method of reducing oxygen and gaining access to the H-mode
  - Use glow-discharge in deuterated trimethyl boron (10%)/He (90%) mixture to deposit ~1.5g elemental B at intervals of 1 – 4 weeks
- Continued density rise in H-mode plasmas can limit pulse length
- Helium discharge cleaning used to control deuterium recycling
  - Applied for 5 – 15 min between most NSTX discharges
- Lithium coating of PFCs has achieved further reduction of recycling in both limiter *and divertor* plasmas
  - Also influenced ELM behavior which affected impurities and density
- *Lithium is a tool for exploring confinement, H-mode, ELMs, pedestal*

Mechanism of Action of Lithium-Coated PFCs

- Fresh solid lithium (density $0.53 gcm^{-3}$) pumps D^+ and D^0 through formation of lithium deuteride LiD
  - Negligible reactivity with molecular H_2, D_2 at room temperature
- Incident 0.5 – 2 keV D^+ calculated to penetrate 100 – 250 nm in lithium*
- Nominal pumping capacity of lower divertor plates, area ~$2m^2$, would be **$(1 – 2.5) \times 10^{22}$ D** (30 – 80 mg, 140 – 340 Torr.l D_2)
- Deuteron content of a typical H-mode plasma: **5×10^{20} D**
- Fueling of a typical H-mode plasma: **$(1–3) \times 10^{21}$ D** (15 – 50 Torr.l D_2)
- Capacity of lithium coating can be reduced by:
  - Coverage of some areas by less than full active depth
  - Localization of interaction to region around divertor strike point
  - Passivation of lithium by formation of more stable compounds (*e.g.* LiOH)
- Capacity could also be increased by microstructure of carbon surface

* J. Brooks, *et al.*, J. Nucl. Mater., **337-339**, 1053 (2005)

NSTX Began Investigating Lithium Coating of Plasma Facing Components (PFCs) in 2005

- **2005**: Injected lithium pellets, 2 - 5 mg, into sequences of ohmically heated helium discharges prior to deuterium NBI shot

- **2006**: LIThium EvaporatoR (LITER) deposited lithium on lower center column and divertor between tokamak discharges

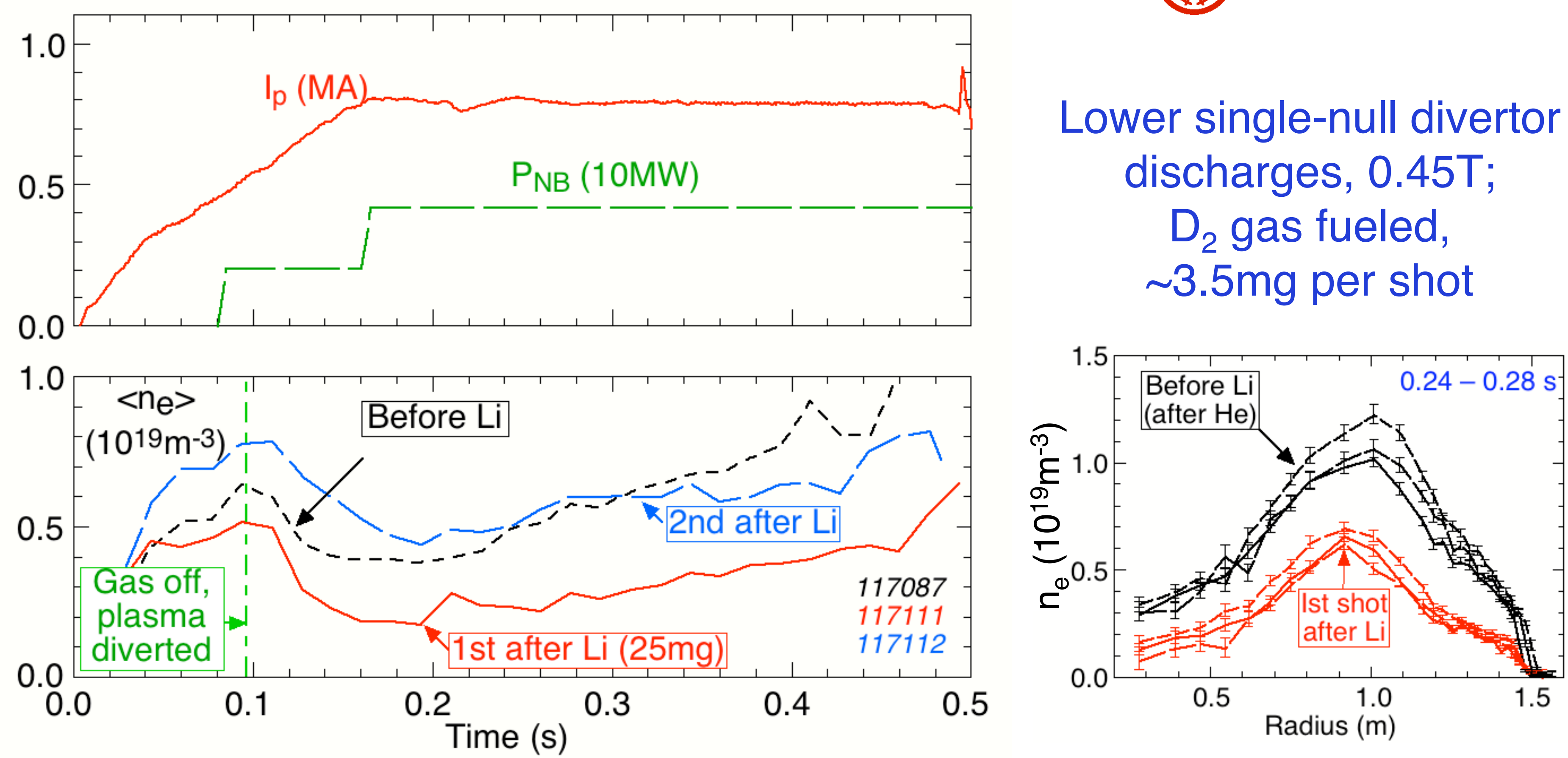
- **2007**: Upgraded heaters, enlarged nozzle and re-aimed it at lower divertor to increase deposition rate; continued evaporation during HeGDC and tokamak discharges
  - Also investigated injecting lithium powder in 2007*

*see D. Mansfield (poster TP8.063)

Pellet Coating Transiently Reduced Density in Deuterium NB-Heated L-mode Divertor Discharges

- Injected low-velocity (~100ms^{-1}) lithium pellets 2 – 5 mg into sequence of 5 – 10 ohmically heated helium discharges
  - Total of ~25mg of lithium introduced
  - Pellets ablated in edge region, lithium was transported through SOL and deposited on contact region of divertor(s)
- Compared reference LSN divertor, deuterium, L-mode shots with NBI heating and small gas puff
- After pellet coating, reference shot had much lower density (factor ~ 2), higher T_e, T_i than before
  - Some of the reduction in density may have been attributable to conditioning effect of the repeated helium discharges
  - Effect was transient and essentially disappeared on next shot

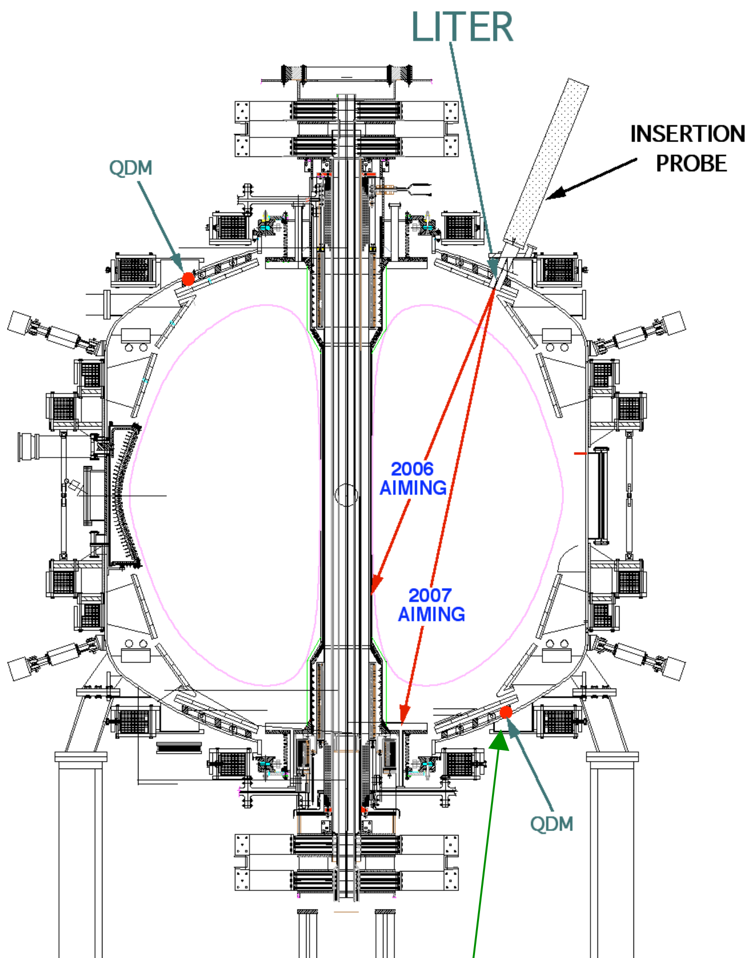
Lithium Pellets Produced Dramatic, but Short-Lived, Effects in L-mode Divertor Plasmas



