# Lithium Research - Progress and Plans

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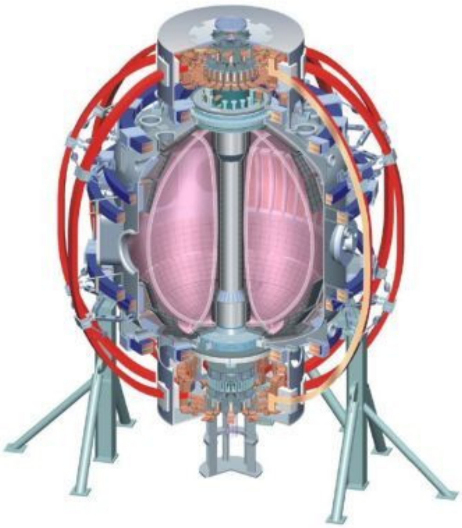
**Charles H. Skinner, Robert Kaita,**
**Michael Jaworski, Daren Stotler**

*for the NSTX Research Team*

**NSTX PAC-29**
**PPPL B318**
**January 26-28, 2011**



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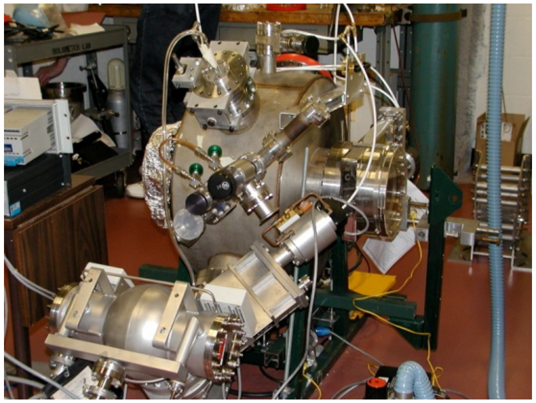
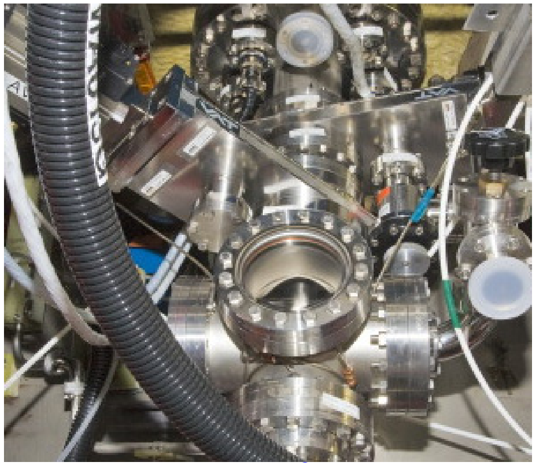
# NSTX lithium research is an integral part of a program to assess viability of Li as a PFC concept for magnetic fusion

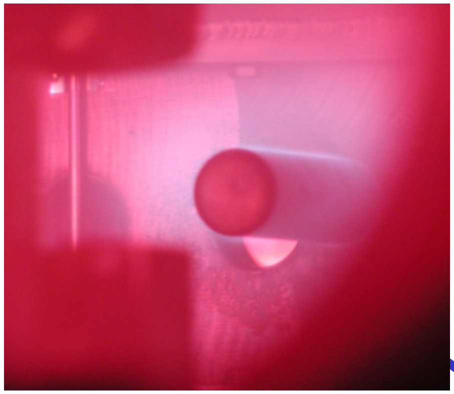


PFC test facility.

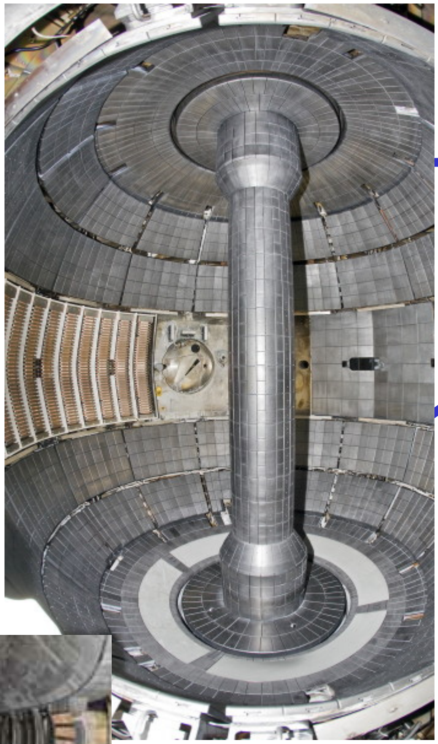


NSTX probe, Purdue collaboration, modeling…

LTX now operating:
Li evaporated into
helium glow ->
All-metal walled
comparison to NSTX.



NSTX: Only diverted,
NBI-heated tokamak
studying Li at present.
LLD installed FY10.



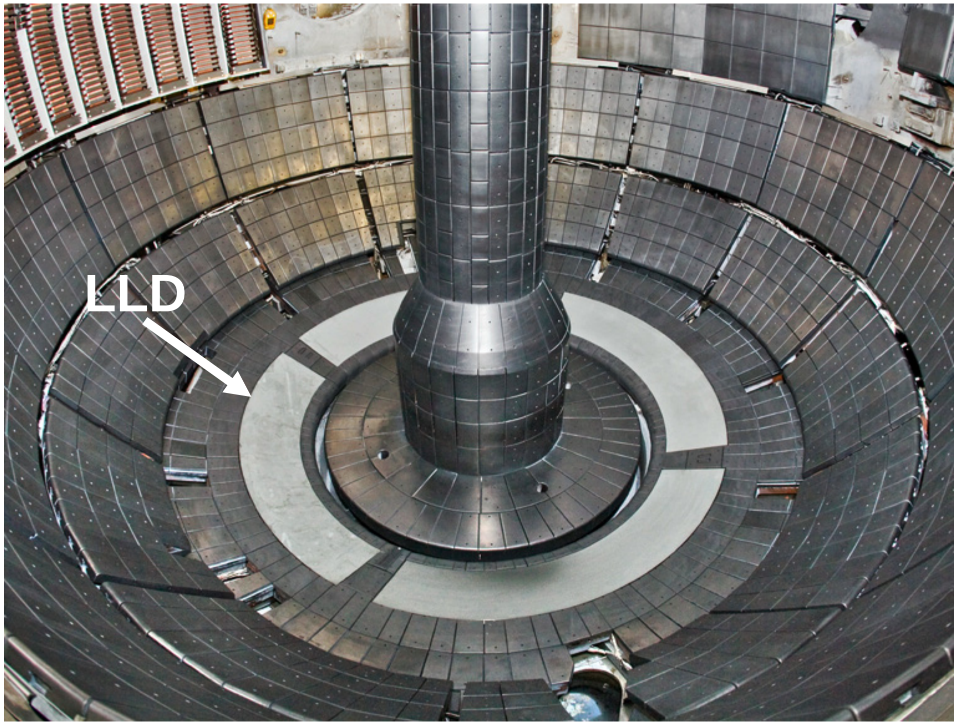
EAST / NSTX: Li collab.
achieved H-mode !

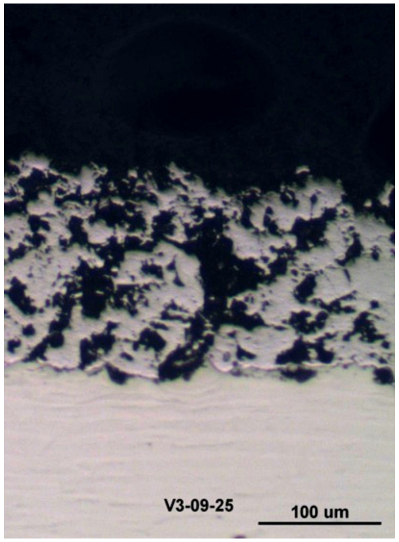
NSTX
Upgrade,
Fusion
next-
steps.

