# Lithium Research Status and Plans

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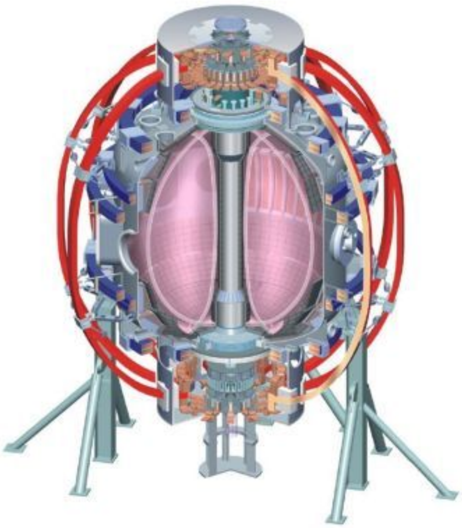
**Charles H. Skinner, PPPL**
**Robert Kaita, PPPL**
**Daren P. Stotler, PPPL**
*for the NSTX Research Team*

**NSTX PAC-27**
**Conference Room LSB-B318, PPPL**
**February 3-5, 2010**



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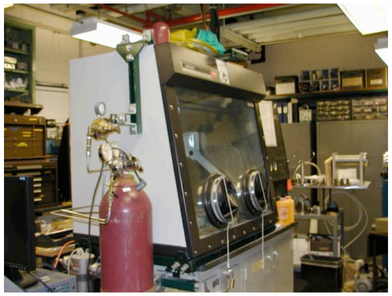
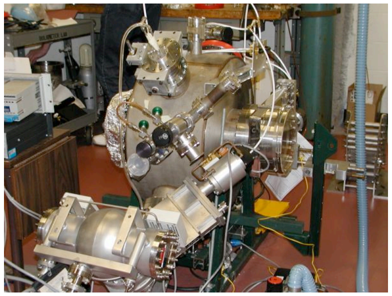
# NSTX lithium research is an integral part of a program to develop lithium as a PFC concept for magnetic fusion

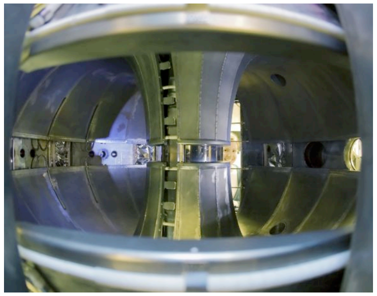
LTX lithium handling facility



LTX PFC test facility

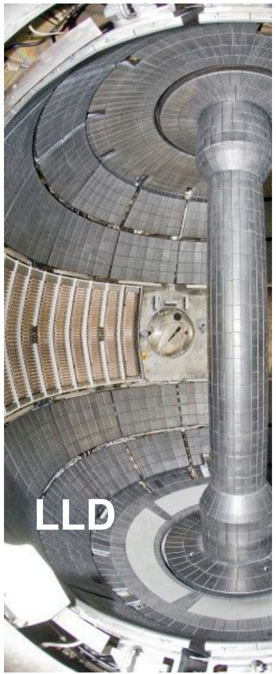


Purdue surface analysis facilities

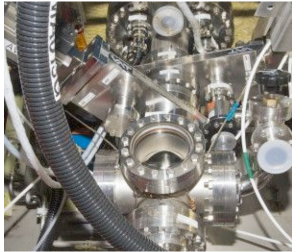


LTX operations commence 2010
- Fully-nonrecycling liquid lithium PFC's
- Profile control with core fueling
- No-carbon comparison to NSTX

**NSTX w/LLD**
- Only diverted, NBI-heated tokamak studying Li.
- LLD to extend density control for NB CD
- LLD compatible with high flux expansion div. solutions



NSTX materials analysis probe



NSTX upgrade, Fusion next-steps

Understand surface physics and chemistry

# Lithium Highlights:

- Confinement improvement and reduction of $P_{LH}$ with Li (T&T TSG)
- Modification of edge profiles and elimination of ELMs (BP TSG)
- ELM pacing to control radiated power rise (ASC TSG)
- Achievement of record NSTX 1.8 s pulse-length (ASC/MHD)
- Mitigation of NTMs, enabled observation of increased NTV braking with increased Ti (MHD)
- Reduced SOL density improved RF coupling (WPI)
- Improved CHI startup and coupling to ohmic plasma (CHI)
- Significantly higher shot rate

In this talk:

- D retention with lithium results (FY09 Joule Milestone)
- Plans for LLD commissioning
- LLD pumping
- Impurity control and exploiting Li Dropper
- Li Modeling
- Plans for FY11 and FY12

# Lithium Research Priorities:

Over-arching goal:

Develop and understand novel Li-based PMI solutions for NSTX, NSTX-upgrade, and a low aspect ratio high-heat-flux / component testing facility. (RENEW Theme IV.)

FY10 priorities:

- Develop and understand high-performance operating scenarios utilizing a liquid lithium divertor (LLD) for pumping and particle control.
- Understand and minimize the sources and accumulation of plasma impurities arising from lithium conditioning of the PFCs.
- Investigate lithium surface chemistry

FY11 priority: Milestone R11-3:

- Assess the relationship between lithiated surface conditions and edge and core plasma conditions. (RENEW Theme III.)

- Steady state high heat flux handling is important longer term goal.

# NSTX contributed unique Li data to FY09 joint research milestone on "...particle control and hydrogenic fuel retention in tokamaks"

DOE JRT milestone
PAC25-10,11

## Edge pressure and wall inventory changes with Li

With Li:

  - lower edge neutral pressure
  - higher wall particle inventory.

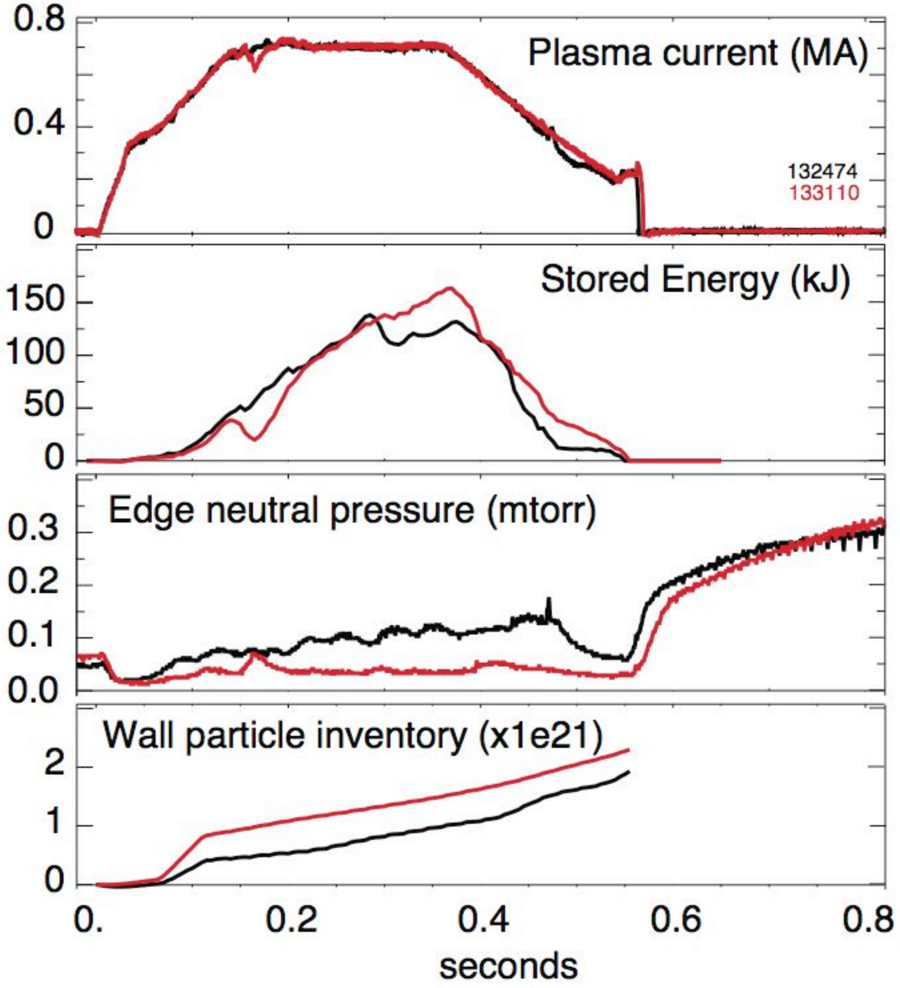
- Additional D wall inventory is released after discharge.

| Retention Summary | Before Li | With Li |
|---|---|---|
| Ohmic | 92% | 94%<br>(48 mg Li) |
| NB heated | 87% | 93%<br>(137 mg Li) |

Wall inventory calculated by dynamic particle balance model.

