The future for lithium conditioning in NSTX

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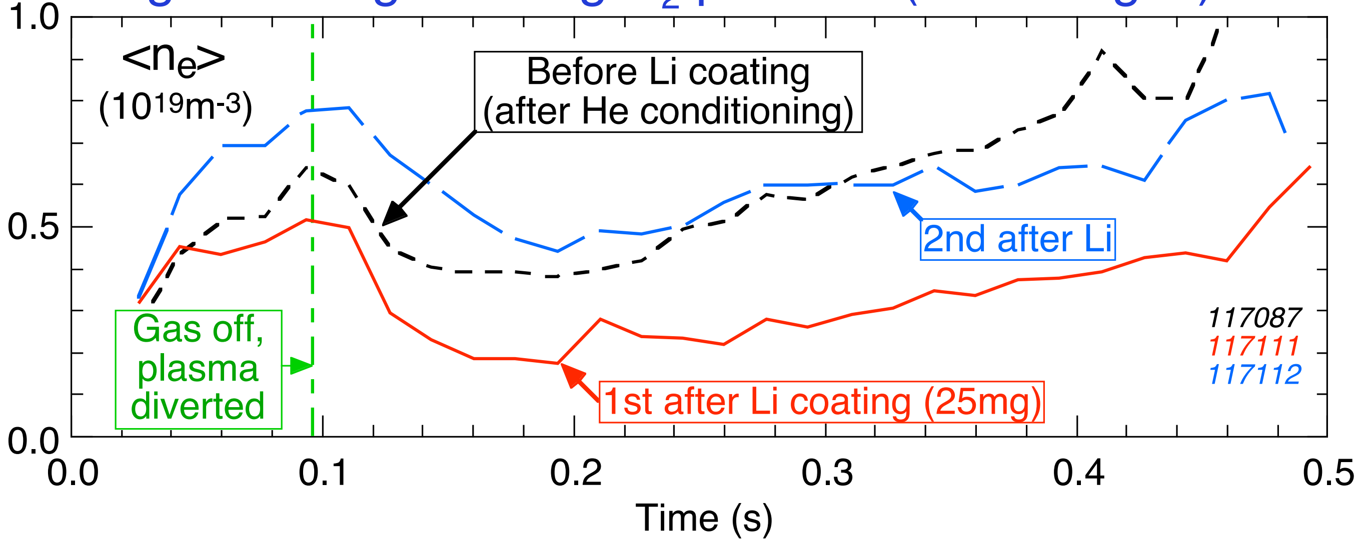
Lithium application has brought real benefits *but ... things will have to change for NSTX-U*

- Started with pellets in 2005 – painfully slow but effects intriguing
- Prototype LITER in 2006 – limited capability but worth developing
- Reliable LITER re-aimed at lower divertor in 2007
- Dual LITERs in 2008; first use of powder dropper
- Lithium dependence undeniable in 2009 – 80% of shots by end
- The LLD in 2010: lithium to the max; supplement with droppers
- Cold-turkey in 2011
- ***Recovery is possible – and desirable***

Lithium from pellets produced a density reduction in L-mode but benefit short-lived

- Injected Li pellets into 10 ohmic He discharges: total **~30mg of Li**
  - Following sequence of ohmic He cleanup at outset
- Ran specifically designed NB heated plasma with minimal fueling

LSN discharges, 0.8MA, 0.45T, 4MW NBI, L-mode;
gas fueling: ~3.5mg D_2 per shot (no HFS gas)



- Density after gas puff reduced by factor >2 after lithium coating
  - After pumpout, rate of density rise less than NB fueling in LSN case
- Effect had dissipated on second similar shot

Development of LITER system in 2006 changed the course of NSTX operation and its overall program