Lower single-null divertor discharges, 0.45T; D_2 gas fueled, ~3.5mg per shot

- Density after end of gas puff reduced by factor >2 after lithium coating
  - Density profile peaked in *both* pre- and post- lithium cases
- Slight effect apparent on second similar shot but absent on third

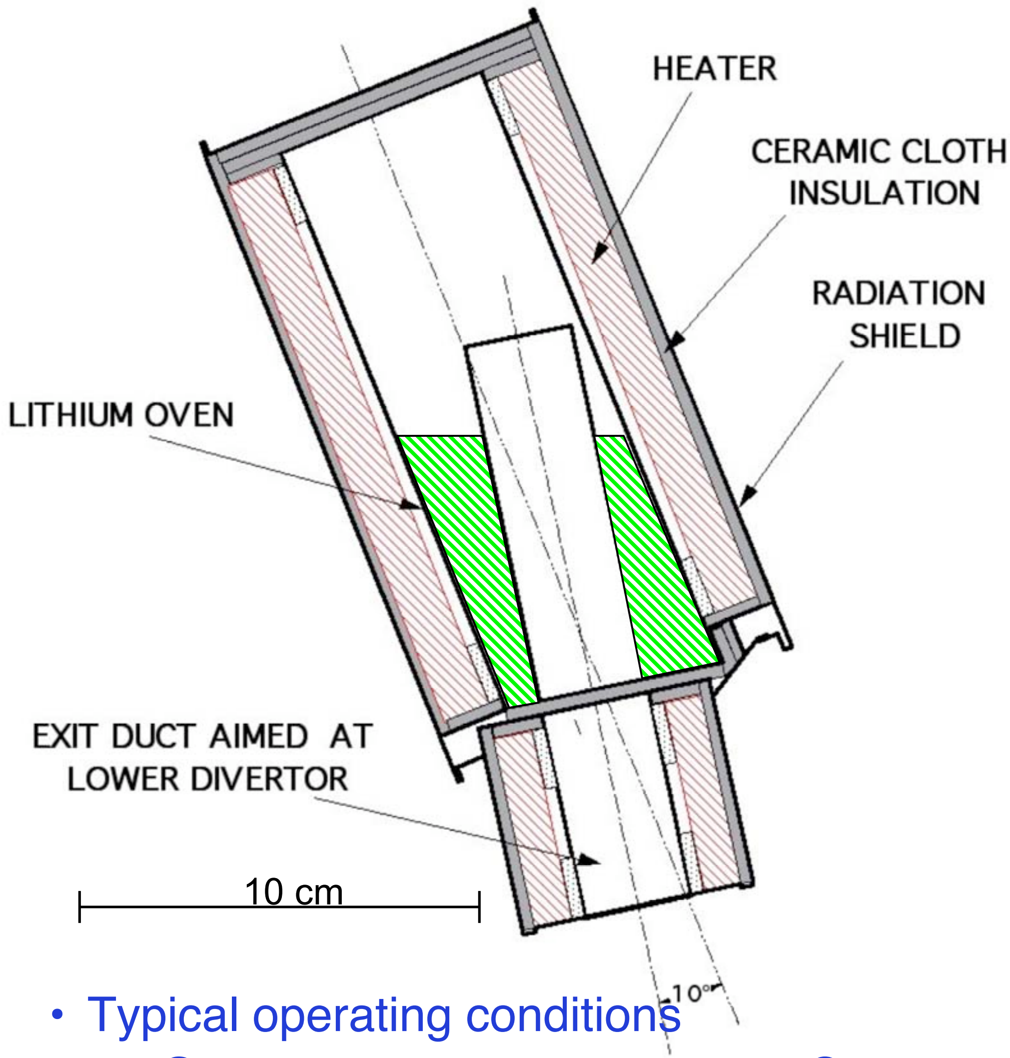
LIThium EvaporatoR (LITER) Used to Coat Lower Divertor Surface in 2006–7



QDM (Quartz Deposition Monitor)

- **LITER 2006**
  - Aimed toward lower center stack
  - Cool-down time ~20 min (to 400°C)
  - Separate HeGDC and evaporation periods
  - Tube heaters brazed to oven were run close to limits and suffered some failures
- **LITER 2007**
  - larger output aperture area (×1.7)
  - reaimed toward lower divertor for increased divertor target deposition (×3)
  - larger capacity (90g *vs.* 60g)
  - more robust radiant heaters for higher evaporation rates (80 *vs.* 10 mg/min)
  - more total thermal mass and outer insulation slowed cool-down time ~1.5 hr
  - to maintain NSTX duty cycle, the long cool-down time required evaporation into HeGDC

Design of LITER 2007

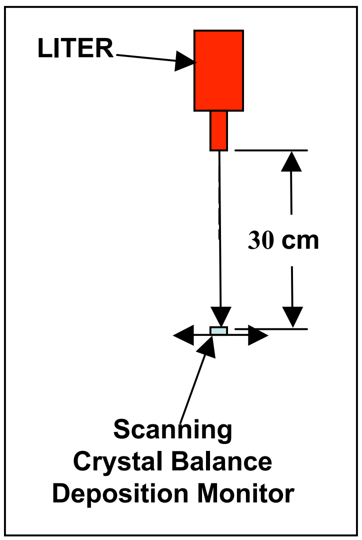


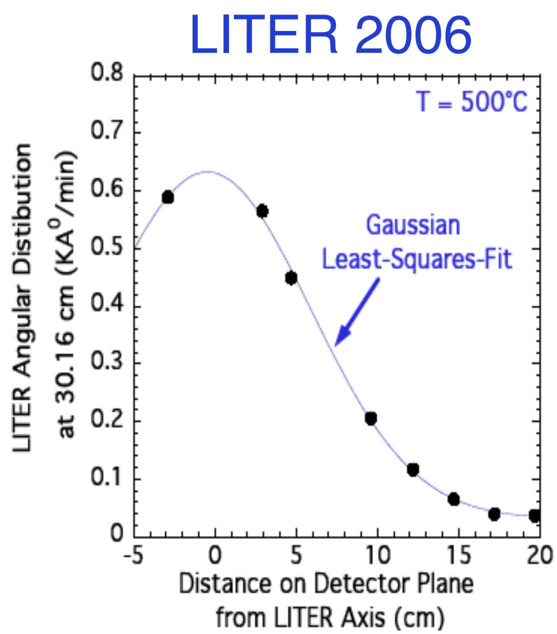
LITER on movable probe, loaded with Li under argon

- Typical operating conditions
  - Oven temperature: 600 – 680°C
  - Evaporation rate: 1 – 80mg/min

LITER Produces Collimated Lithium Vapor Stream; Rate Varies Strongly with Lithium Temperature

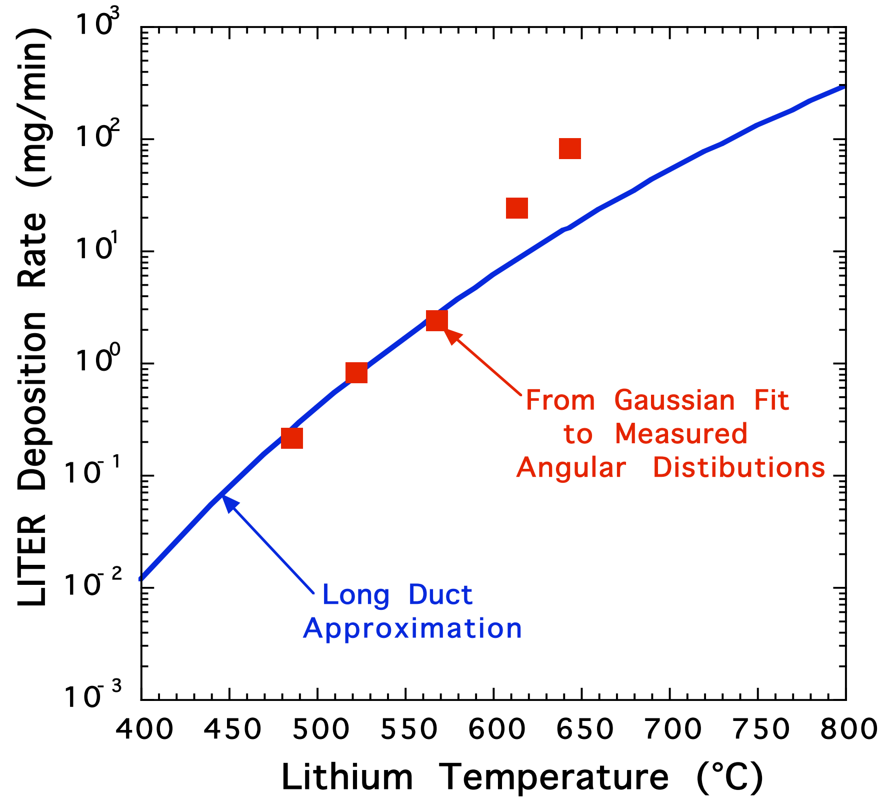
- Angular distribution of deposition measured in laboratory chamber