*Vlad Soukhanovskii*

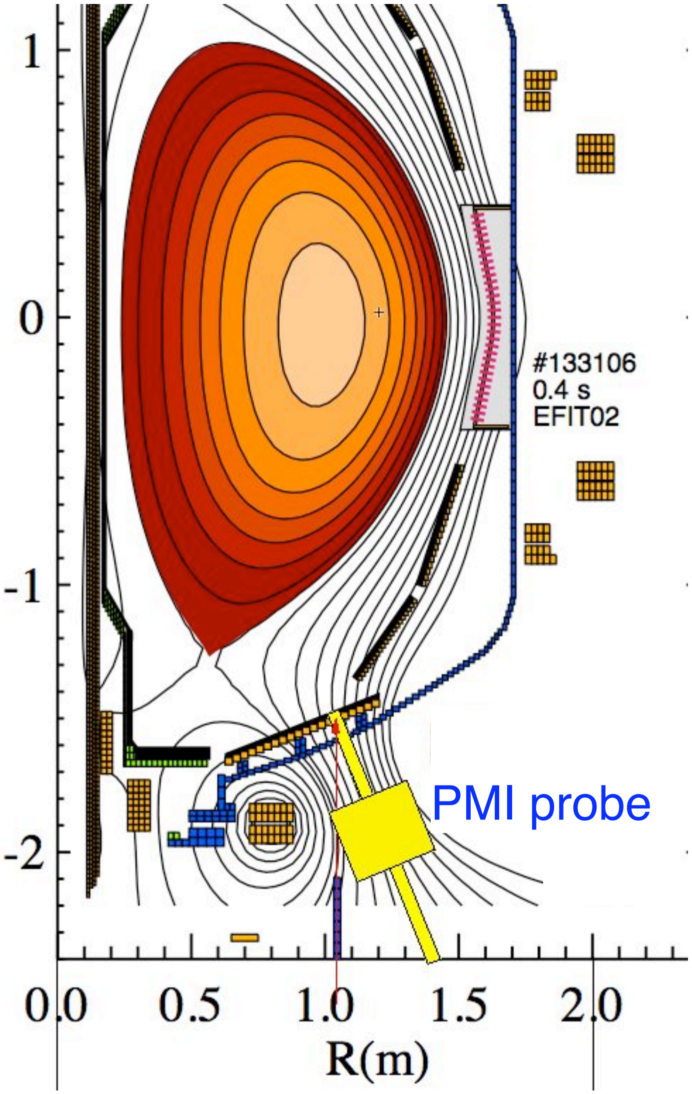
Pre-Li and with Li NB heated discharge



# Gas balance retention measurements correlate with in-situ PMI surface science measurements

DOE JRT milestone, PAC25-10,11

| GAS BALANCE: | SURFACE ANALYSIS |
|---|---|
| Retention higher with Li, difference increases with Li concentration | X-ray Photo-electron Spectroscopy shows D atoms are weakly bound in regions near lithium atoms bound to either oxygen or the carbon matrix.<br>Chemical bonding changes with Li concentration. |
| Additional D retained with Li is released promptly after discharge | Weak D bonding with Li conditioning observed in Thermal Desorption Spectroscopy. |



# NSTX will greatly extend solid Li PFC research with recently installed liquid lithium divertor (LLD).

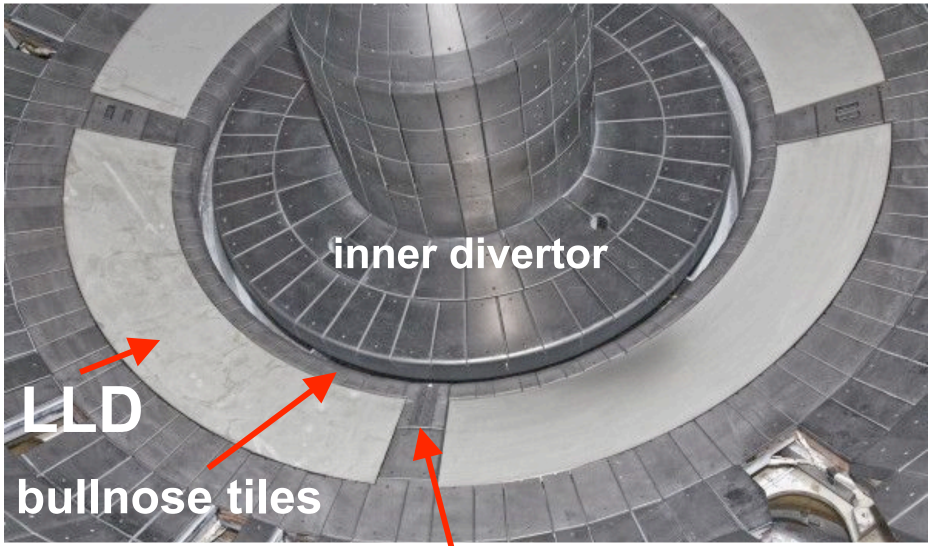
PAC25-14

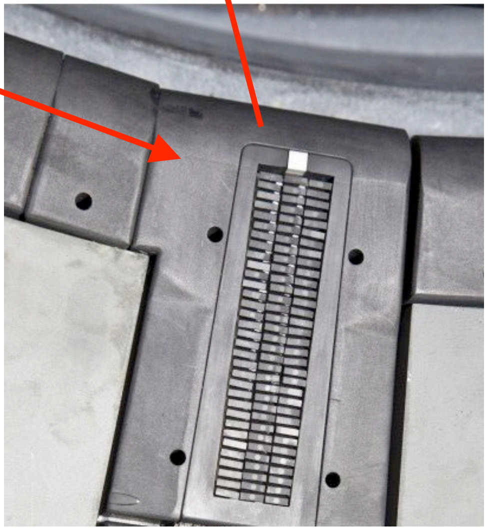
In collaboration with SNL

- PISCES and CDX experience shows liquid Li has more capacity to retain D than solid Li.
- Mo porosity provides surface tension to hold Li in presence of JxB forces.
- Clean Mo allows liquid Li to flow across metal surface (wetting capability).

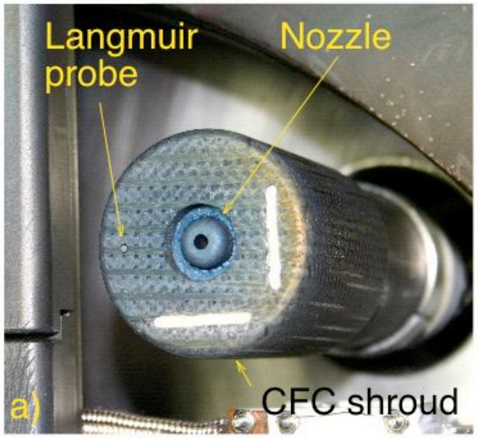
- Diagnostic upgrades to study Li coverage, heat flux and plasma footprint include*:*
  - Langmuir probes including 99 probe array and triple probe (UIUC)
  - Fast IR and visible filtered LLD cameras (ORNL)
  - Lyman-alpha diode array (LLNL)
  - Divertor spectrometer for Mo, Li , D, C (LLNL)
  - Upgraded divertor bolometer  (12 -> 20 channels)
  - Halo current diagnostic
  - Core lithium density measurements with CHERS
  - PMI probe upgrade planned for FY11 (Purdue - MAPP probe)

- 5 New Postdocs in Li/Boundary area.





# Tools for lithium program



Supersonic Gas Injector

10 ms pulses

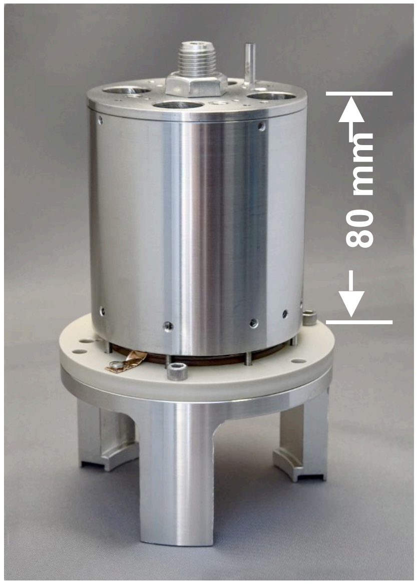
PMI probe.

prompt ex-vessel surface analysis

Dual LiTER

evaporators

≤ 40 mg Li / min each



Dual Li Droppers

≤ 7 g / min

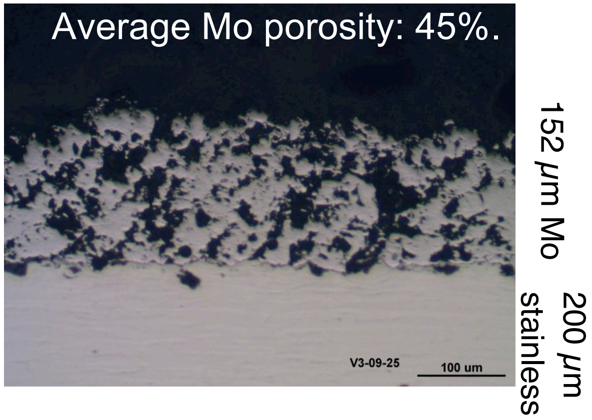
each

# NSTX will assess and utilize the LLD in 4 stages

PAC25-14

1. Commission LLD for pumping
   - Begin with 3-week bakeout + HeGDC
   - 1-2 days LiTER for 250 nm Li coating of LLD
2. Characterize LLD pumping, plasma response to LLD
   - Strike point on inboard divertor and bullnose
   - Test Li coating of LLD
   - LiTER shuttered, LLD Li molten @ 200°C - 300°C, SGI fueling
   - Compare to 2009 performance and pumping predictions.
3. Utilize LLD pumping in milestone/high priority experiments
   - Apply optimal scenarios in all TSGs
4. Assess high heat flux handling capability of LLD
   - Move strike point onto LLD
   - Compare to 2009 and pumping predictions
   - Decommission LLD at end of run (evaporate remaining Li)

Cross sectional views of plasma sprayed porous molybdenum LLD sample

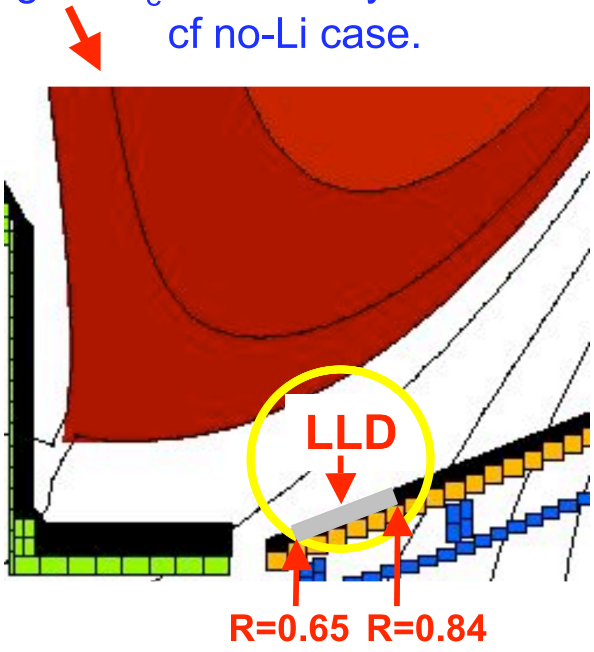


# NSTX will systematically characterize the pumping capabilities of the LLD in FY2010

PAC25-12

- FY09 Results:
  - Li reduces recycling and edge neutral pressure - up to factor 2 higher fueling needed
  - Supersonic Gas Injector (SGI) facilitates constant or decreasing D density
- FY10 goal: test LLD predictions of 33% - 56% reduction in Ne with LLD compared to no-Li.
- Analyse results with particle balance models and 2D fluid (e.g. UEDGE) modeling.
- Study pumping in SGI-fueled discharges vs.
  - strike point location,
  - core ion density,
  - divertor ion flux (vary by SGI fueling),
  - LLD temperature
- Qualify a range of $I_P$ and $P_{NB}$ scenarios for subsequent XPs.