# Motivation for usage of Lithium

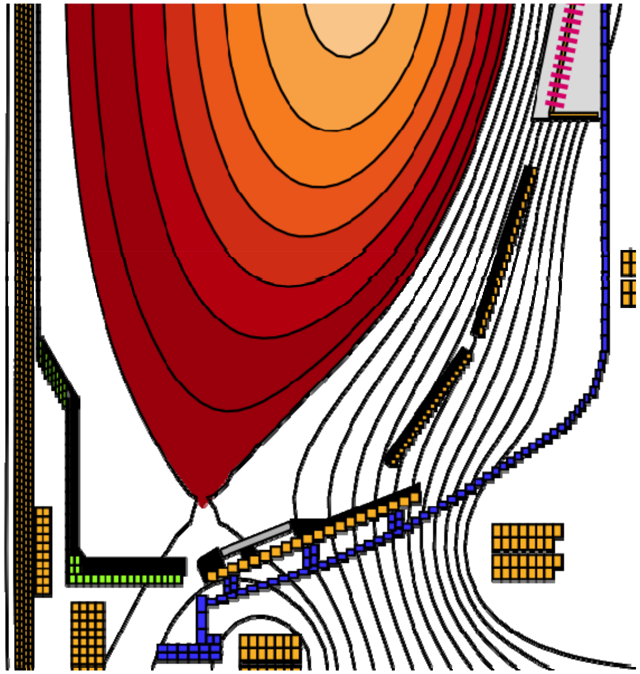
- NSTX lithium program on diverted H-mode plasmas grew from major benefits with TFTR and CDX limiter plasmas.
- Dual lithium evaporators (LITERs) are routinely used to deposit lithium on the NSTX lower divertor between discharges.
- Liquid Lithium Divertor (LLD) installed for FY10 to provide volume D pumping.
- Significant lithium benefits: reduced D recycling, significant D ion pumping, ELM suppression, improved confinement (+20%-30%) and stored energy, improved plasma purity (CDX), faster shot duty cycle (40% more shots/week), no intershot GDC or boronization needed.
- Long term potential benefits for fusion include:
  - Divertor pumping over large surface area for high flux expansion power exhaust
  - High-heat flux handling
  - No neutron damage and erosion lifetime issues in future fusion reactors.
  - OFES research theme II: “Materials in a fusion environment and harnessing fusion power”
    – relevant to FSNF geometry and PFC materials.

# LLD successfully installed and utilized in FY10





LLD surface cross section: plasma sprayed porous Mo



Outer strike point on LLD
EFIT02 142512 @ 547 ms

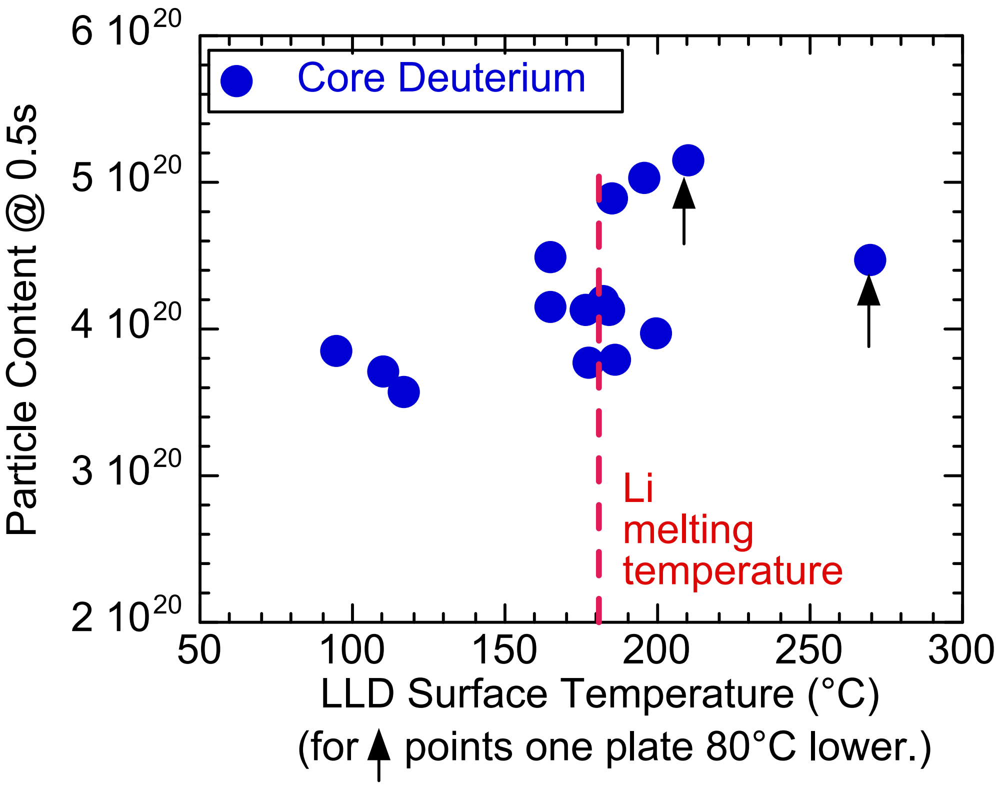
- Liquid Lithium Divertor (LLD) aims to provide volume D pumping capacity (> solid Li surface) for longer pulses with potential for handling high heat flux.
- LLD installed, commissioned and over campaign filled with 67 g-Li by evaporation, (twice that needed to fill the porosity). Strike point controlled on LLD.
- LLD surface temperatures 160 – 350+ °C.
- No major Li or Mo influx observed even with strike point on LLD.