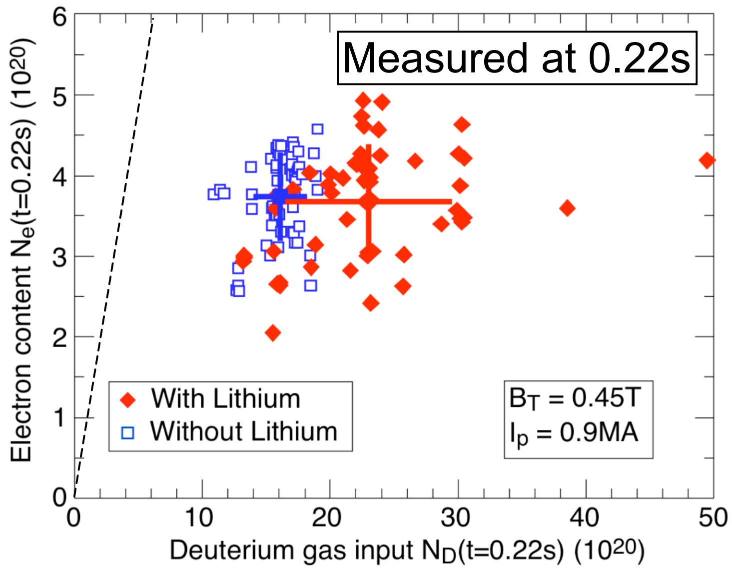
- Major effort by Mansfield, Timberlake, Kugel, Roquemore, Kaita, Majeski ...
- Experiments, now in H-mode (& RS), revealed many of the familiar benefits
  - Higher *central* T_e, T_i; global τ_E improved
  - Reduction in density for same gas input; reduced D_α and oxygen emission
  - Reduced poloidal flux consumption
- Benefits transient and not apparent unless ~400mg deposited
  - Oxygen reduction did persist for several days
  - Clear evidence for migration of lithium away from divertor strike points
  - Concerns about passivation by H_2O, CO_2; intercalation into graphite
- *We concluded we needed bigger artillery and to aim at the target*
- LITER-1d in 2007: evaporated ~80g into NSTX
  - ELMs suppressed ⇒ impurity accumulation and radiative collapse in ~1s
- Dual LITERs with bigger barrels & shutters in 2008: 108g on PFCs in 2008
- Increased to 285g in 2009 – 80% of discharges with evaporation
- Finally >800g in 2010 – and kicked our previous boron habit

The benefits of lithium blinded us to the lingering issue that we still could not control the density

- Lower density was achievable early in discharges with lithium but likelihood of deleterious locked modes increased

⇒ We increased the gas fueling to compensate

- Heavy gas puffing is used in NSTX to allow very fast current ramp-up

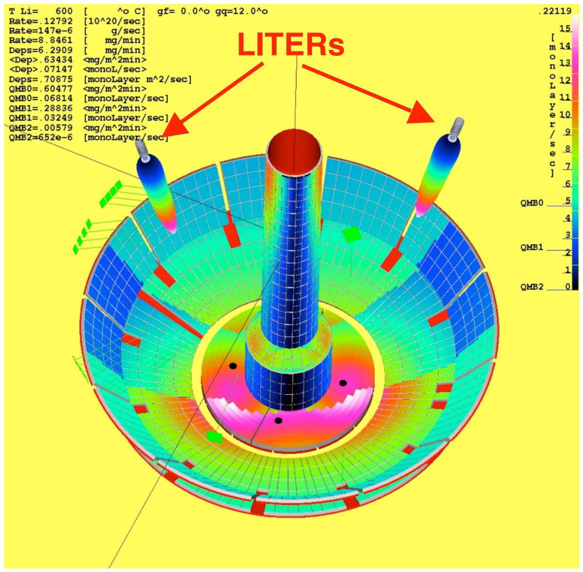


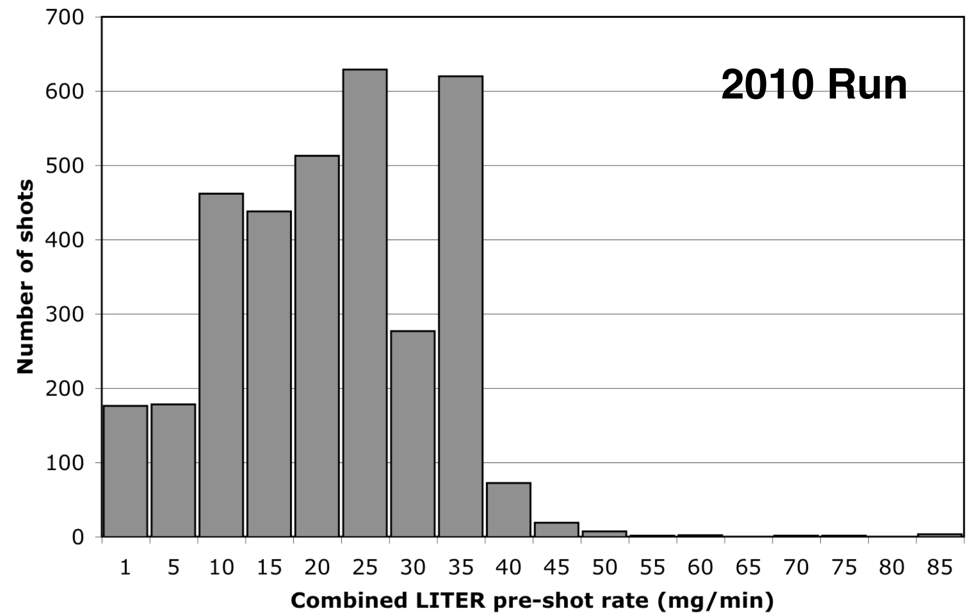
- D_α camera showed lower neutral D density at outboard midplane with Li
- Also reduced density early after running He and RF conditioning discharges