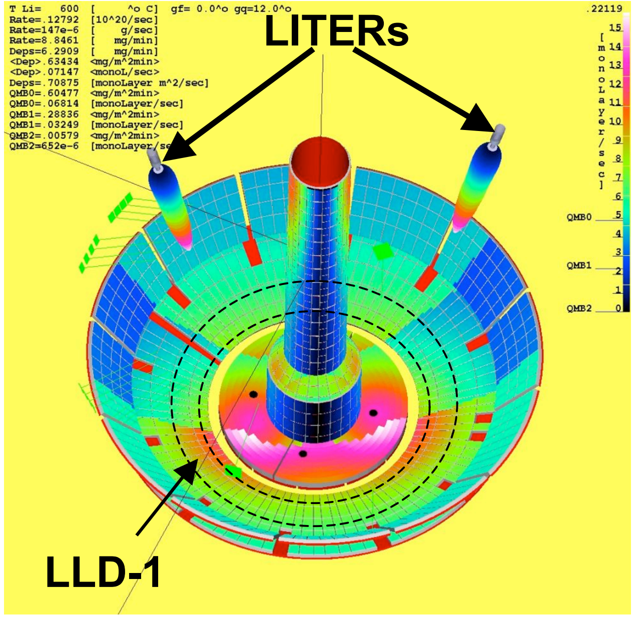
Particle balance model [R. Maingi]:
High $\delta$: $n_e$ reduced by 33% cf no-Li case.



Low $\delta$: $n_e$ reduced by 56% cf no-Li case with strike point on LLD.

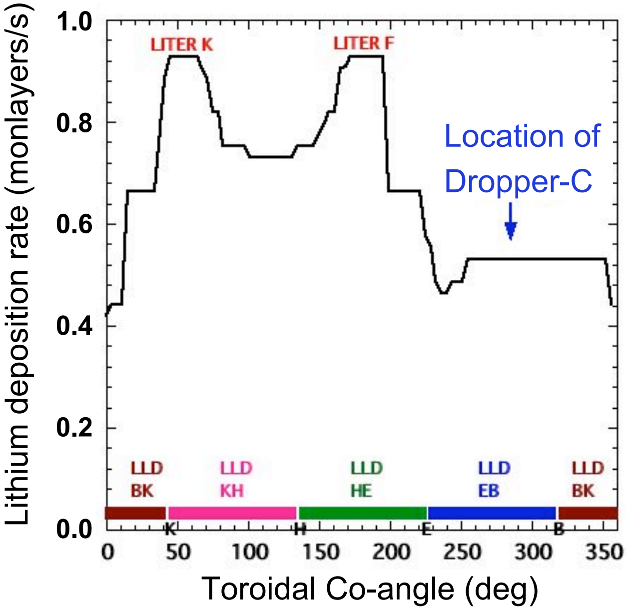
Look for LLD effect with LLD molten Li @ 210°C but LiTER shuttered.

# Plan to wet and fill LLD with lithium from dual LITERs, possibly supplemented by lithium Droppers



```
T Li=   600  [      ^o C]  gf= 0.0^o gq=12.0^o
Rate=.12792  [10^20/sec]
Rate=147e-6  [    g/sec]
Rate=8.8461  [   mg/min]
Deps=6.2909  [   mg/min]
<Dep>.63434  <mg/m^2min>
<Dep>.07147  <monoL/sec>
Deps=.70875  [monoLayer m^2/sec]
QMB0=.60477  <mg/m^2min>
QMB0=.06814  [monoLayer/sec]
QMB1=.28836  <mg/m^2min>
QMB1=.03249  [monoLayer/sec]
QMB2=.00579  <mg/m^2min>
QMB2=652e-6  [monoLayer/sec]
```

**LLD loading at 120 mg/min total rate**



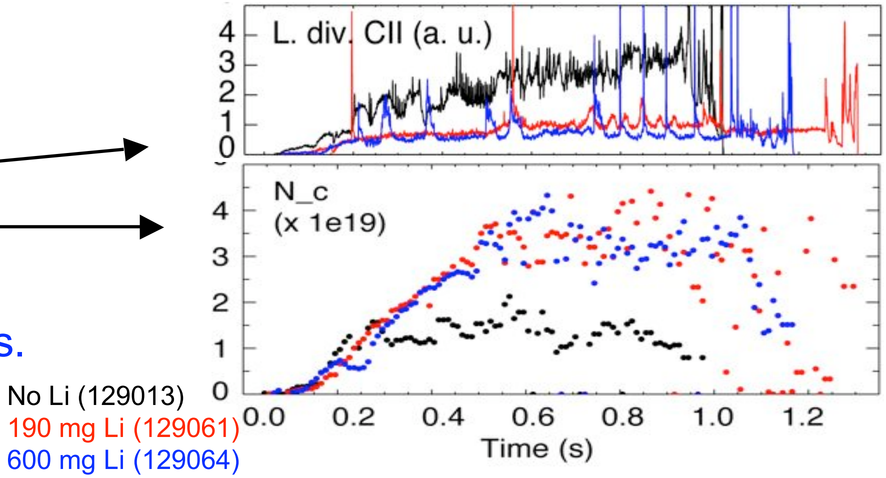
- Rely on liquid wetting the porous Mo surface to spread the lithium
- Wettable area in porous Mo estimated at ~8 times plate area
  - 1.1g lithium on LLD would coat wettable area to 250nm penetration depth of incident $D^+$ ⇒ 15g evaporated ~ 1 day at normal evaporation rate.
  - 7% of lithium evaporated by LITERs reaches LLD-1 plates.
- Estimate ~40g lithium required to fill porous volume in Mo coating
- Lab tests of Li evap. + Li flow techniques to load LLD more efficiently

# NSTX will assess impurity sources and elimination techniques for Li ELM-free H-mode scenarios.

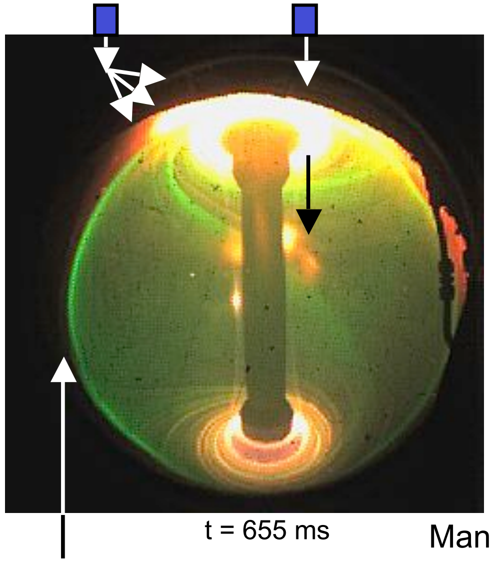
PAC25-9

Key results:

- Little Li in core plasma (~ 0.1%)
- Carbon did not increase with Li but core C density increases !
- Diffusive Li evaporation into He improved Li coverage but had mixed results on impurities.
- Li Dropper shows promise.
- ELM pacing reduced Prad.



Lithium powder dropped from above



Mansfield

Quiescent edge, $Li^{+1}$ radiative mantle

Goals/methods for impurity reduction:

- Identify source of impurities.
- ELM pacing (ASC TSG).
- Vary divertor temperature and pressure to control impurities.
- Continue Li evaporation into He.
- Combine Li Dropper with evaporator.
- Li evaporation from ~ 400°C LLD to upper vessel.
- FY11,12: Further improve tile alignment, considering switch to Mo inboard tiles.

# NSTX will assess the LLD surface chemistry (FY11) and assess a high flux expansion LLD (FY12)

FY11 Milestone R(11-2): Assess relationship between lithiated surface conditions and edge and core plasma conditions.

- PMI probe upgrade (MAPP) to address surface physics.
  Correlation of NSTX behavior with lab data from Purdue.
- Joint experiments with LTX on recycling, fueling, SOL physics…
- Continue experiments
  - reduce impurity influx from wall / divertor by extended Li coating and
  - reduce impurity transport to core plasma with ELM pacing.