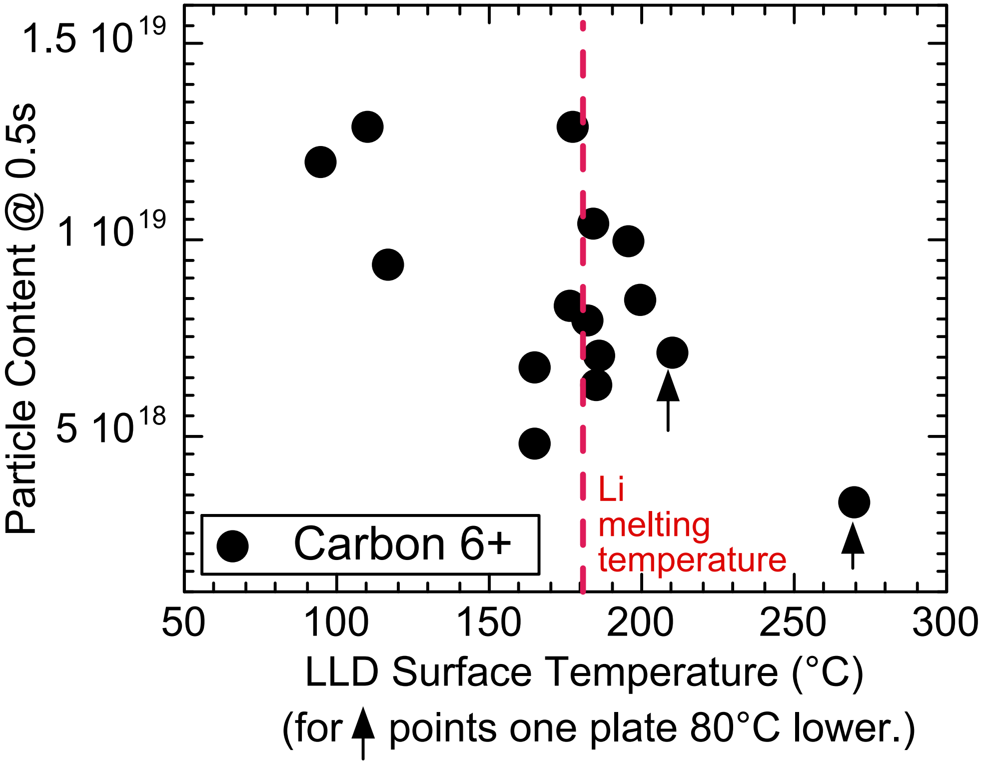
# FY10 Li /LLD operational summary

- Rapid startup with Li conditioning and without boronization.
- Total of 1.3 kg Li evaporated (2x 2009 level), extensive lithium coverage of PFCs.
- Devoted 11 run days, 6 XPs, 452 discharges to LLD commissioning and characterization.
- Performed 0.6 run day for increased Li delivery via Li powder injection.
- Explored plasma D content and gas balance vs.
  - LLD Li fill,
  - LLD temperature,
  - strike point location,
  - fueling,
  - divertor gas injection etc…
- Porous Mo (LLD) and ATJ samples exposed by PMI probe, retrieved and analyzed.
- 2-color thermography and high density Langmuir probe array commissioned.

# LLD pumping similar above or below Li melting temperature

**PAC27-13**



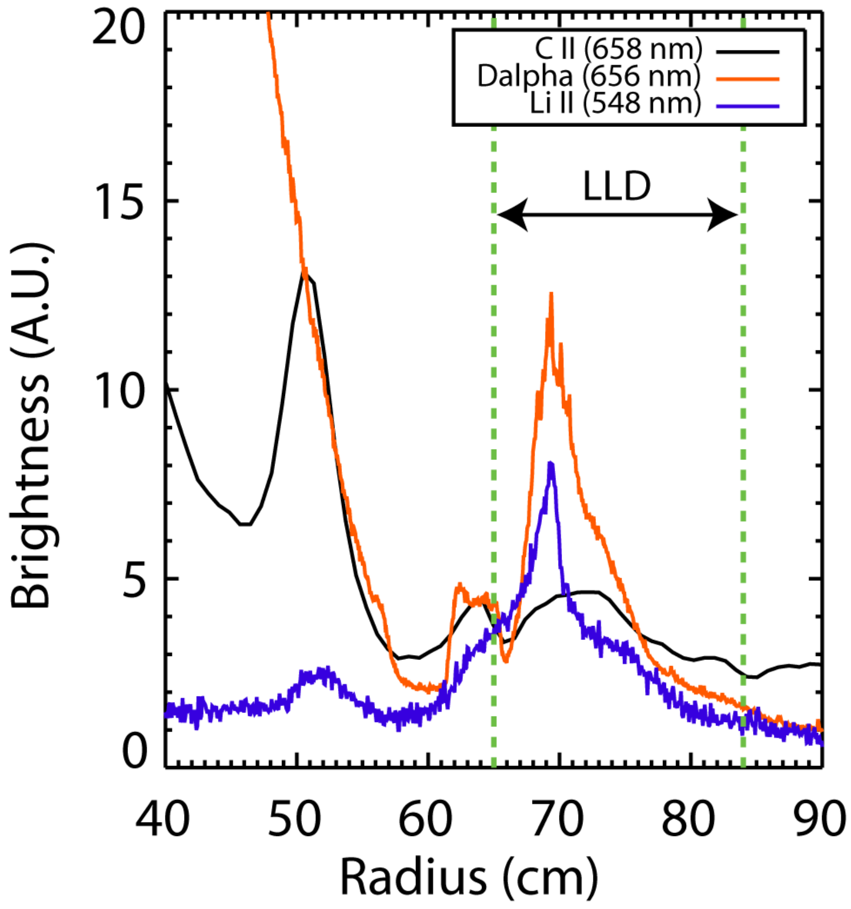


- Constant deuterium fueling for LLD 100% Li fill conditions, 4 plates air heated.
- As LLD surface temperature transitioned from solid temperatures to the liquid regime, the plasma electron and deuterium content remain relatively constant.
- Core carbon C6+ content decreased - may be due in part to increased ELMing and edge turbulence.

- No systematic trend in D-alpha, wall inventory, or ion pumping with a transition above the Li melting temperature.

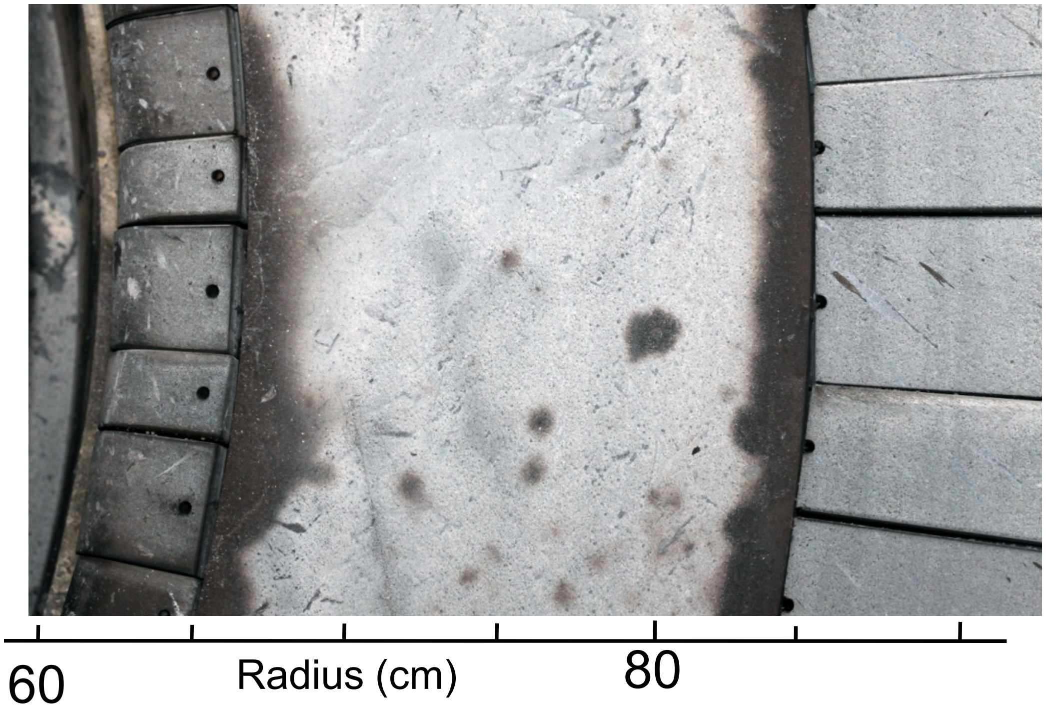
# LLD surface is not pure Li

**PAC27-15**



- Carbon, lithium, and deuterium emission extends across LLD surface after overnight Li evaporation.
- No marked change at LLD location