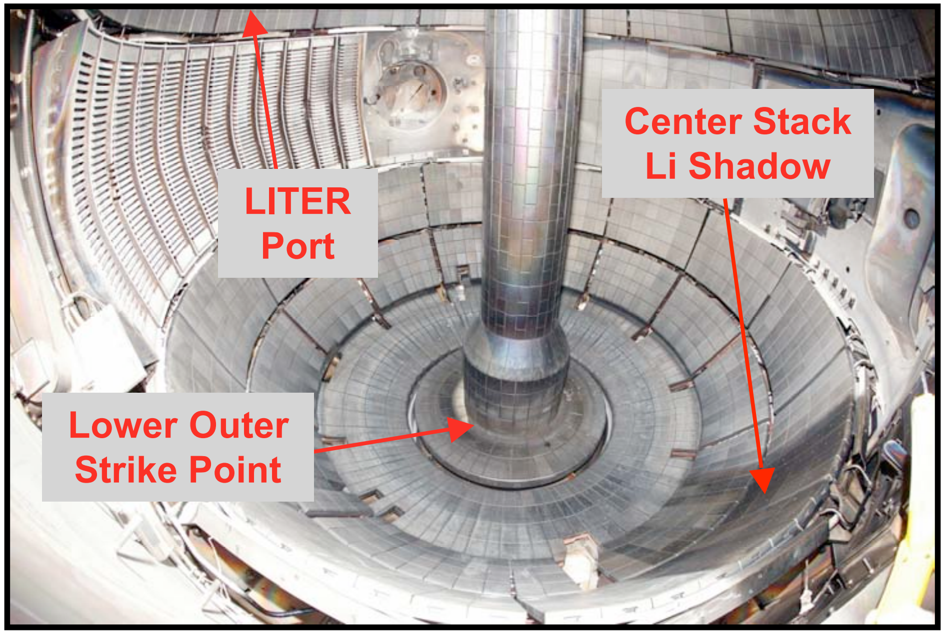


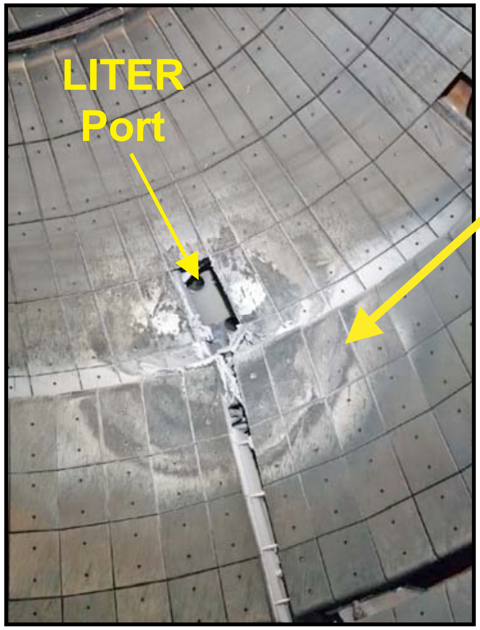
- Average Gaussian half width ~ 11° over operating temperature range

- Above 600°C, deposition rate increase may be due to non molecular flow



Areas of Lithium Deposition Visible After the Run Through Conversion to Stable Lithium Compounds





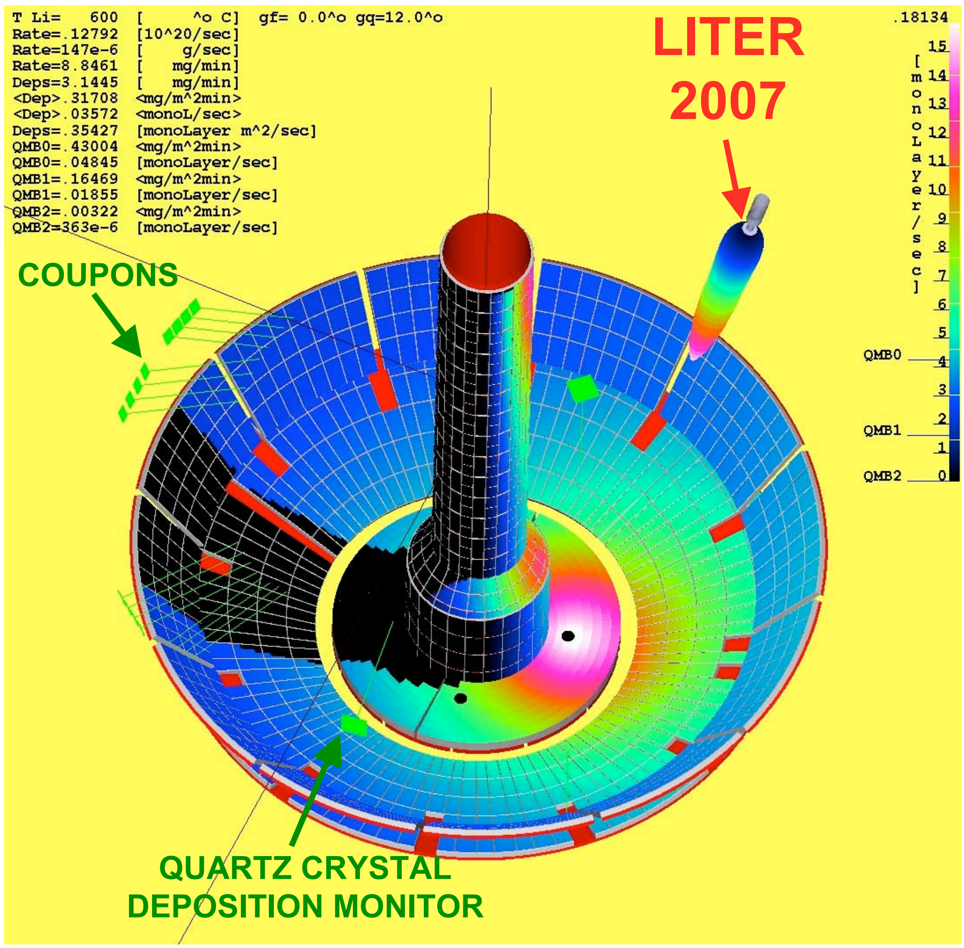
Accumulation around port

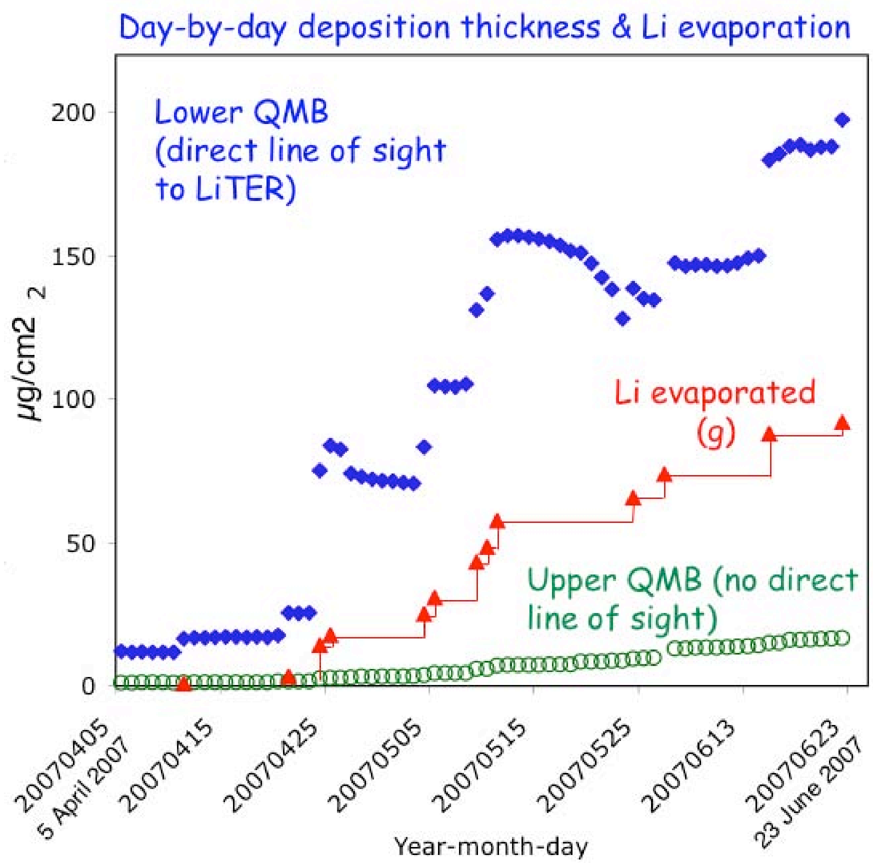
<u>After total of 93g lithium evaporation in 2007 experimental campaign</u>