FY12: Assess a liquid lithium divertor utilizing a fully metallic substrate and high flux expansion (with BP TSG)

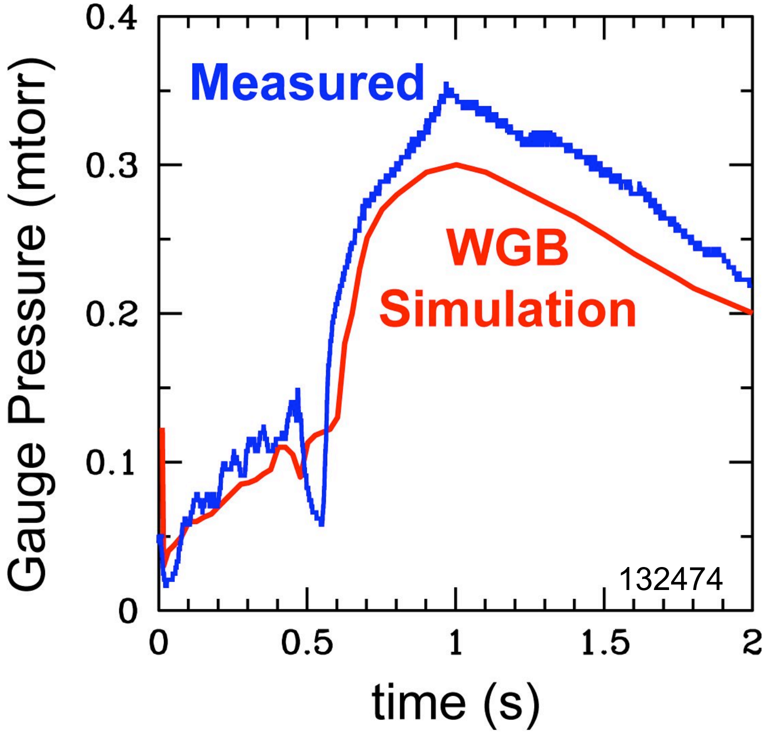
- Planning for heatable, Mo inboard divertor tiles + replace outboard C bullnose with Mo (present plan for LLD-2).
- Utilize temperature-controlled metallic OBD and IBD and assess liquid lithium divertor particle pumping and power handling as a function of LLD temperature, strike-point, flux expansion, divertor configuration, and a range of SOL conditions.

- (Test stand (e.g. with E-beam) under consideration through PPPL proposed collaboration with Rutgers, Penn State, & SEAS.)

# Modeling of Lithium Experiments Includes Particle Balance, Plasma Analysis, Li Deposition & Erosion

PAC25-2, 3, 10, 12

- Particle balance analysis:
  - Wall Gas Balance (WGB) simulations of retention experiments (UCSD),
  - Estimate core fueling due to edge sources ⇒ global recycling coefficient (PPPL).
- SOL & edge plasma modeling with Li & LLD:
  - UEDGE (UCSD) modeling of D-Li-C discharges,
  - LLD probe data may permit use of Onion Skin Model (PPPL).
- LLD thermal response & resulting Li evaporation / sputtering:
  - With WGB / WallPSI (UCSD).
  - Detailed 2-D heat transfer calculation (UIUC),
  - Extrapolate to NSTX-U & high temperature operation.
- Li erosion / redeposition modeling (Purdue),
  - Of lab experiments,
  - & NSTX, based on analyzed plasma data.
- Validate model of diffusive Li evaporation into He (PPPL) ⇒ tool for controlling Li deposition by LiTER.



Wall Gas Balance simulation of retention experiment

# Summary: NSTX has made, and will continue to make, substantial progress in assessing novel Li-based PMI solutions.

- LLD and many new diagnostics installed, + additional personnel onboard

FY10 plan:

- LLD commissioning will use staged approach to minimize heat load.
- Cross cutting XP to develop LLD scenarios.
- Characterizing LLD pumping.
- Control of impurity sources & transport and exploiting Li dropper.
- Supporting XPs.
- Continuing modeling of Li in wall and plasma.
- Prepare for FY11 milestone: "*Assess relationship between lithiated surface conditions and edge and core plasma conditions.*"

FY11, 12:

- Mo tiles, MAPP probe, strengthen design basis for NSTX-Upgrade.
- Prepare for FY12 milestone: interaction between LLD and high flux expansion divertor (with BP TSG).

# Backup slides

| | |
|---|---|
| Slide 17-25 | Joule Milestone Retention results (APS oral). |
| Slide 26 | Li and D coverage of 2009 tiles |
| Slide 27 | Radiation increase from metals |
| Slide 28 | Li Dropper |
| Slide 30 | LLD diagnostics |

NSTX

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# Deuterium retention in NSTX with lithium conditioning.

Charles H. Skinner,
W. Blanchard, H.W. Kugel, L. Roquemore, *PPPL,*
J.P. Allain, C.N. Taylor, *Purdue University,*
R. Maingi, *ORNL,*
V. Soukhanovskii, *LLNL.*
and the NSTX Research Team

**51th APS/DPP meeting, Atlanta, GA,**
**2-6 November, 2009**

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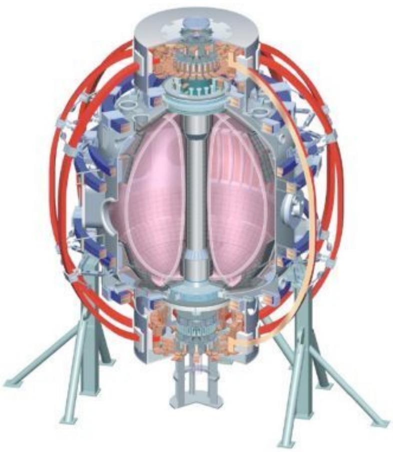

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*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*
*U Quebec*

# Outline:

FY 2009 Joule Milestone

Aims:

1. Measure the effect of lithium on fuel retention in NSTX.
2. Develop understanding of fundamental processes governing fuel retention.

Tools:

1. Gas balance - compare fueling and exhaust.
2. Develop probe to expose and retrieve samples, and study surface chemistry.

NSTX Main Conclusions:

1. Deuterium retention high (~ 90%) at end of discharge, slightly higher with lithium conditioning.
2. Deuterium outgassing reduces retention after a discharge.
3. PMI probe exposed and retrieved samples - analysis shows D atoms weakly bonded in regions near Li atoms bound to O or C.
4. Interesting correlations between gas balance and surface analysis data…

Also: S. L. Allen, Monday CO4.00002:
“Particle Control and Carbon Transport Experiments on DIII-D”

# High retention in ohmic discharges

Extensive calibrations preceded experiments.

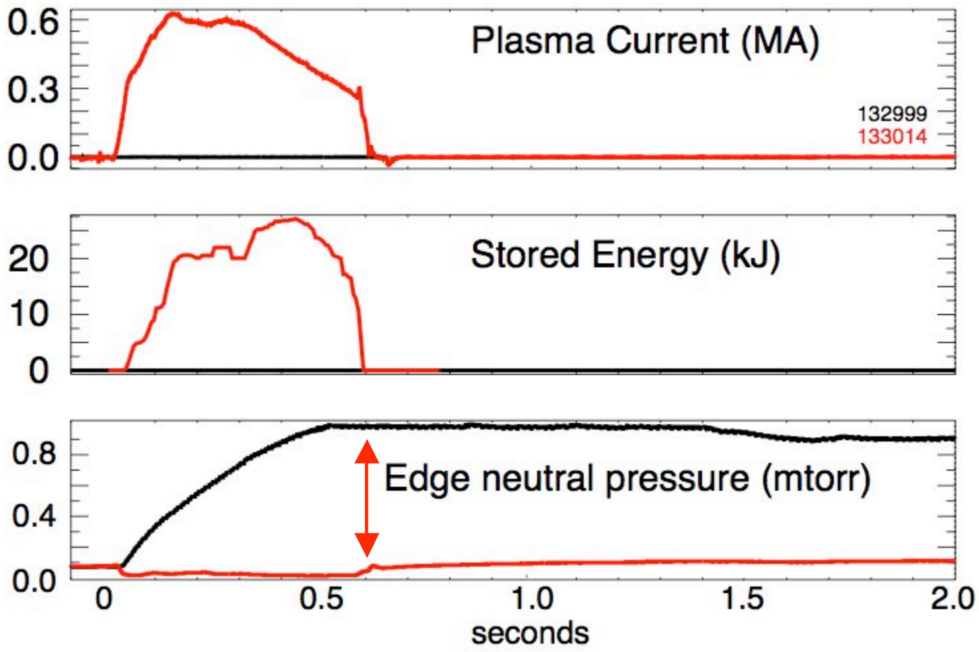
Four gas balance cases:

1. Before-Li ohmic discharges (vessel closed)
2. Before-Li NB heated discharges.
3. With-Li ohmic discharges (vessel closed).
4. With-Li NB heated discharges.

Discharge rampdown controlled to avoid minor disruptions.

1. and 3. are straightforward measurement with all pump valves closed:

Comparison of gas-only and ohmic discharge



$$\text{Retention} = 1 - \frac{\text{pressure after discharge}}{\text{pressure after gas-only shot}} \times \text{ratio of gas input}$$

Before-Li ohmic retention = 92% of D fuelled.