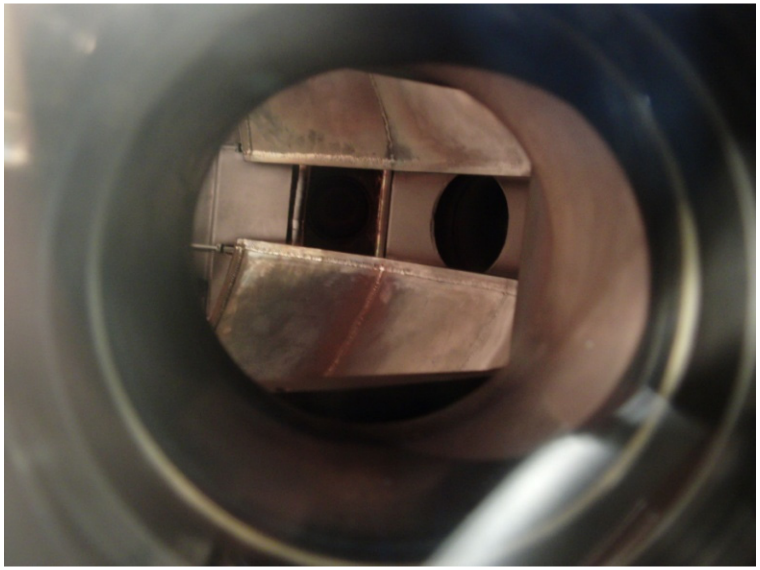
LLD after vent at end of run



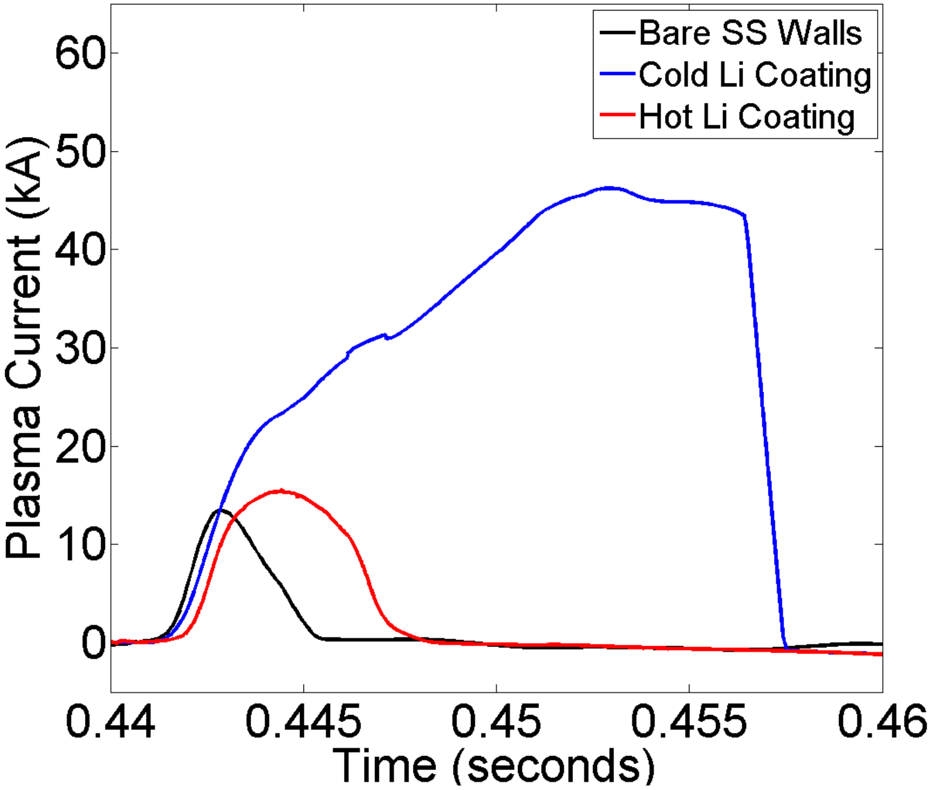
- LLD surface converted to $Li_2CO_3$ following vent
- LLD edges exhibit evidence of sputtered graphite from plate to graphite tile (vessel-ground) arcing.
- Acetic acid tests on the LLD after run suggests that Li does wick into Mo pores and is depleted from the surface at blackened region.
- Reactions with residual gasses also likely

# Full metal wall data from LTX shows thin liquid film reacts rapidly with residual/background gasses

- LTX is a full high temperature, high Z wall operation of a tokamak
  - lithium evaporated into 5 mTorr helium fill to disperse coating.



- Deposition rate ~0.75 g/hour/evaporator
  - 3 hour duration
  - est. 1.6 micron average thickness.
- Thin liquid lithium coating darkened rapidly
  - indicative of reactions with background gases or oxidized substrate
  - no visual evidence of metallic surface.

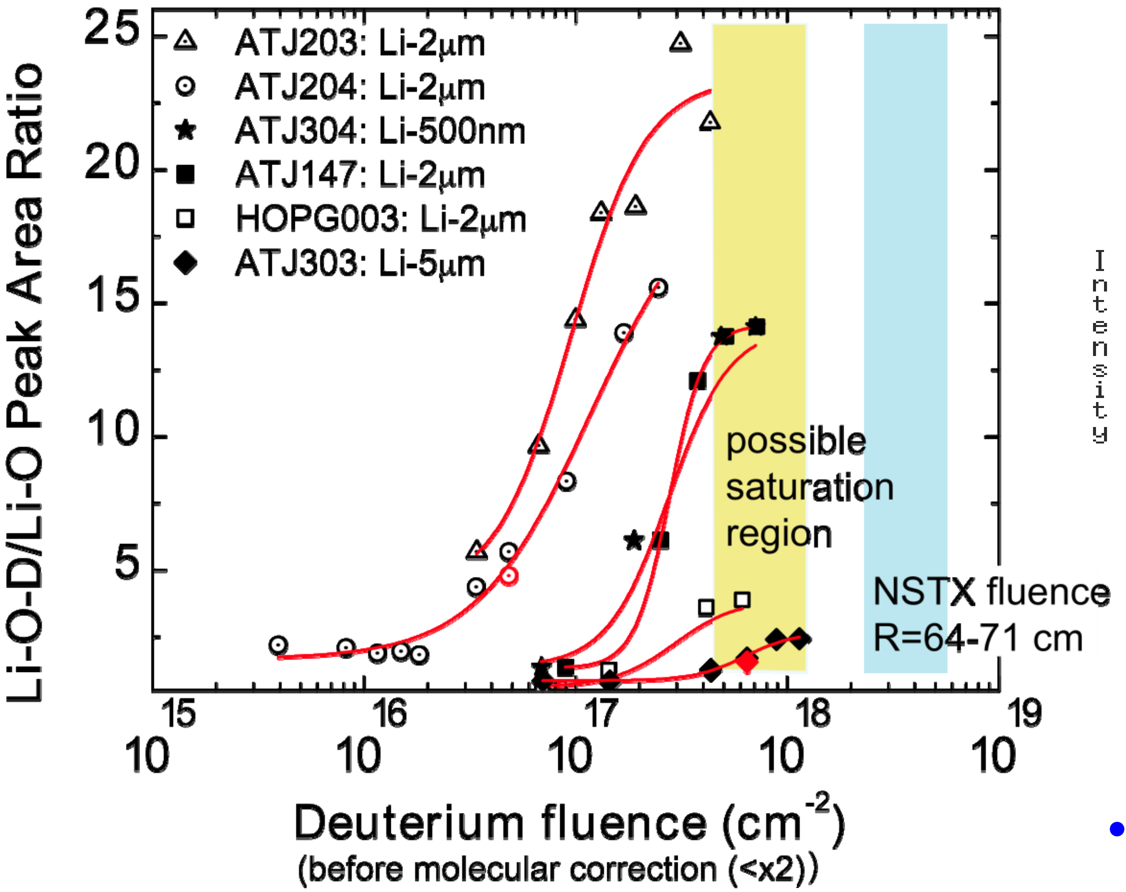


- Hot (300 °C) shell with thin lithium coatings does *not* exhibit reduced recycling
  - but strong lithium emission observed
  - relevant to NSTX LLD operation.