- Including evaporation into HeGDC
- Accumulation around evaporator port due to elastic scattering of Li by He and acceleration of Li^{+} by GDC voltage
- No local deposition observed in 2006 when LITER was cooled after each application and there was no evaporation during HeGDC

Simulation of Evaporated Lithium Distribution Reproduces Observed Features

- Model* includes molecular dynamics in evaporator duct and full geometry of components in the vacuum vessel



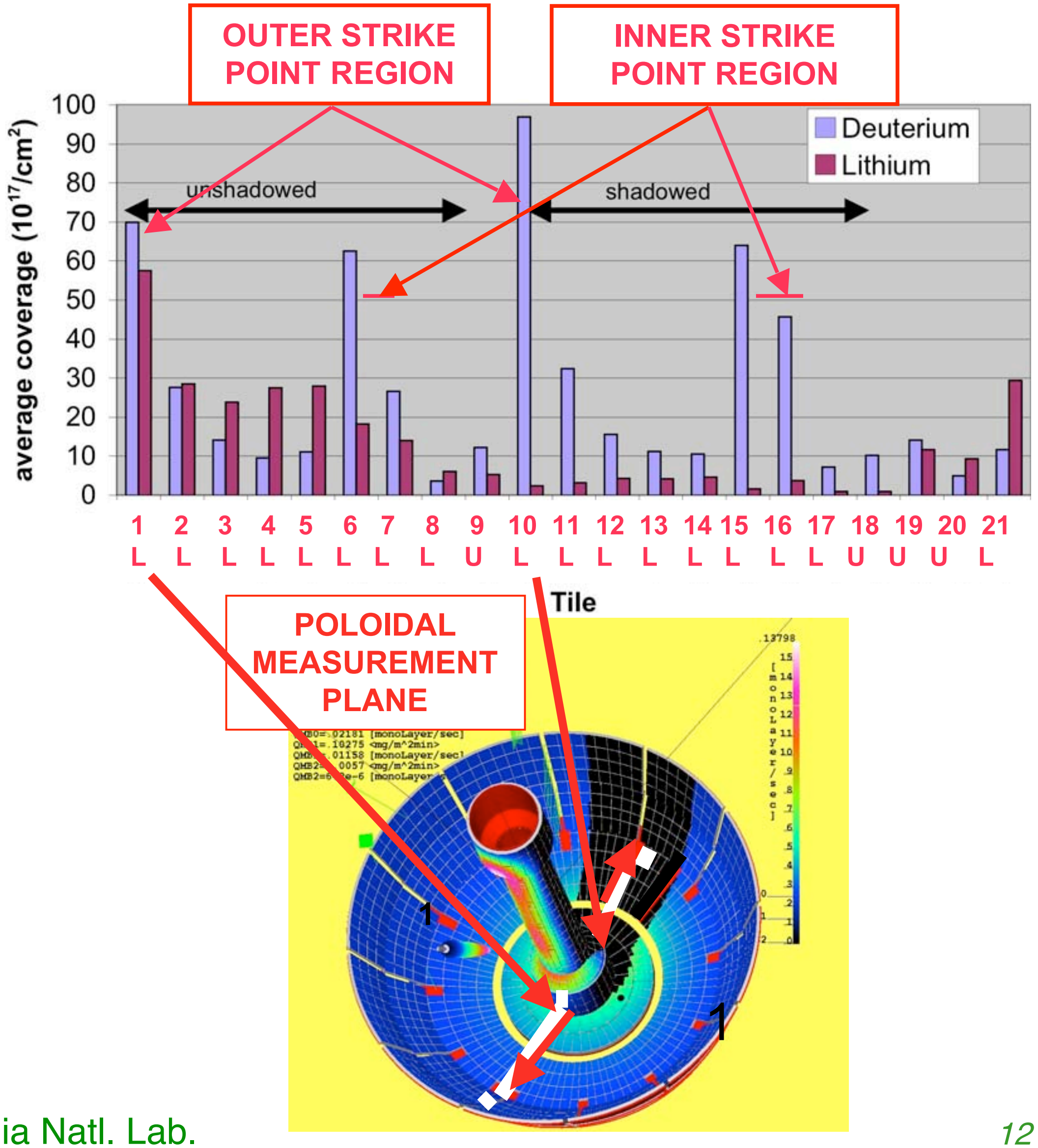


D-saturable layer of lithium is ~250nm thick $\equiv^t$ 13μgcm^{-2}

* L. Zakharov

Near-Surface Li & D Measured on PFC Tiles Removed after the Run from Two Toroidal Locations

- Ion Beam Analysis* of 21 tiles in or near poloidal plane after 2006 run:
  - Lower tiles (L) exhibit more lithium than upper tiles (U)
  - Tiles shadowed by center stack have ~ 10x less lithium than tiles receiving direct deposition ($\sim 10^{17}$ to 10^{19} Li atoms/cm^2)
  - D coverage similar in shadowed and unshadowed regions
  - Li was within 5 μm of the surface everywhere. On tiles with low Li coverage, Li was within 2μm. *Li in mixed concentration with unresolved components*



* W. Wampler, Sandia Natl. Lab.

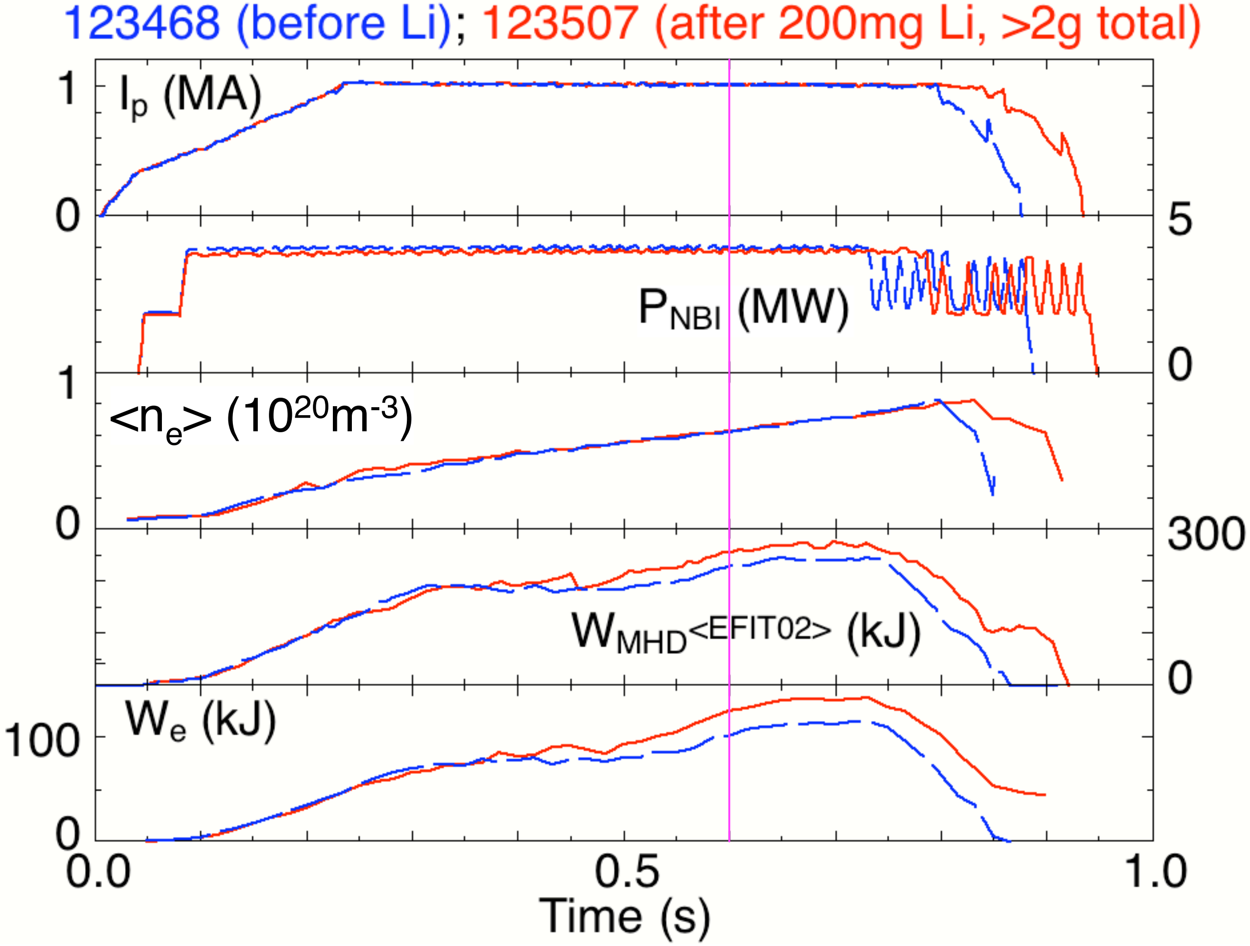
Observed Increased Levels of Helium in Discharges After Li Evaporation During He GDC