- 2 × 10^{21} D would need only ~2.3mg of lithium to form LiD
  - Not much of the applied lithium actively contributes to the pumping
- **Had planned to develop scenarios with less fueling in 2011** (sigh)
- Upgrade will have Vs to allow varying I_p ramp rate to see if that helps

Lithium can become contaminated by reactions with residual water, mainly during evaporation

Modeled deposition pattern



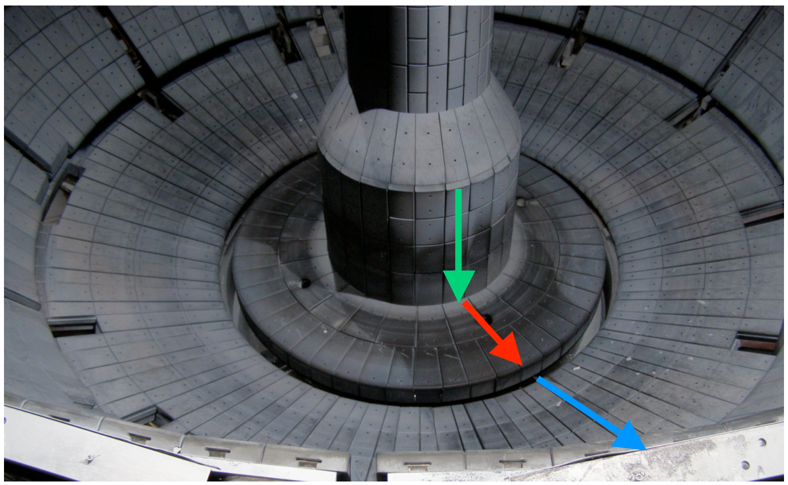


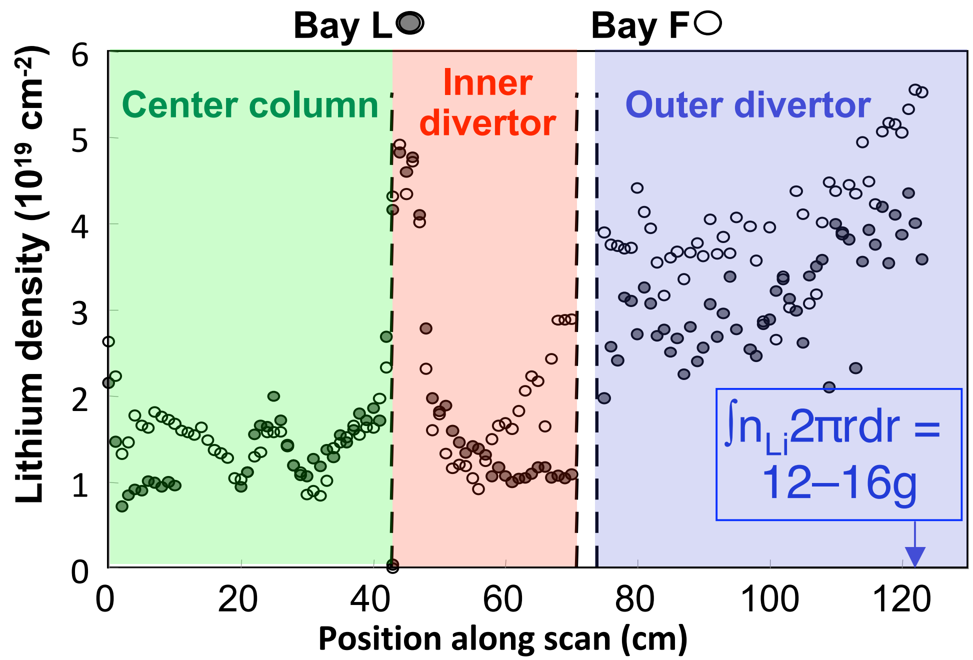
- Deposition rate on lower divertor 1 – 20 x 10^{15} Li $cm^{-2}s^{-1}$
  - Water impingement on IBD equals 1.3 x 10^{15} $cm^{-2}s^{-1}$ Li rate at ~3 x 10^{-7} Torr
- RGA 17–20 AMU equivalent pressure up to 10^{-6} Torr during deposition
  - Difficult to reconcile RGA with ion gauge pressure (which is usually lower)
- **To minimize contamination, keep NB valves open during evaporation!**
- No evidence from QMB for oxidation of the bulk lithium *after* evaporation
- Plasma accesses deeper lithium below layer oxidized by thermal molecules