# Lab analysis of NSTX exposed samples (Purdue U.)

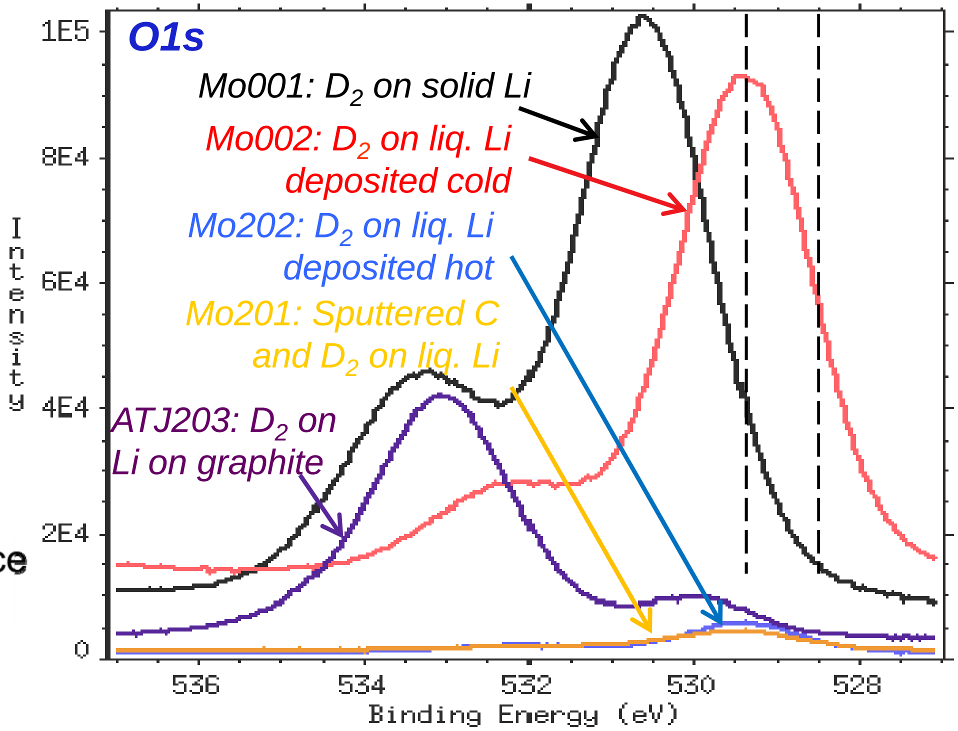
**PAC27-14, 15**

## Deuterium saturation of Li



- Modeling by the TBDFT code showed the probability for D to bond to a Li-C complex is 3 x larger than to C

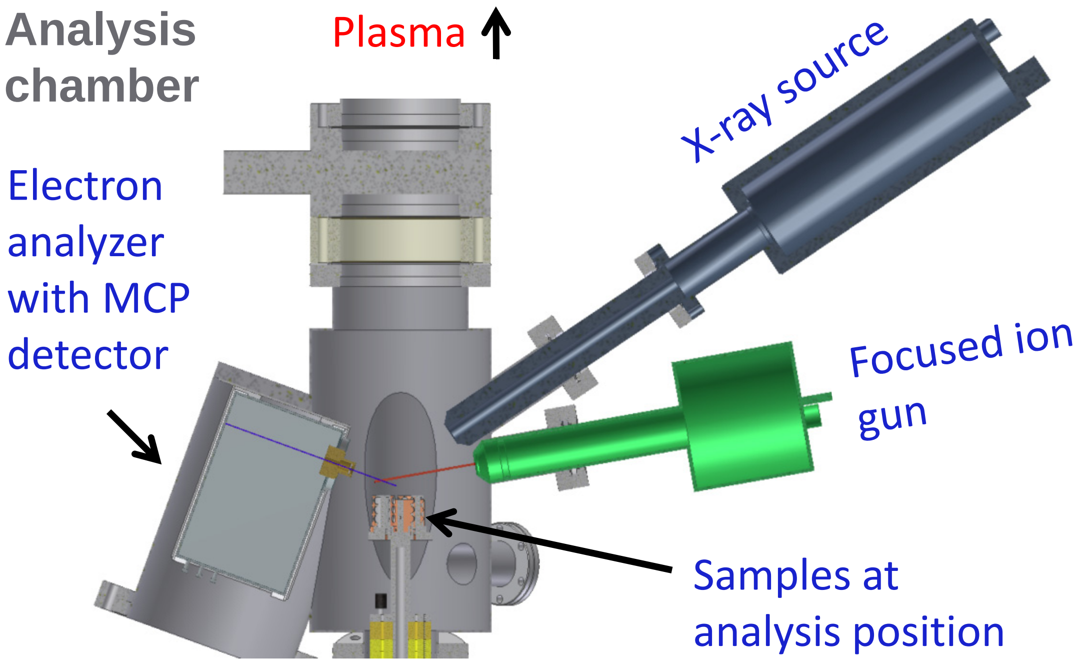
## XPS O1 spectra for the LLD samples 30 mins $D_2$ irradiation of Li on:

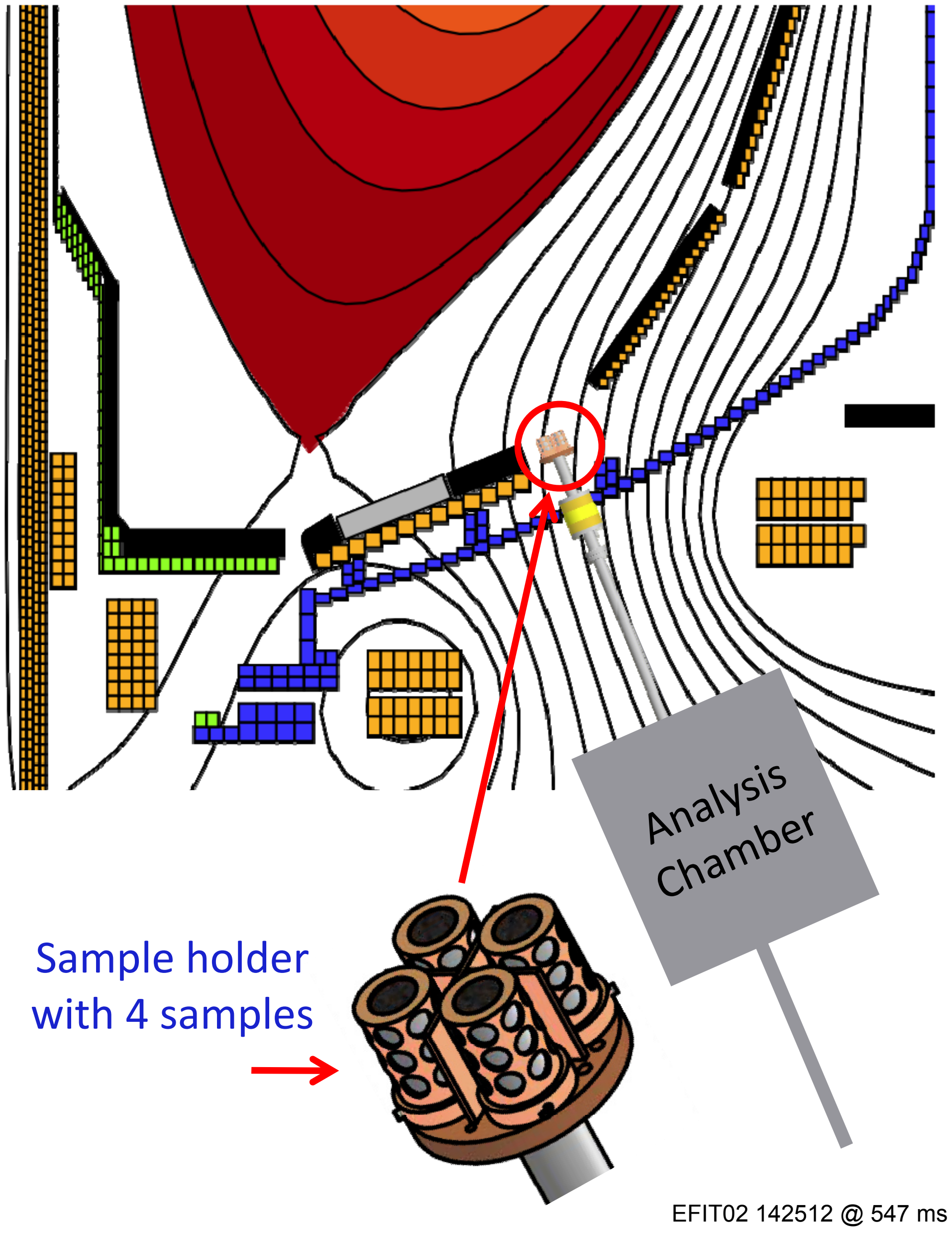


- XPS O1s spectra show changes in surface chemistry with D irradiation of Li deposited on cold / hot / C contaminated Mo and graphite.
- Suggests Li on Mo is interacting with D and diffusing into Li.

# MAPP probe will be installed for FY11-12

- MAPP is the first in-vacuo surface analysis diagnostic directly attached to a tokamak, capable of shot-to-shot chemical surface analysis of material samples (solid Li, liquid Li, Mo etc).
- MAPP will enable the correlation of PFC surface chemistry with plasma conditions and point the way to improved plasma performance. (R12-1)

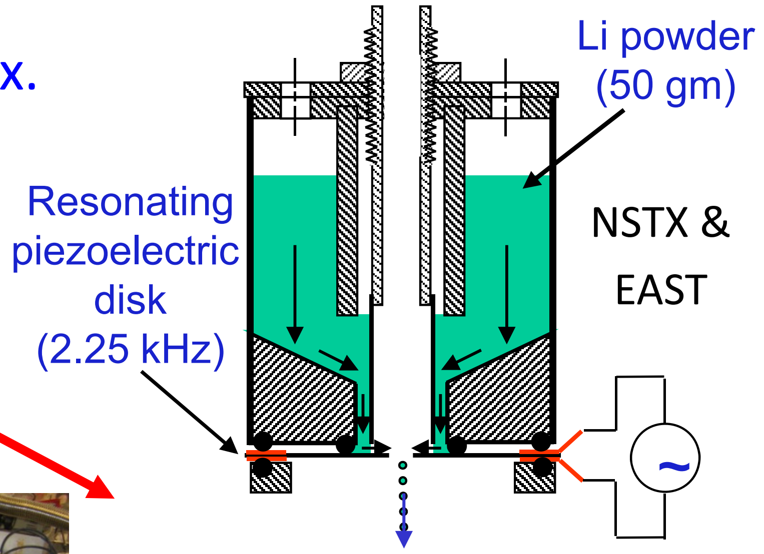




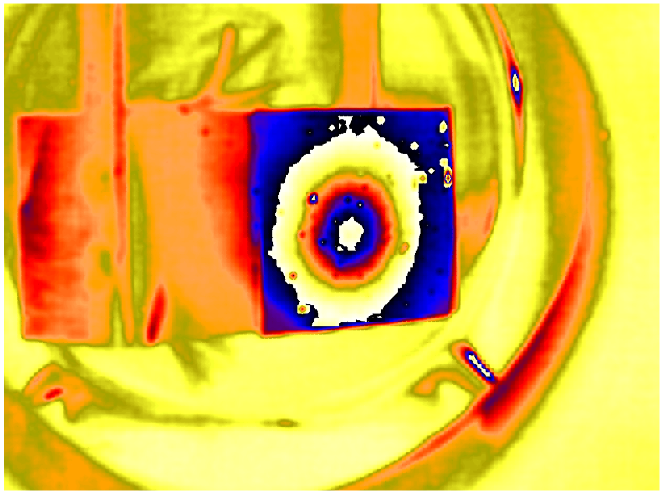
# Lithium Technology developed for NSTX needs

- R&D continuing for LLD performance at high heat flux.
- Continuous Li replenishment systems:

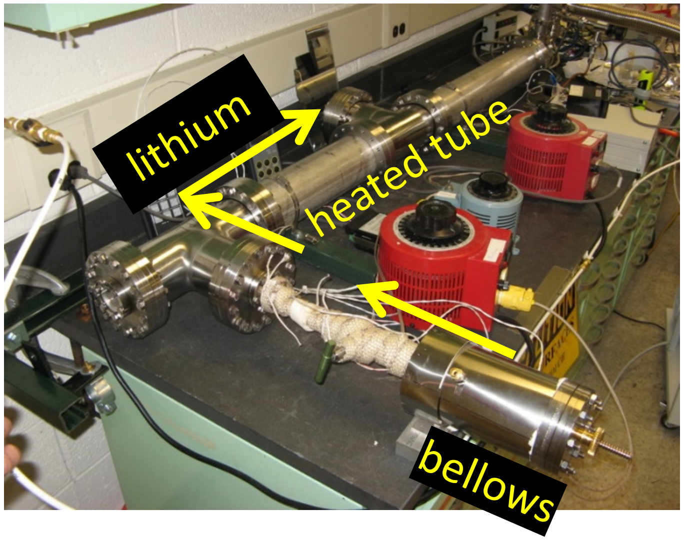
Li delivery by: powder → granules



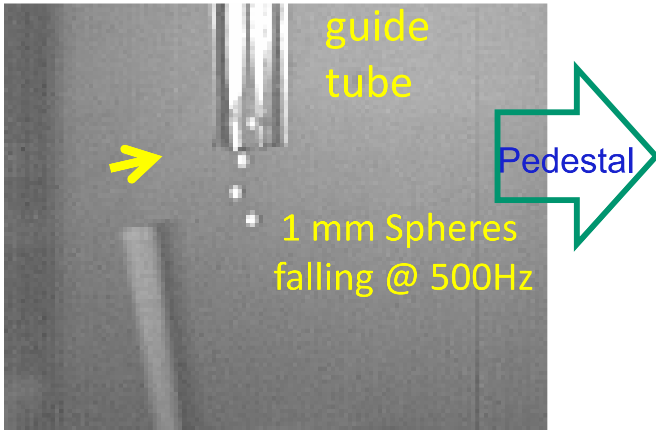
High heat flux test



False color image of LLD sample during NB exposure T ≤ 225 °C @ 1.5 MW/m$^2$ - 3s. Potential PFC for upgrade



10 g of molten Li moved 1.1m in vacuum and ejected 7.6 cm from nozzle



500 Hz Impeller Rotating @ 95 m/s

Midplane injection for ELM pacing

# Plans for FY11-12 Lithium Research:

- Commission MAPP probe.
- Develop plasma shapes that move strike point progressively closer to MAPP.
- Measure fueling efficiency and recycling.
- Compare MAPP results to laboratory experiments and modeling.
- Assess Mo tile performance with lithium (if tiles are present).
- Assess ELM pacing with lithium granules at midplane.
- Explore continuous Li delivery for long pulses with Li powder & granule injector.
- Investigate reactions between evaporated lithium and plasma facing materials and residual gases in NSTX.
- Assess diffusive Li evaporation to upper vessel to reduce impurity influx.
- Obtain results for: R(12-1): Relate core plasma performance to Li-coated PFC conditions using materials analysis and particle probe (MAPP).