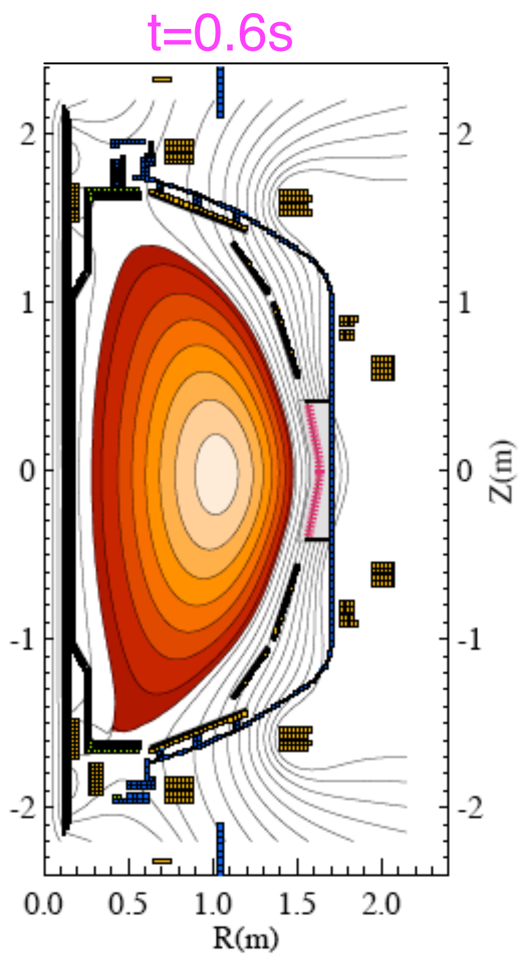
- Codeposition of helium with condensation and solidification of lithium vapor on a surface has been observed previously (Mirnov, Evtikin, T-11; Hirooka, PSI 04)
  - Attributed to helium trapping in interstitial voids in lithium film
- Slow helium outgassing affected subsequent deuterium discharges
  - Timescale for outgassing ~10s of min
- Also, sporadically through the 2007 run, some NB-heated plasmas developed high total and centrally peaked radiated power
  - Spectroscopy revealed high-Z metal (Fe, Cr, Ni) radiation
  - Surface analysis of divertor tiles after the run detected Fe and Cr
- Discharges with elevated P_{rad} occurred before use of LITER *but*
- Their frequency appeared to increase when LITER was being used

S.F. Paul (poster TP8.065)

Effects of Lithium Deposition Initially Studied in Standard H-mode Deuterium Discharges

- Used NB-heated deuterium H-mode plasmas in Lower-Single-Null (LSN) divertor configuration

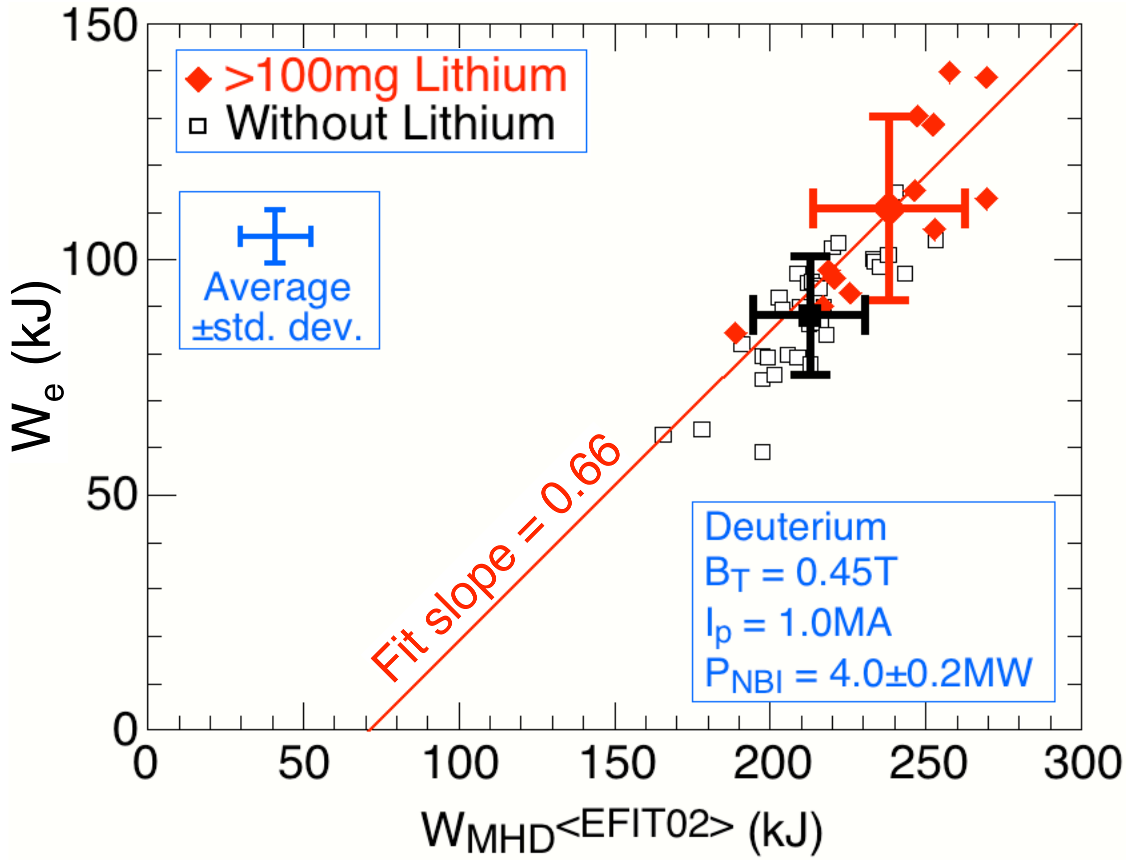




Lithium Increased Total Plasma Energy Largely Through Increasing Electron Stored Energy

NSTX

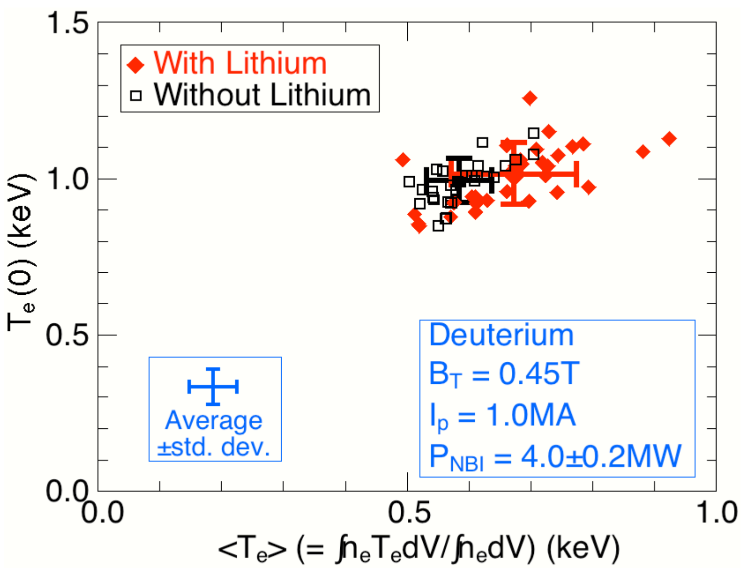
- W_{MHD} from EFIT analysis constrained by external magnetics, including diamagnetism, and total pressure profile shape matching electron pressure
- W_e from integration of TS pressure profile using EFIT volume elements