From D-alpha and Langmuir probe data:

$$\frac{\text{D retained}}{\text{D ion fluence to outer divertor}} = 6 - 8\%$$

# High retention in neutral beam heated discharges

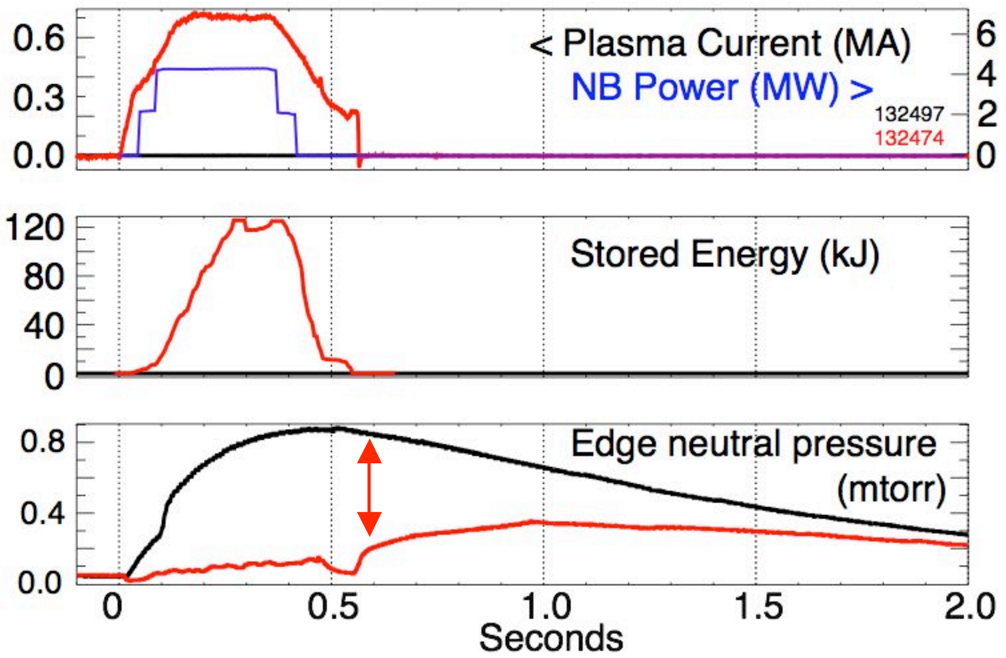
- NB heated discharge.
- Discharge rampdown controlled to avoid minor disruptions.
- Neutral beam valve open, account for
  - gas pumped by cryopanels
  - center stack gas injection
  - cold gas from NB.

$$\text{Retention} = \frac{\text{Gas retained}}{\text{Gas fueled}}$$

$$= \frac{\text{D input during Ip, less D pumped, D in VV}}{\text{D input during Ip}}$$

| **Retention Summary** | Before Li | With Li |
|---|---|---|
| Ohmic | 92% | 94%<br>(48 mg Li) |
| NB heated | 87% | 93%<br>(137 mg Li) |

Gas-only and neutral beam heated discharge

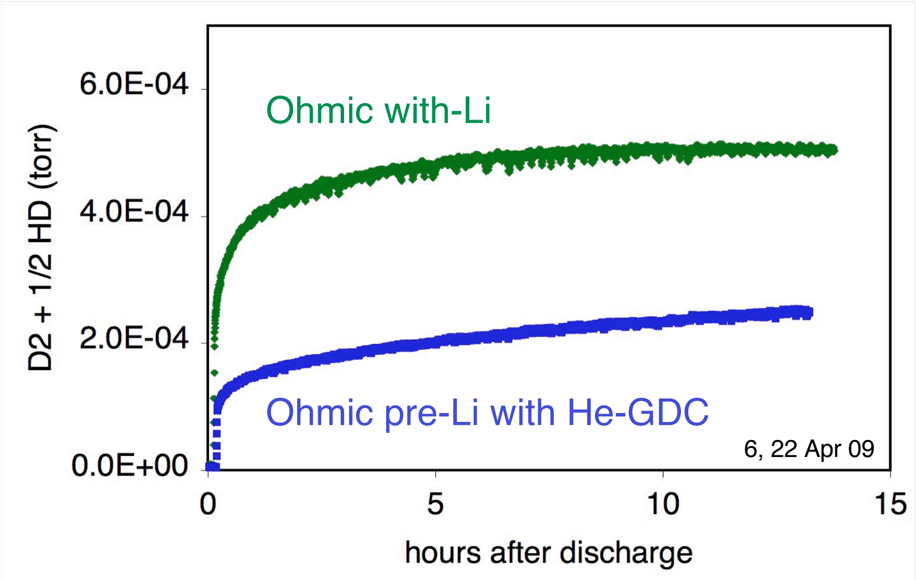


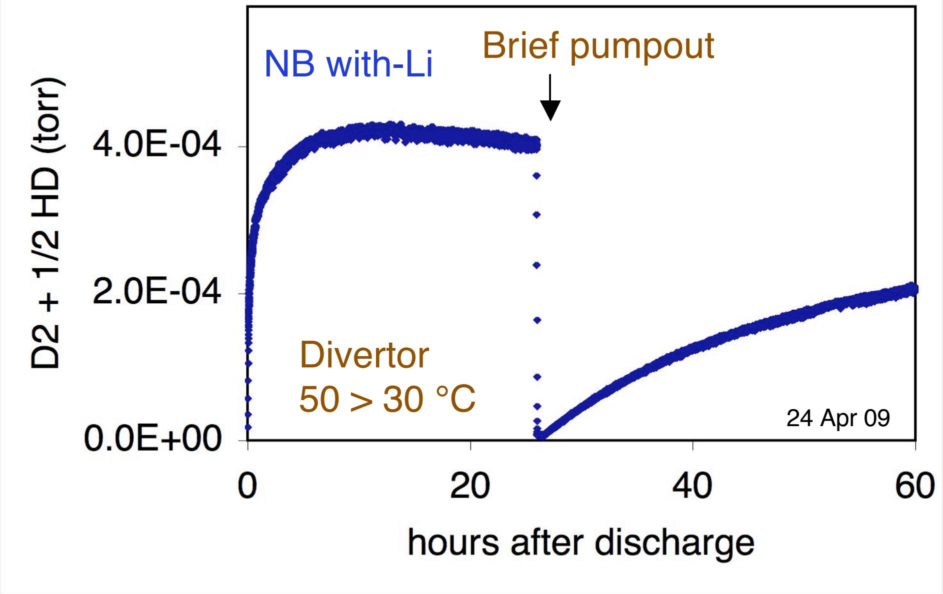
Before-Li NB heated prompt retention = 87%

Validation of methodology with pumping:
#132493 ohmic retention with pumping = 90%
#132490 ohmic retention valves closed = 92%

# Post discharge D outgassing reduces retention

- Pump valves closed for up to 72 h to integrate outgassing.
- Pre-Li case had intershot He-GDC that depleted D from wall.
- $D_2$ rate of rise is pressure dependent
  - wall pumping of $D_2$ as divertor cools.
- Long time scale for outgassing (> weeks) makes long-term retention % uncertain.





# PMI probe elucidates Li chemistry

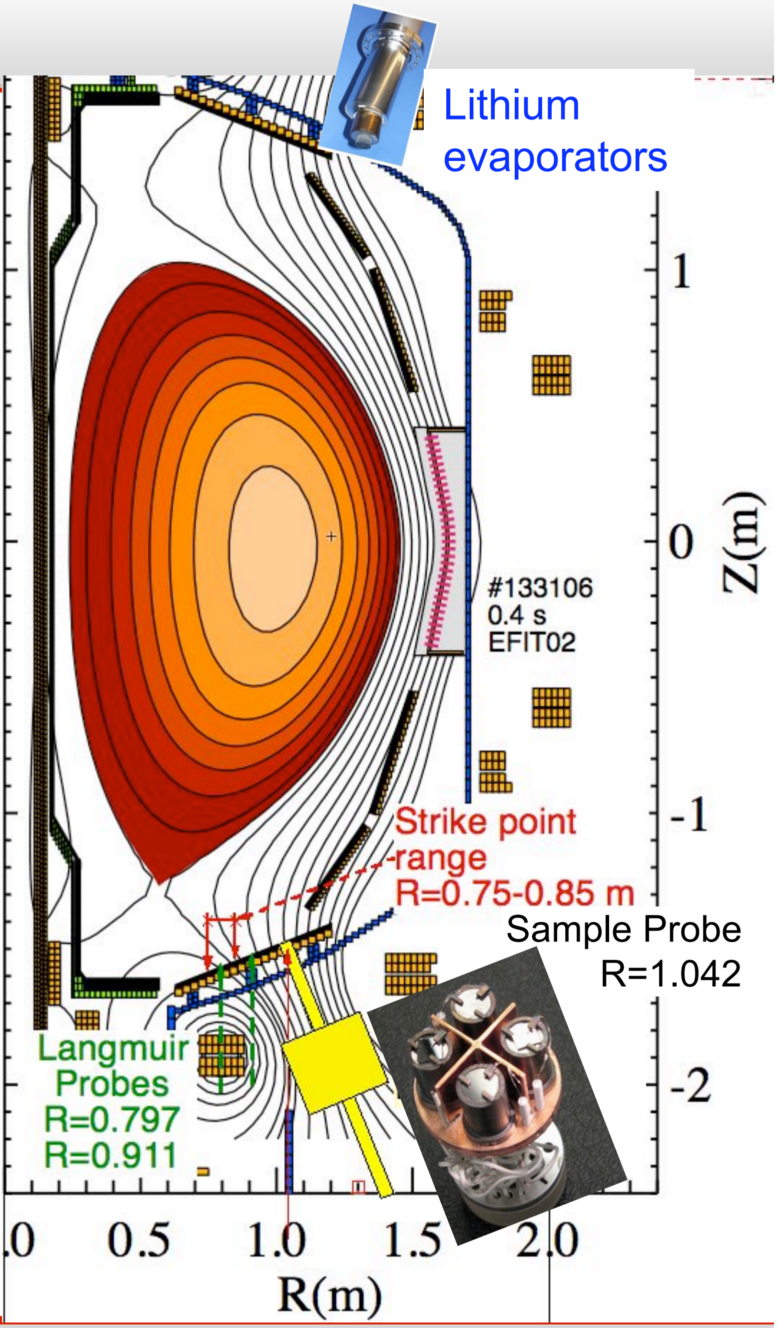
Specification:
4 samples on a 2" dia. probe
(two ATJ graphite, Si and Si/Pd)

- Secure, disruption- proof mechanical attachment
- Thermal cooling,
- 16 thermocouple wires connections
- 2 Langmuir probes
- Heater connection(s).