# Initial planning for FY13-14 outage period

- Complete analysis, publication of FY11-12 data.

- Design, analysis activities preparing for post-Upgrade ops:
  - Design new particle pumping systems – new LLD ?
  - Analyze possible LiTER improvements in efficiency, reliability, shuttering
  - Scope/design new divertor/PMI/LLD diagnostics
  - Explore liquid Li wetting, heat removal technologies.

- Collaborations at other facilities e.g.:
  - LTX – no-carbon comparison to NSTX
  - EAST assess Li PFCS for very long pulses.

- Fundamental studies of plasma-lithium interactions with new surface analysis facilities at PPPL and Princeton University.
  - Investigate lithium pumping of deuterium vs. surface contaminants, temperature, and substrate in controlled laboratory plasma coupled to analysis facility.
  - Measure, model D diffusion in solid and liquid lithium.

# Summary

- Li conditioning reduces recycling, suppresses ELMs and improves stored energy of diverted plasmas. Also enables faster shot cycle.
- LLD implemented in FY10 to test D pumping in liquid Li.
- LLD surface temperature raised above Li melting temperature,
  - no significant Li or Mo influx.
- So far D pumping / performance similar to lithiated graphite.
- Spectroscopy indicates surface is not pure Li – this can affect D pumping.
- NSTX data linked to model lab experiments and fundamental chemistry calculations
  – insight into D pumping by Li-C complexes.

FY11-FY12 aims:

- Investigate D pumping, plasma performance and surface chemistry including measurements by MAPP probe in preparation for FY12 milestone.
- Assess Mo tile performance with Li (if tiles present).

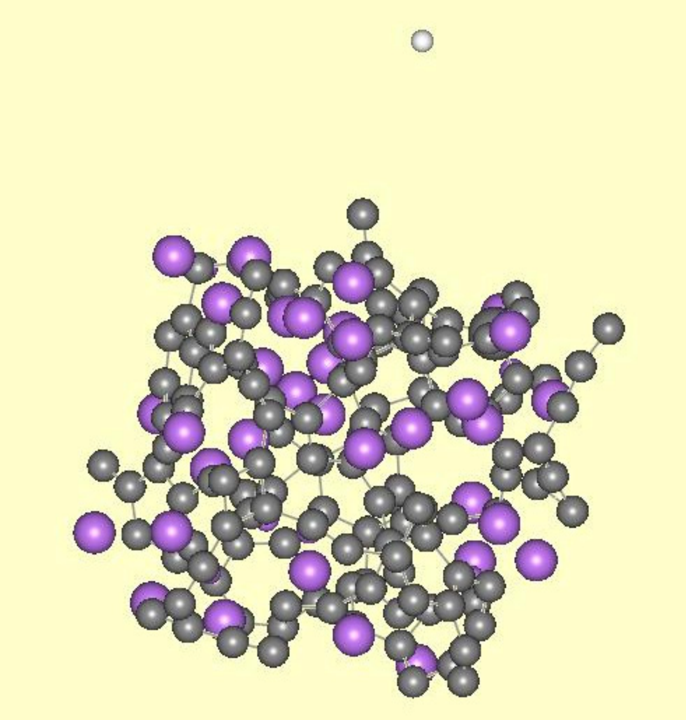
# Backups:

- BACKUPS

# MAPP enables time-dependent PMI analysis

- Off-line *in-situ* experiments at Purdue have elucidated on D interactions with lithiated graphite surfaces
  - Critical time-dependent (fluence) have been identified
  - Need to correlate D exposure, plasma performance to the lithiated graphite surface.
- Post-mortem analysis give us archeological data that is important to assess where lithium ends up integrated over the whole NSTX campaign
  - However, we cannot decouple to connect with specific plasma performance variables.
- Location of MAPP is not ideal, however it will help us make critical progress in closing the gap on PMI behavior in this complicated environment.

# Computational simulations of Li-C-D interactions (P. Krstic ORNL)



- Cell of 200 atoms of lithiated amorphous carbon (32% of Li), at 300K
- bombarded by 5 eV D atoms, perpendicularly to the shell interface
- 4800 various trajectories
- Of 4800 trajectories, 2967 led to D retention.

- A site where both Li and C are present defined by radius of 3 A for Li and 2 A for C:
  -Number of D bound to Li (or Li-C ) is 1247, 351 seem to be bound for Li only (no C in radius of 2 A around D).
  - Number of D bound to both C and Li is 1720, only to C 824 (no Li in radius of 3A).

Interpretation of the results:

There is 3 times more C than Li , those that bonded to both Li and C is 1247-351 = 896 , similar to “only C”.

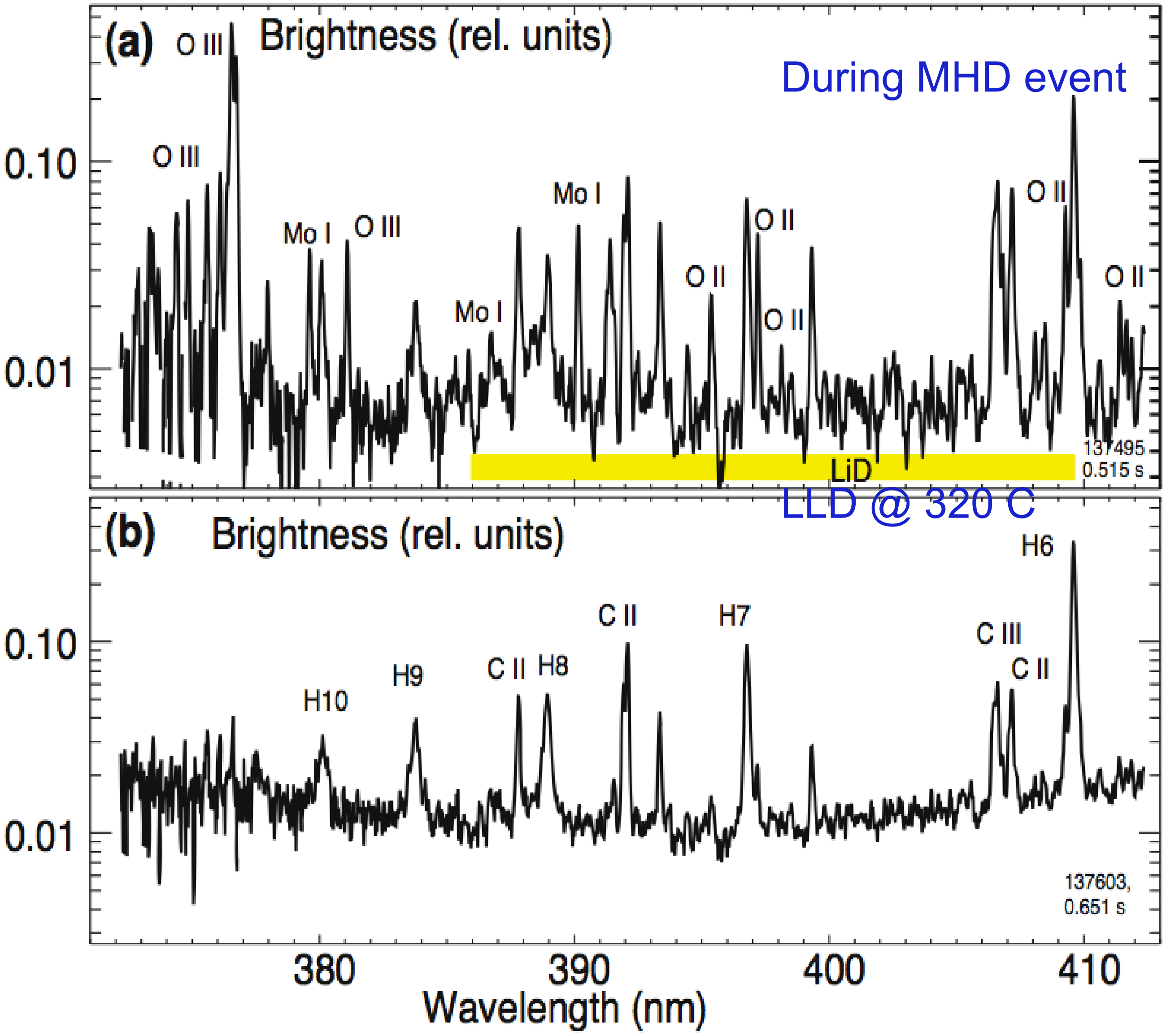
**Probability to bond to Li-C (3/4) is 3 times larger than the one to C (1/4)**