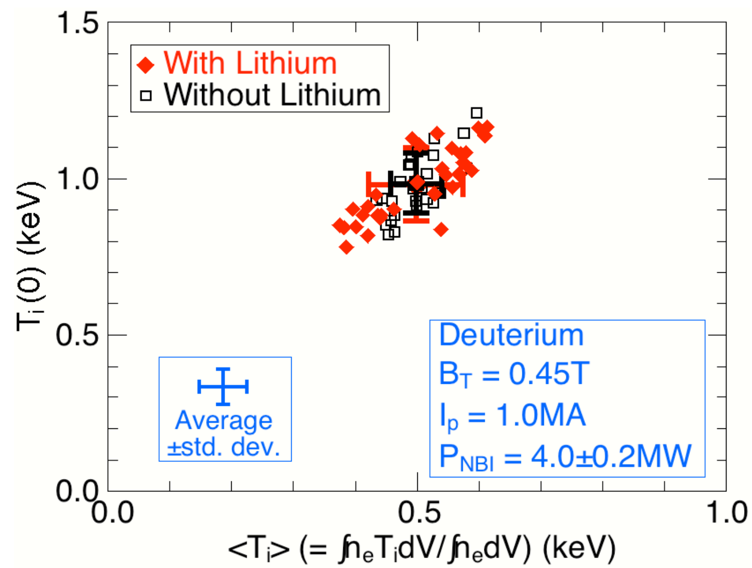


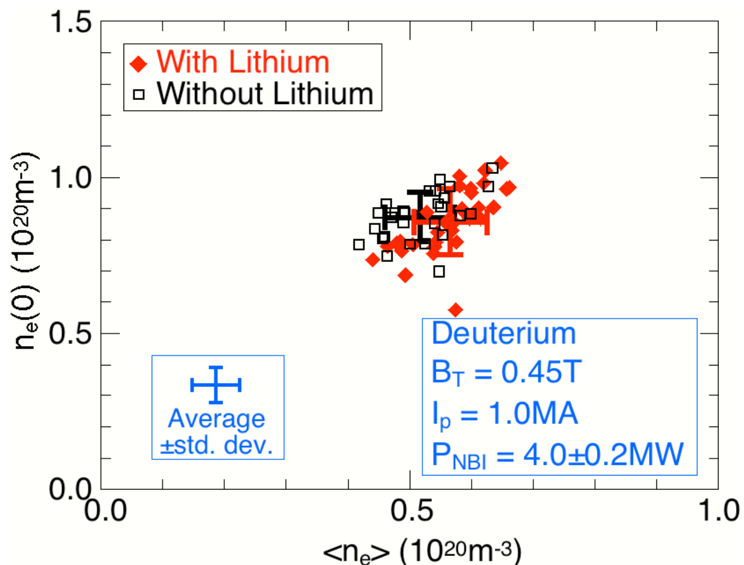
Non-lithium shots include data from experiments preceding lithium evaporation as well as reference shots on day of first lithium use

Data sampled at time of peak W_e

T_e Profile Broadens with Lithium but Central T_e, and Profiles of Density and Ions Largely Unaffected



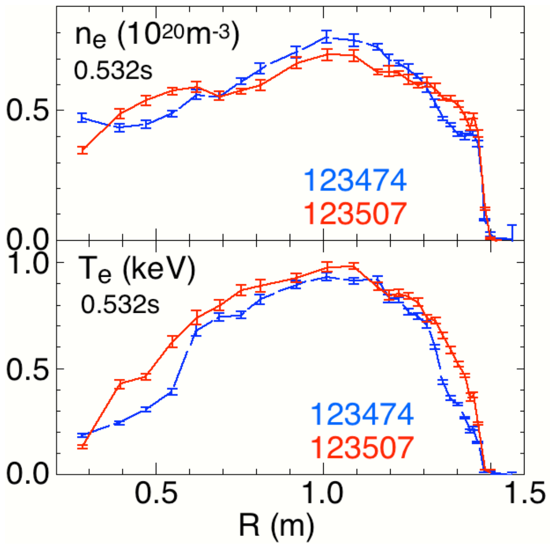




- Ion temperature from CHERS
- Shots with lithium reached peak W_e ~50ms later on average
  - Gas input was slightly higher
    2.3×10^{22} D *vs.*
    2.5×10^{22} D

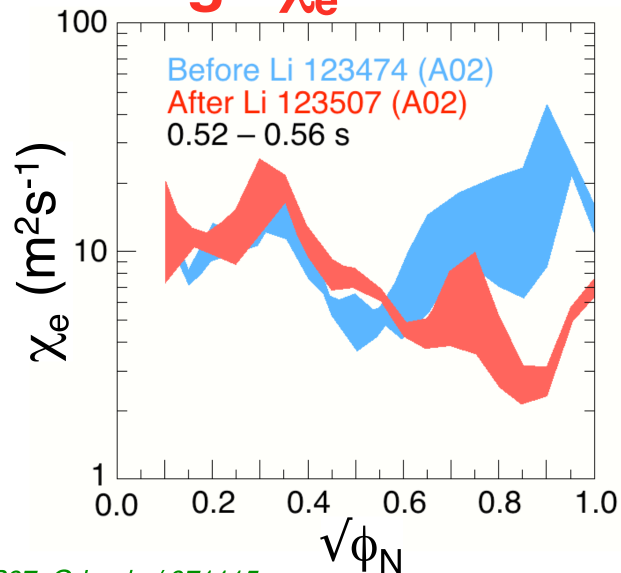
B.P. LeBlanc (poster TP8.064)

Broadening of T_e Profile with Lithium Reflected in Reduced χ_e in Edge Region

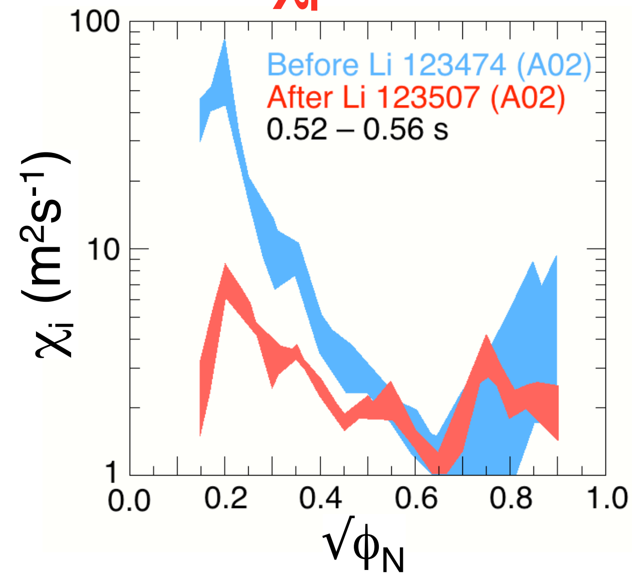


- On average there was little change in density with lithium, *but*
- In some matched pairs of shots with and without lithium, a broadening of the density profile occurred after lithium
  - TRANSP infers lower central χ_i as a result of reduced heating