Must be installed and removed by one hand reaching through an argon-filled glove bag and through 4" diameter port and without using any tools.

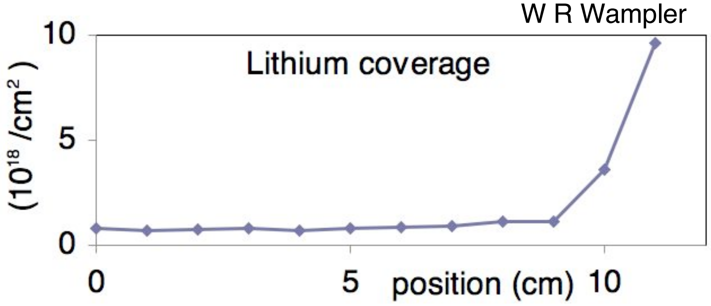
The design met all the specifications and was installed in-time to get before-Li measurements.

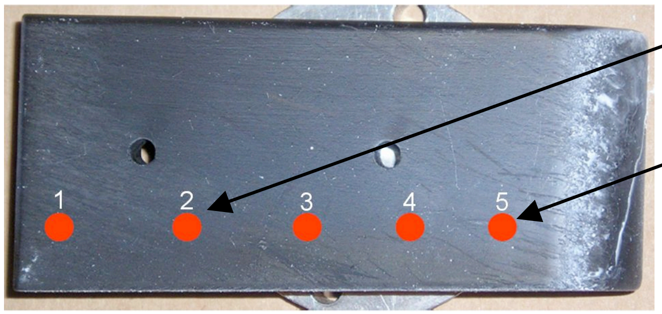
*Lane Roquemore*



# Chemical bonding revealed by X-ray photo-electron spectroscopy

ATJ graphite tile exposed to NSTX

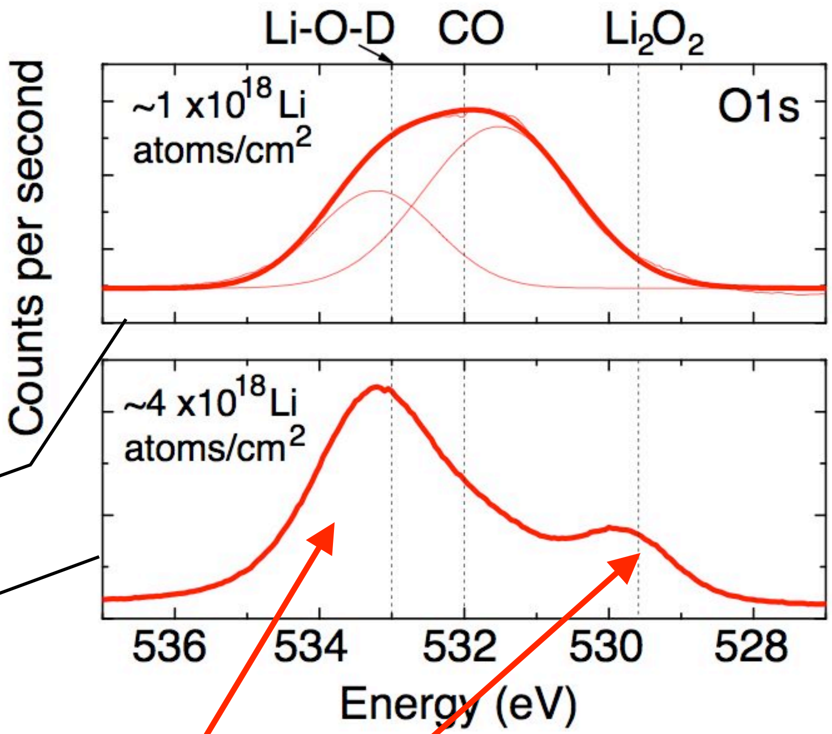




A235-021

See C. N. Taylor et al., Wed 2:00 PM  PP8.00040
*"Time dependent chemical interactions of  Li, D, and O on lithium-coated graphite surfaces."*

Molecular state changes with Li concentration.



- Li-O-D and Li-O peaks appear at high Li concentration
- [XPS spectra after 7 h Ar cleaning removed passivated amorphous layer due to $O_2$ exposure.]

# Increased Li changes chemical bonding state

Li induced changes in D-C and D-O functionality seen in both samples and tiles

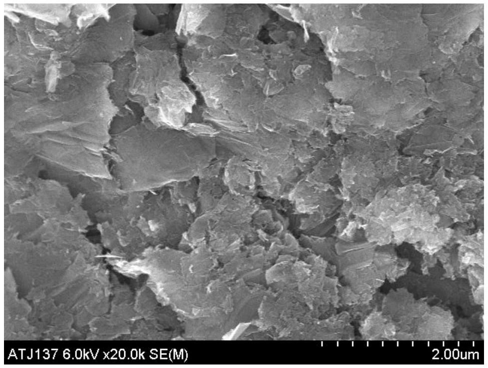
After 0.56 g Li evaporation
~ 63 nm nominal Li ‘thickness’

ATJ graphite exposed to 6 NB heated discharges

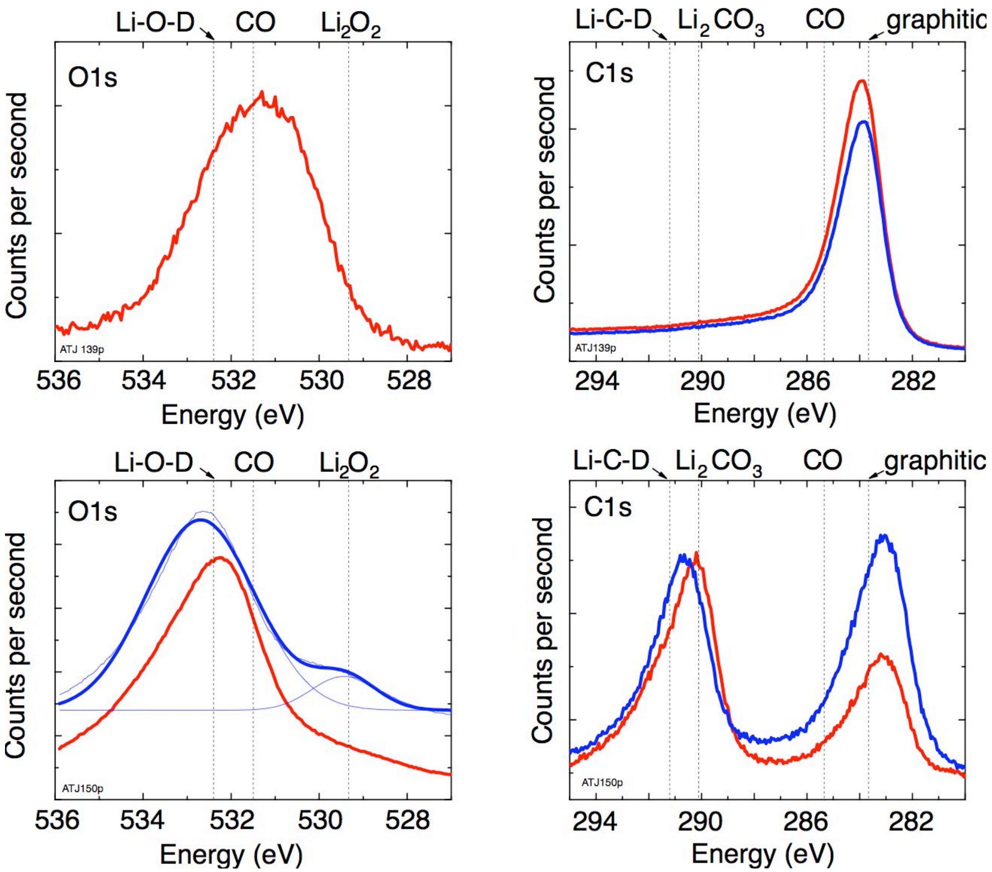
**After 7.3 g Li evaporation**
**~ 817 nm nominal Li ‘thickness’**

**ATJ graphite exposed to 40 NB heated discharges**

Polished graphite surface as modified by NSTX plasma.



XPS analysis of exposed samples shows molecular state changes with Li concentration.



After 15m (red curve) or 45m or 1h (blue curve) Ar cleaning removed passivated layer due to trace $O_2$. Consistent with increased Li effect on retention with higher Li evaporation.