**Findings in qualitative agreement with Purdue experiments. (Li-C-D).**

Krstic APS poster 2010.

# Oxygen, molybdenum emission from LLD

- Little oxygen or Mo observed during normal plasma ops.
- Absolute intensity calibration in progress



During MHD event

LiD

LLD @ 320 C

Soukhanovskii et al. Rev. Sci. Instrum, 81, 10D273, (2010),

# REDEP/WBC code package--computation of sputtered particle transport

## 3-D, fully kinetic, Monte Carlo, treats multiple (~100) processes:

- Sputtering of plasma facing surface from D-T, He, self-sputtering, etc.
- Atom launched with given energy, azimuthal angle, elevation angle
- Elastic collisions between atom and near-surface plasma
- Electron impact ionization of atom→impurity ion
- Ionization of impurity ion to higher charge states
- Charge-exchange of ion with $D^0$ etc.
- Recombination (usually low)
- q(**E** +**V**x**B)** Lorentz force motion of impurity ion
- Ion collisions with plasma
- Anomalous diffusion (e.g., Bohm)
- Convective force motion of ion
- Transport of atom/ion to core plasma, and/or to surfaces
- Upon hitting surface: redeposited ion can stick, reflect, or self-sputter
- Tritium co-deposition at surface, with redeposited material
- Chemical sputtering of carbon; atomic & hydrocarbon A&M processes
- Mixed material characteristics/evolution

# R12-1 Milestone

- **R(12-1): Investigate the relationship between lithium-conditioned surface composition and plasma behavior.**
- **LR + BP TSGs responsible**
- The plasma facing surfaces in a tokamak have long been known to have a profound influence on plasma behavior. The development of a predictive understanding of this relationship has been impeded by the lack of diagnostics of the morphology and composition of the plasma facing surfaces. Recently, a probe has been used to expose samples to NSTX plasmas and subsequent post-run analysis has linked surface chemistry to deuterium retention. However, with very chemically active elements such as lithium, more prompt surface analysis is likely required to characterize the lithiated surface conditions during a plasma discharge. In support of prompt surface analysis, an in-situ materials analysis particle probe (MAPP) will be installed on NSTX. The MAPP probe will enable the exposure of various samples to the SOL plasma followed by ex-vessel but in-vacuo surface analysis within minutes of plasma exposure using state of the art tools. The reactions between evaporated lithium and plasma facing materials and residual gases in NSTX will be investigated. Correlations between the surface composition and plasma behavior will be explored and compared to laboratory experiments and modeling. Measurements of fueling efficiency and recycling will be made. The results will deepen the understanding of plasma-wall interactions and inform the plans for particle control in NSTX-Upgrade.

# Responses to PAC-27 LRTSG questions:

| PAC Recommendation/Response Number | PAC Report Section | PAC Recommendations and Comments. | NSTX Response, slide # |
|---|---|---|---|
| PAC27-13 | 3.2 | A clear plan to measure the pumping by the LLD separately from the rest of the chamber has not been delineated but should be done as soon as possible. One could consider experiments where first fiducial discharges are well characterized with the LLD well coated. Then the LLD is heated (Li removed) and the fiducial discharges repeated - the difference in pumping corresponding to the loss of LLD pumping. Perhaps the group could also derive a measure of the pumping from planned measurements (Ly-alpha and probes). | Experiments were performed to identify pumping from the LLD (as distinct from the rest of the chamber) by (i) varying the LLD temperature above and below the lithium melting point; (ii) by varying the lithium fill of the LLD and (iii) by comparing plasma performance to previous years without the LLD. The Langmuir probe array data is still being analysed, but unfortunately the Ly-alpha diagnostic had technical problems. The overall conclusion from both local and global measurements at the moment is that the LLD pumping was similar to that of lithiated graphite.<br>Slide 6 |
| PAC27-14 | 3.2 | For example, what is the thickness of the Li on the surface? Is it 10s of nm, several times the depth of the implanting ions as assumed for the pumping predictions? Or, does most of the Li wick into the Mo mesh? | The thickness of the lithium on the LLD surface is not easy to quantify. Simple chemical tests with acetic acid indicate that Li does wick into Mo pores and is depleted from the surface at blackened regions.<br>Slide 7 |
| PAC27-15 | 3.2 | Do Li wetting experiments on Mo, as done, e.g., by UIUC and by SNL and collaborators, reliably apply to NSTX? The answers to these questions affect the understanding of how to use the LLD in NSTX and should be remedied by offline experiments (if the information does not already exist). An additional question is how multiple Li depositions change the surface – does it build up in thickness or does it wick into the Mo leaving the same thickness. | It is clear that a tokamak is a more complex environment than a lab experiment. The base vacuum conditions, lithium deposition history and plasma and thermal exposure are significantly different.<br>Spectroscopic measurements show that the NSTX plasma facing surface is not pure lithium but rather a mixed material including lithium carbon, deuterium and oxygen. Analysis of FY10 samples retrieved from the vessel is in progress, and we are looking forward to the extended analysis capabilities of the MAPP probe in FY11.<br>Slides 7, 9 |
| PAC27-17 | 3.2 | The Mo surface can reach higher temperatures than C without causing problems for the core. At the same time, the Mo is potentially more dangerous in terms of effect on the core plasma even with lower sputtering yields than carbon, under plasma conditions of high Te and low ne, which could be obtained at the inner divertor due to high D pumping by the LLD. Such plasma conditions would lower the sputtered particle re-deposition and allow a higher fraction of sputtered material to reach the core plasma. Also, melting of Mo tiles can be a problem. Also, modeling of sputtered Mo transport, prior to installation, would seem highly feasible and desirable. | Mo emission from the LLD was not observed except during ELMs and disruptions indicating negligible contamination of the core plasma. Modeling by Brooks is consistent with this data. Lab tests with neutral beam heating of a porous Mo LLD sample showed only minor changes to the surface morphology at 1.5 MW/m2.<br>Slides 5,11,12 and NSTX_PAC29_Particle_Maingi.ppt slide 10 |