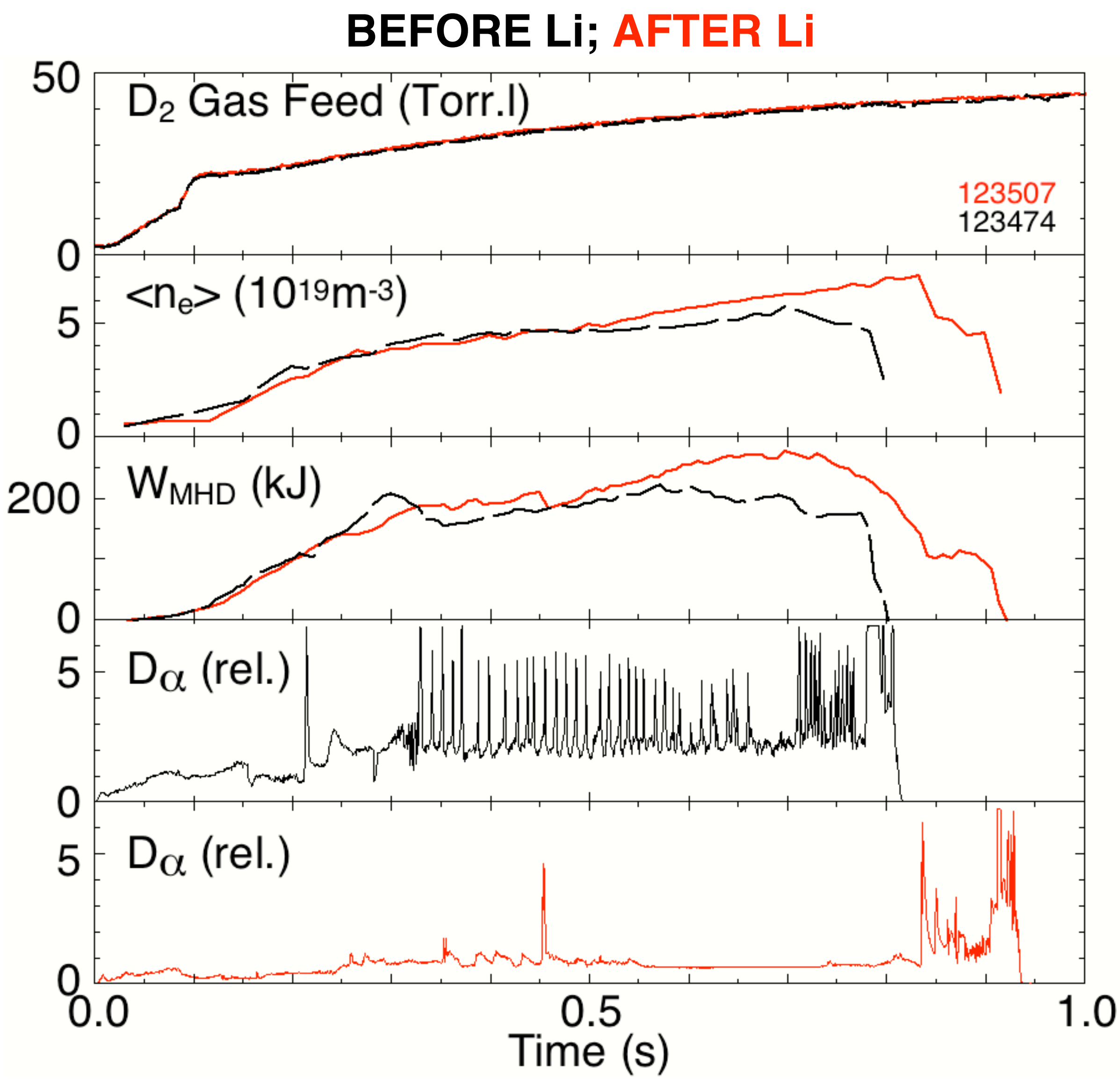
- **Edge χ_e decrease**



- **Core χ_i decrease**



ELM Behavior Significantly Changed by Lithium



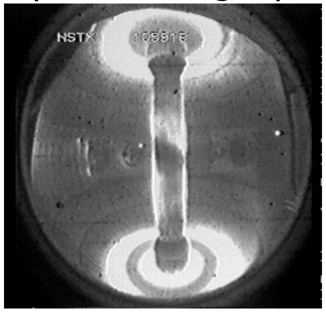
After lithium, D_α signal reduced *and*

Frequency of large ELMs greatly reduced, *including*

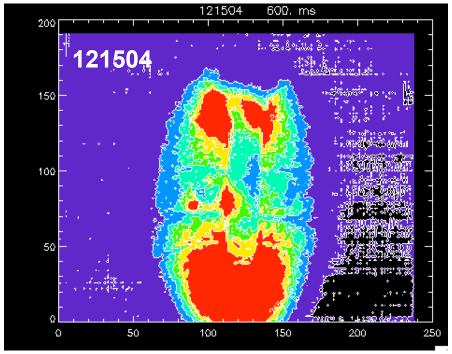
Long quiescent period

Edge Dα Emission Decreases Following Lithium Deposition

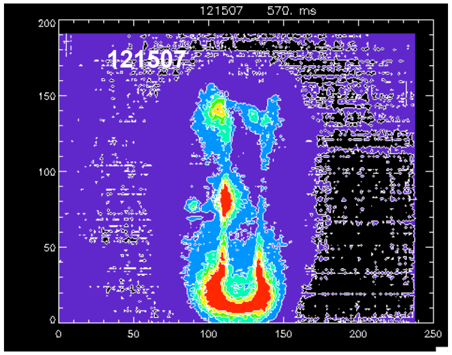
Plasma TV view (visible light)



TV D_α Intensity Contours (same scale, t = 0.6s)

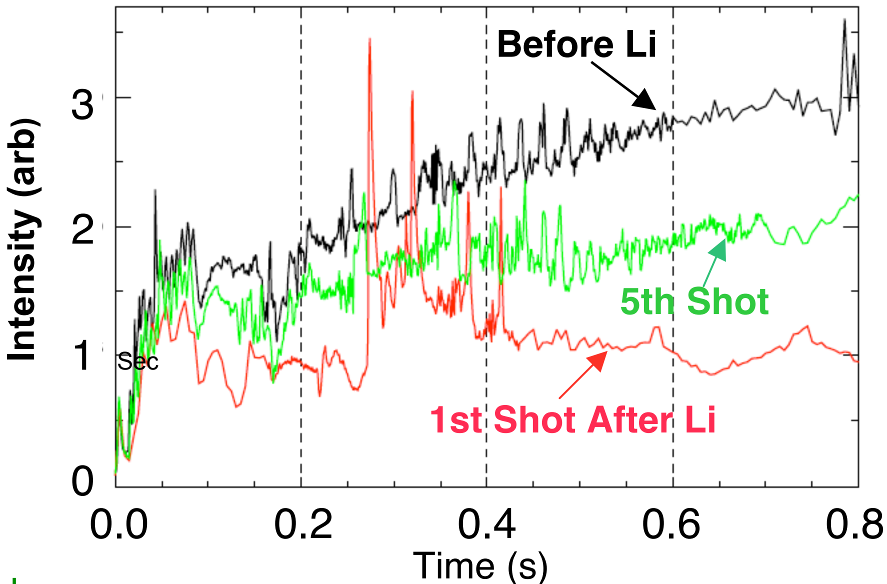


H-mode Before Li



H-mode Shot after 4.8g Li

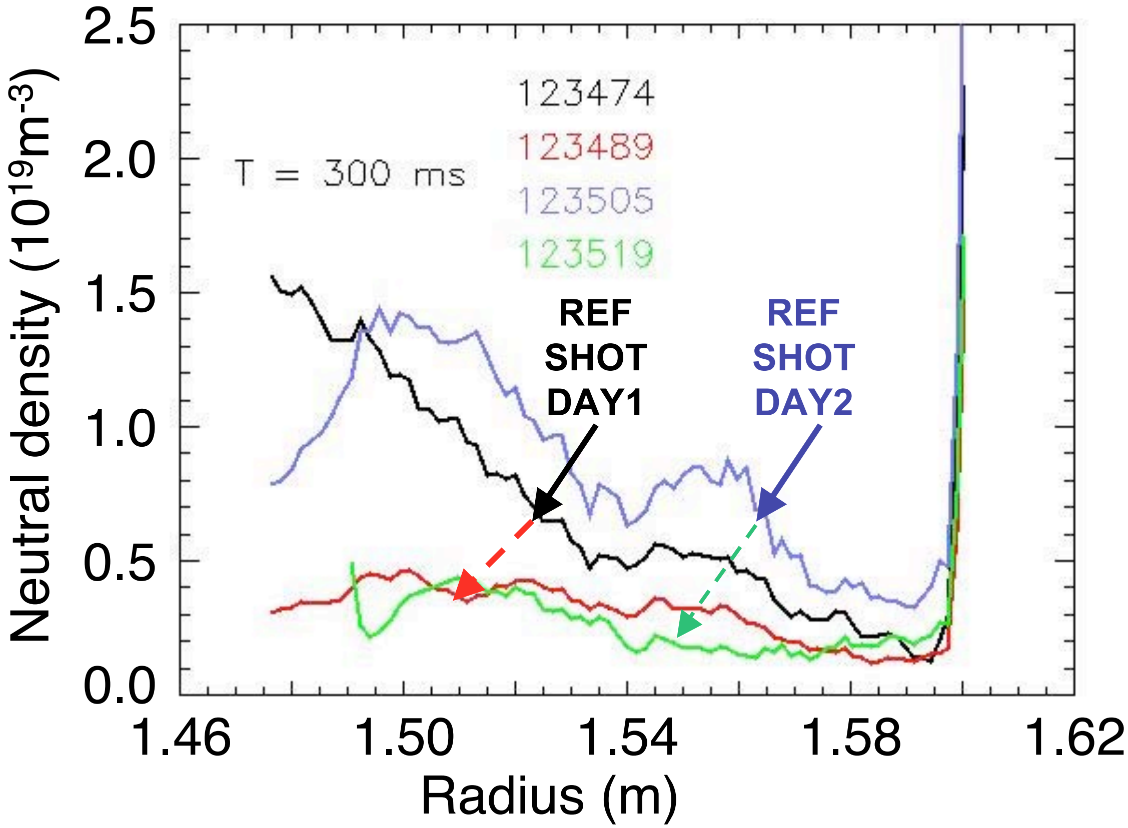
Spatially Integrated D_α-filtered Image



- **Integrated D_α reduced by factor 3 in first shot after lithium**
- **Remained lower in subsequent shots**

C.E. Bush

Edge Neutral Density Calculated from Dα Profile Decreases During Lithium Deposition



Lithium deposited before shot and running total

Shot	Before (mg)	Total (mg)
123474	0	0
123489	260	1876
123505 (Day 2) (+64 hr)	0	1876
123519	516	8349

- **Lithium strongly reduces edge neutral density by final shot of Day-1 but effect completely disappears by reference shot of Day-2**
- ***May indicate that lithium coating reacts with graphite substrate and/or residual gases***

P.W. Ross (poster TP8.073)

Mode Conversion Efficiency of Plasma Thermal EBW to O-Mode Increased with Lithium Deposition