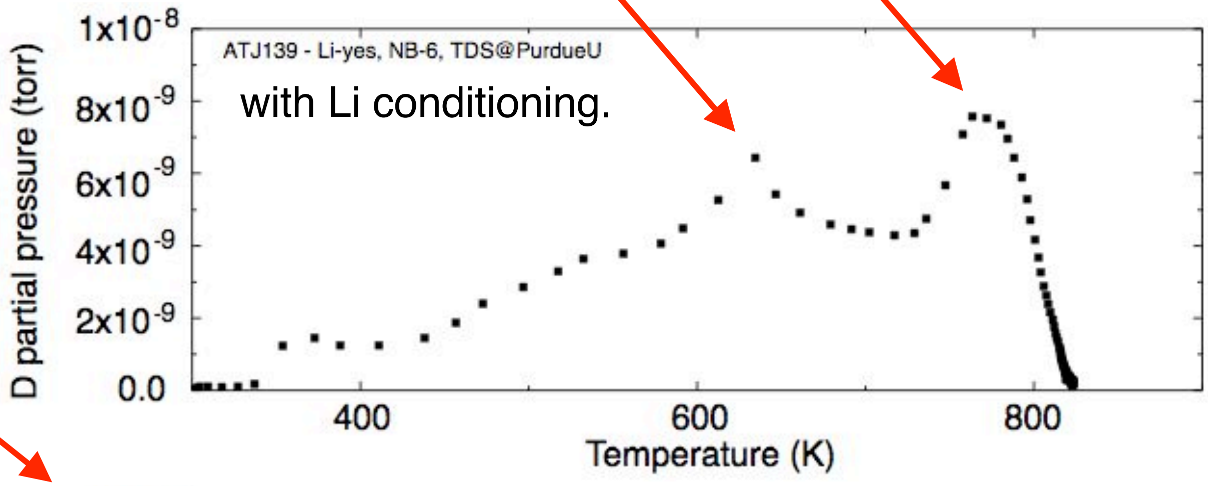
# Weak D bonding with Li found

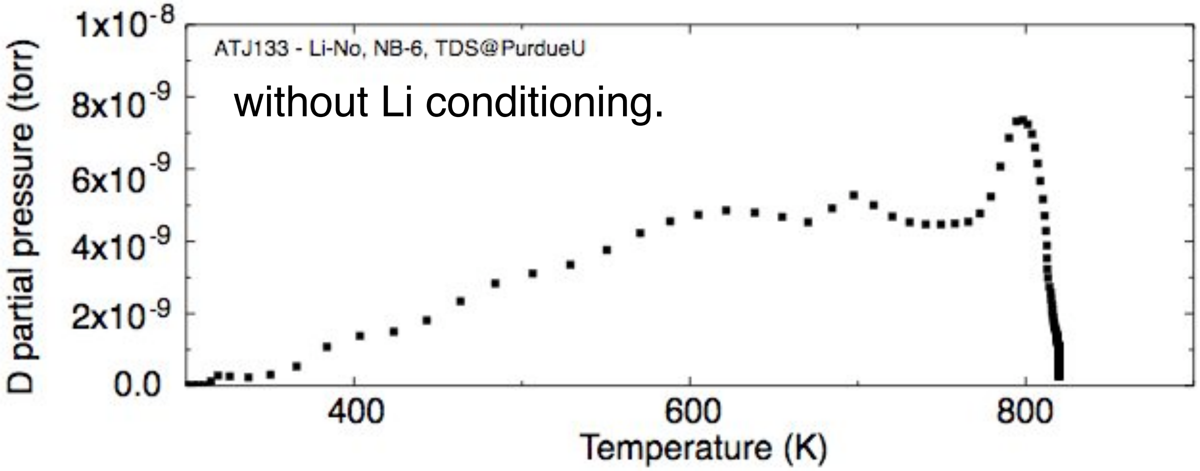
Thermal desorption spectra (TDS) of ATJ graphite samples exposed to neutral beam heated discharges
- with Li conditioning

and
- without Li conditioning.

600 K peak with Li has weaker bonding of D ‘in solution’.

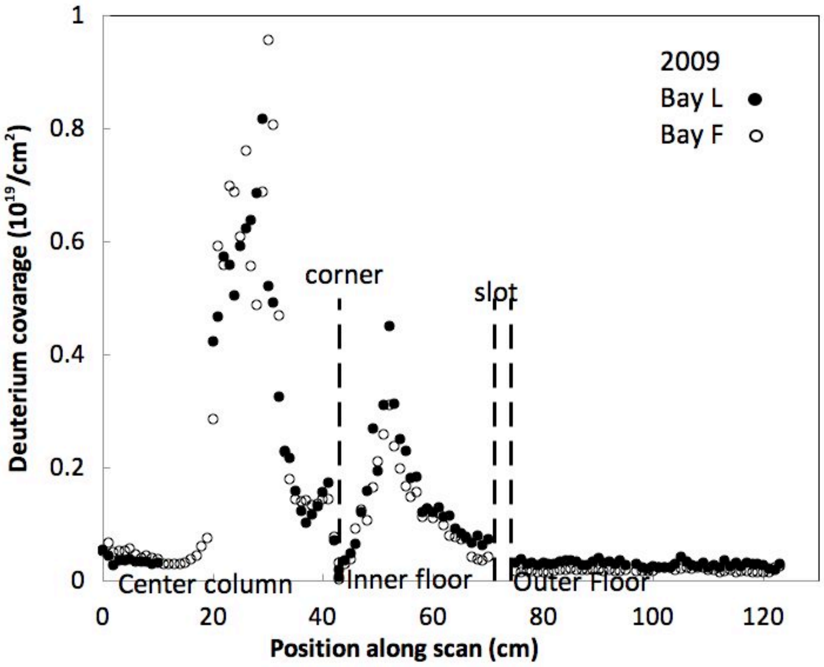
800 K peak indicates covalent bonding of D to Li, O and/or C.

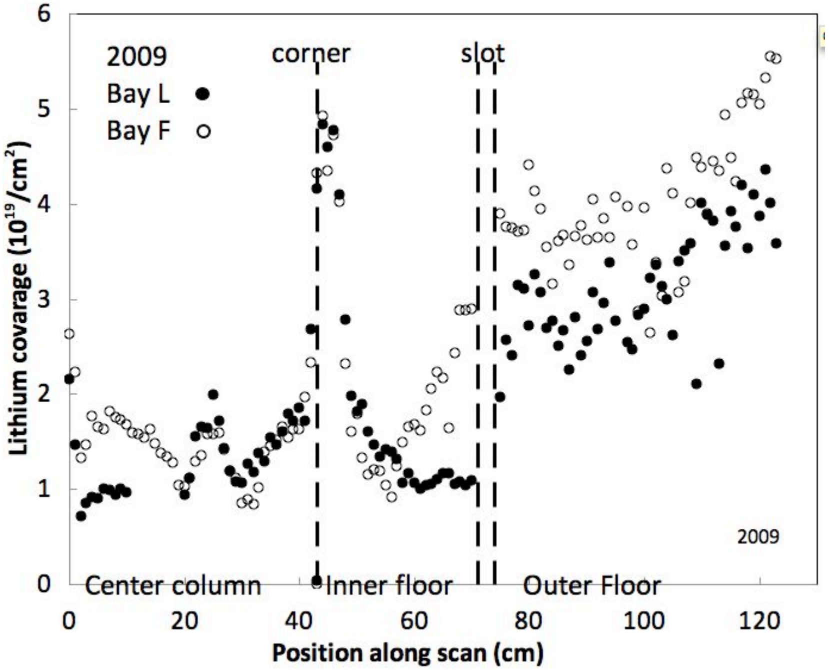


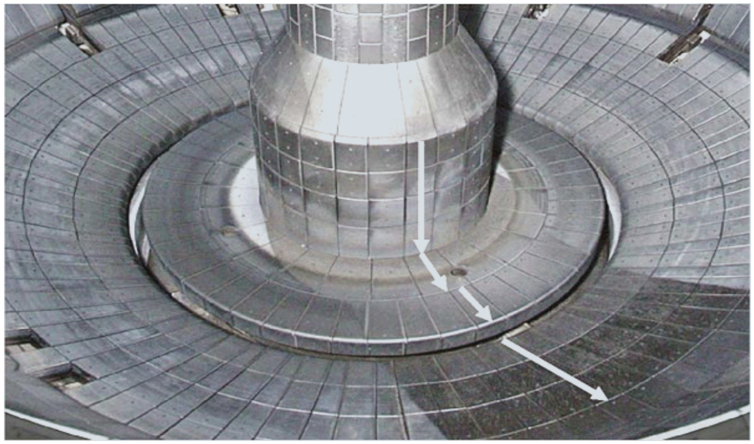


- Two TDS peaks correspond to effective release of D.
- Consistent with prompt release of additional D after NSTX discharge in previous slide.
- Investigation of D hybridization with Raman spectroscopy planned (Purdue U.)

# Li and D coverage of 2009 tiles



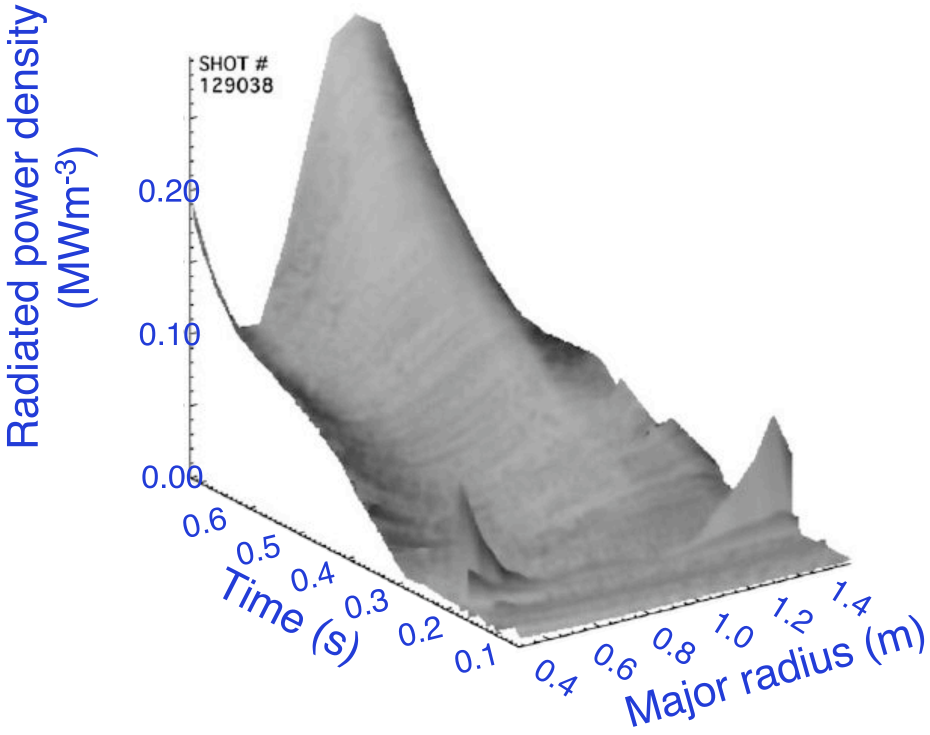


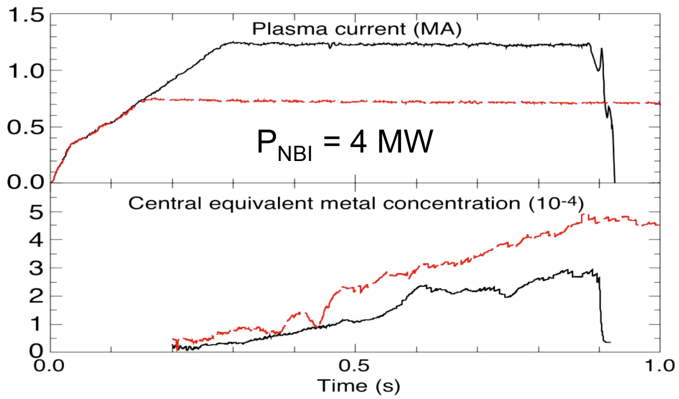


- Coverage of lithium and deuterium on the 2009 tiles after campaign. The position is measured downwards from the lower bevel on the center stack, then radially outwards across the lower floor.
- Ion Beam Analysis depth 15 μm Li, 4 μm D.