Lithium rapidly migrates from where it is applied under plasma fluxes

- NRA for Li and D performed on tiles *as removed from vessel* at end of 2009
- Measures Li:C atomic ratio to depth ~15μm: data always < 1 - *why?*
- Most within ~2μm of surface: little evidence for sequestration within graphite

Scan across lower divertor





- Lithium remaining on inner divertor: peak ~0.6, average 0.2 mg·cm^{-2}
- Total deposition estimated at ~6 mg·cm^{-2} (280g over 1.2m diameter)
- Most of residual Li probably deposited while emptying LITER at end of run

⇒**MOST deposited lithium removed from OSP region on each 1s shot**

In 2010, we had high hopes for the LLD but ...

- This was another major engineering effort *and* involved collaborators
  - Thanks to R. Nygren and SNL team, S. O'Dell and PPI, Kugel, Ellis, Kaita, Viola, Schneider, engineering and NSTX machine techs
- We encountered many problems with the heaters
  - One plate failed in Feb before the run started, two others in Aug
  - Tried air heating but only reached ~200°C and developed leak at end
- Filling the LLD required evaporating large amounts of lithium
  - Only ~7% of evaporated lithium ended up on the LLD
  - 15g before the first plasma, 22 days with >10g applied
- It was very difficult to separate the effects of the LLD from those of the lithium background
  - With all that lithium deposited, its effects were more persistent
  - Most operation with the LLD was similar to that with Li on C
- Plasma on liquid lithium effects were only observed with OSP on LLD
  - Heating by plasma itself raised surface above lithium melting point
- Argon vents to repair LITER shutters may have contaminated the lithium

What have we learned of importance to NSTX-U?

- Unless lithium can control the density, it has limited use in NSTX-U
  - The gain in confinement is welcome but the impurity price is high (with carbon)
- Evaporation will not be able to apply enough lithium to last 5s
  - It required a lot of lithium to service a 1.5s pulse: the lithium is mobile
- Too little of the lithium introduced by evaporation is effective
- The shutters are a weak link in the present application scheme
- Large quantities of lithium in the vessel are a real liability
  - Any vacuum problem escalates into a major setback
  - Despite a big effort, the LLD fell short of expectations on performance
- A flowing lithium system in the vessel would require a huge effort
  - There are difficulties in wetting and distributing lithium over surfaces
  - How can spent lithium be removed from plasma contact?
  - The lithium bearing surfaces would probably have to be removable
- **Do you want NSTX-U to study ST physics or lithium technology?**

What should be the role of lithium in NSTX-U? – my current view

- **Molybdenum on the divertor might help alleviate carbon influx**
  - *It is (personally) disappointing we were unable to investigate this*
  - There will still be a lot of carbon around in NSTX-U however *and*
  - High-Z impurities were also a problem when ELMs were suppressed
- **Targeted flash evaporation of lithium would be more effective**
  - Leverage LTX development in this area
  - Investigate masking lithium stream at evaporator
  - Be vigilant about vacuum conditions during evaporation
- **Don't attempt to use a flowing lithium system (at least initially)**
  - This would dominate and potentially derail the NSTX-U program
- **Use continuous resupply of lithium to SOL near divertor**
  - It puts the lithium where it's effective
  - Less off-target application and collateral damage
  - **Granule injector:** *disappointing that trial was thwarted → EAST*
  - **Directed powder accelerator**: *needs collaborator development*