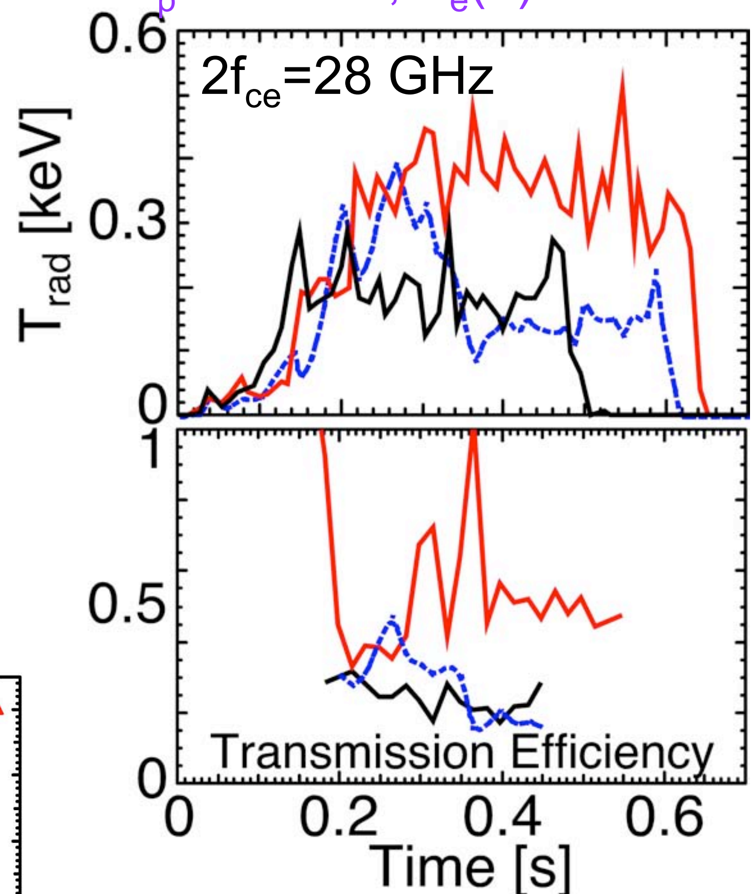
0 mg (0 mg/min) Li (124284)

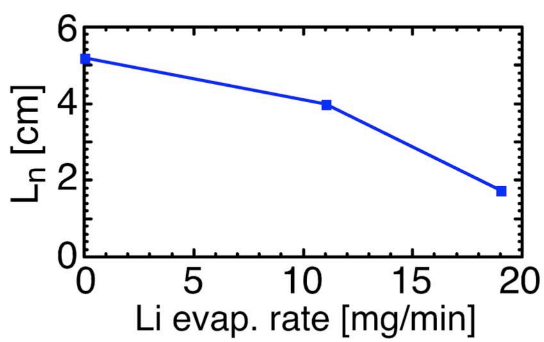
170mg (11 mg/min) Li (124290)

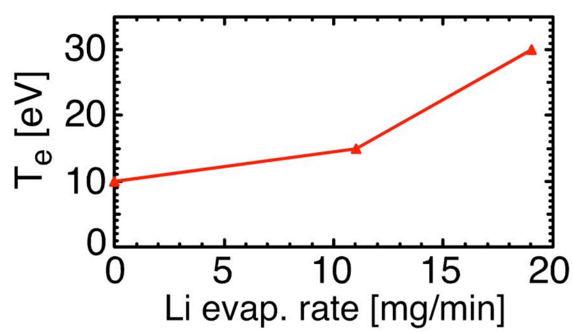
290mg (19 mg/min) Li (124309)

- Measured T_{rad} increased from 200eV to ~400eV
- Conversion efficiency increased:
  - ★20 → 60% for f_{ce} = 18GHz
  - ★20 → 50% for $2f_{ce}$ = 28GHz

I_p = 0.8MA, $T_e(0)$ ~ 0.7keV







- Lithium increases T_e, reduces L_n near B-X-O mode conversion layer

S. Diem, G. Taylor (poster TP8.103)

Lithium Coating of Carbon PFCs Produced Some Benefits to Operation and Plasma Performance

NSTX

- Lithium introduced as pellets produced a significant reduction in recycling and density in L-mode divertor discharges
- Lithium evaporated onto lower divertor and surrounding PFCs produced in H-mode divertor discharges:
  - Broader electron temperature profiles;
  - Improvement in total energy confinement;
  - Reduction or suppression of ELMs;
  - Reduced global recycling; *but:*
  - No significant, consistent reduction in density for same fueling;
  - Increased helium content resulting from evaporation during HeGDC
  - Increased frequency of discharges developing very high P_{rad}.
- Many experimenters requested lithium evaporation as a way to achieve repeatable conditions
- There were some deleterious impacts on diagnostics, notably gradual coating of the MPTS viewing window

Status and Plans

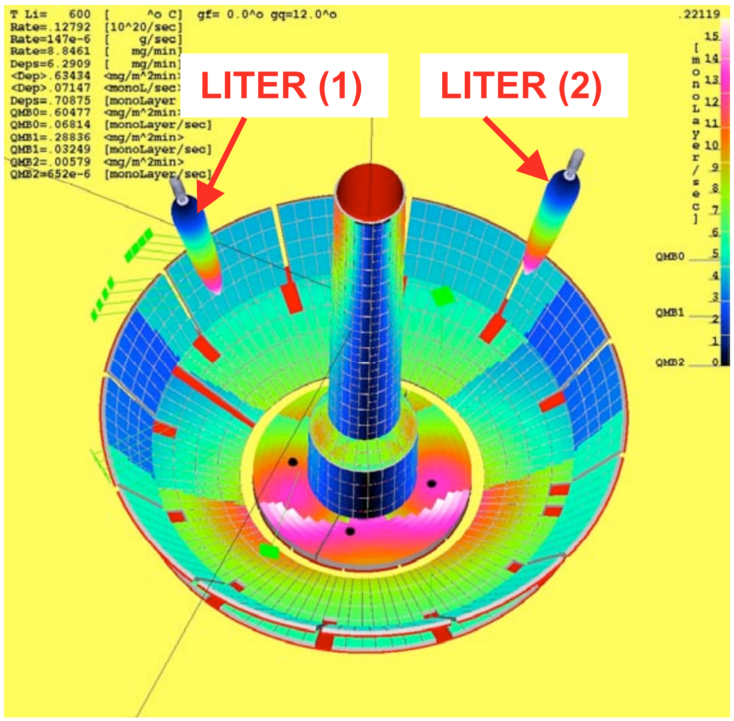
- Installing second lithium evaporator for coating entire divertor
  - Both will have shutters to stop deposition during the shot
  - Need to protect vulnerable diagnostic windows and prevent local buildup on PFCs
  - Plan to be ready for lithium experiments in 2008 run
- In collaboration with Sandia National Lab., currently developing a divertor module to provide a liquid-lithium plasma contact area
  - If laboratory testing of filling, wetting and control of lithium are successful, system will be installed next summer

Planning Liquid Lithium Divertor for Particle Control

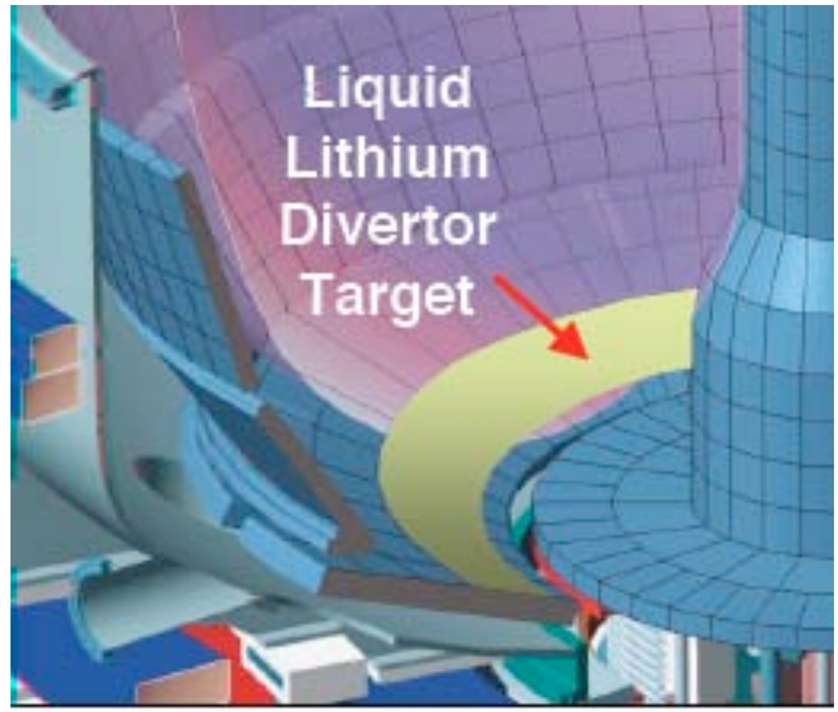
Unique Capability for Diverted H-mode

NSTX

- Install Second LITER for 2008



- Start LLD operation in 2009



- Optimize divertor in 2012
  - Higher power flux
  - Longer pulse
  - Operate with core fueling