W.R. Wampler et al., SNL

# Metals Responsible for Most of the Increase in Radiation When ELMs Suppressed by Lithium



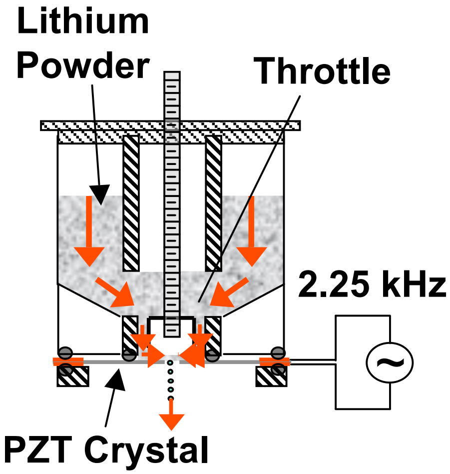


- Radiated power centrally peaked in ELM-free discharges
- VUV and SXR spectra show iron lines (Fe X – XVIII) increasing during ELM-free periods
- Radiated power profile remains hollow when ELMs are present
  - Metals still present early but do not accumulate
- If increase in radiation is ascribed to iron-like metals:
  - $n_{\text{"Fe"}}/n_e \sim 0.1\%$
  - $\Delta Z_{\text{eff}}(\text{“Fe”}) \sim 0.3$
- Dependence of rate of rise of radiation on $I_p$ suggests sputtering by unconfined NB ions is source

*S. Paul, S. Gerhardt, J. Kallman, P. Beiersdorfer, J. Lepson*

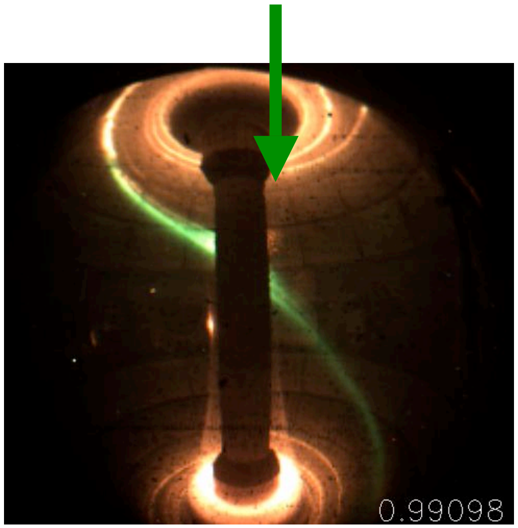
# Investigated Lithium Coating by Dropping a Stream of Lithium Powder into SOL

- Lithium powder (~40μm) stabilized against rapid oxidation in air by surface coating of $Li_2CO_3$ or paraffin (<0.1%).
- Introduced by oscillating a piezo-electric diaphragm with a hole in the center on which the powder is piled.
- Typical flow rates 5 – 80 mg/s: *well tolerated by plasma, even in startup*

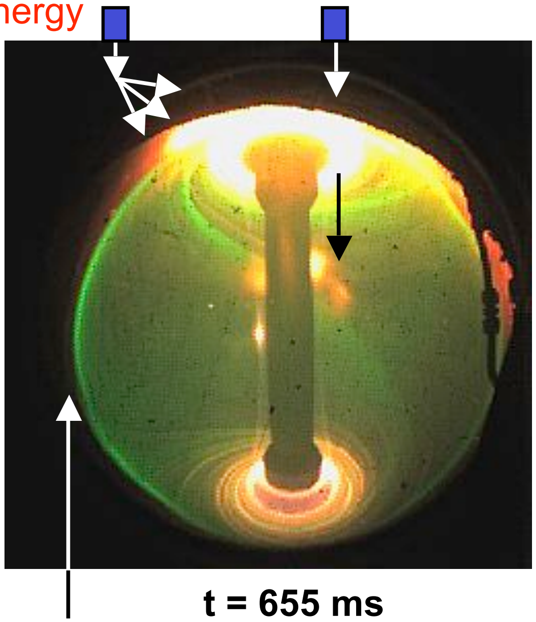


- Can modulate flow at up to 10Hz

Lithium powder dropped from canister above during discharge



- No ELMs or MARFEs
- Peak Stored Energy
- Peak Neutrons
- Low Radiated Power



- Quiescent Edge !
- $Li^{+1}$ Radiative Mantle !

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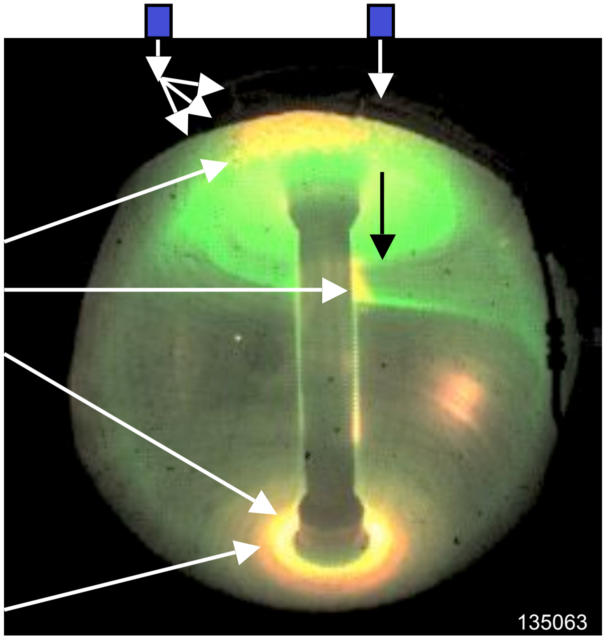
# Lithium powder could be used to replenish the LLD

Li Droppers

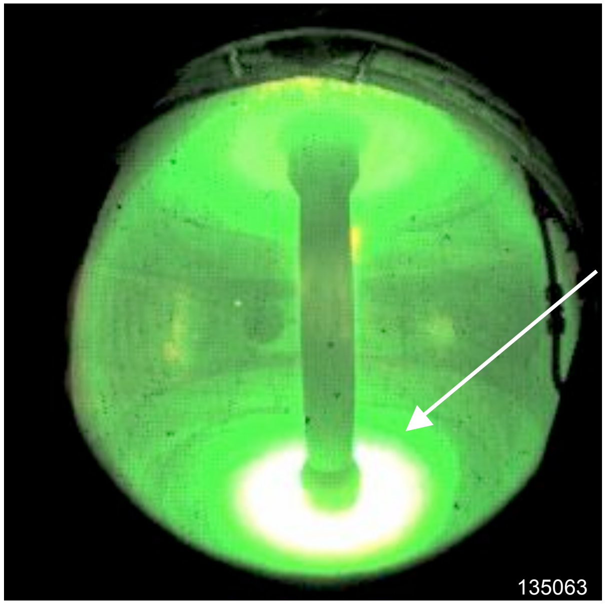
Li aerosol droplets



t = 79 ms

Just before LSN

Li powder dropped before breakdown



t = 91 ms

LSN forms & “finds” Li:

Camera saturated with green (5485 Å $Li^{+1}$)

- Massive evaporation of Li droplets near LLD
- More Li atoms than D!

Mansfield

# LLD Operation will be Monitored with Several Diagnostic Systems

- Visible Cameras
  - 2 high-speed views from above
- Plate surface temperature
  - Fast IR Camera
  - Slow IR Cameras
  - Thermocouple arrays in plates for calibrating surface emissivity
  - Also developing 2-color IR capability to avoid emissivity issue
- Lyman-$\alpha$ photodiode array (for recycling rate)
- Divertor region extractable PMI probe
- 3 Quartz Deposition Monitors
- Langmuir probes in diagnostic tiles between plates
  - Including high-density array of 99 probes

# How to tell LLD is coated sufficiently with lithium ?

Assume 250 nm coating with Li will not make LLD glisten and Li coating on LLD will not be visibly obvious.

- Divertor Imaging Spectrometer will monitor Mo I (384nm), LiI (670nm), LiII (584nm) emission from LLD.
  Also VIPS2 visible spectrometer.
- Fast cameras filtered with Mo I (384nm), LiI (670nm) LiII (584nm) filters will view whole LLD.
- LLD sample will be exposed with PMI probe at LLD temperature and analysed at Purdue using:
    - X-ray photo electron spectroscopy (XPS)
    - Low Energy Ion Scattering Spectroscopy (LEISS)
    - Direct Recoil Spectroscopy (DRS).
  - PMI probe is further in the wings of LiTER distribution than LLD but is direct measurement of material surface.
- Purdue can perform lab experiments on Li coating of LLD samples in presence of carbon coatings.
- Unipolar arcing may be visible on fast cameras or on PMI probe samples.