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NSTX Plasma Operation with a Liquid Lithium Divertor (LLD)

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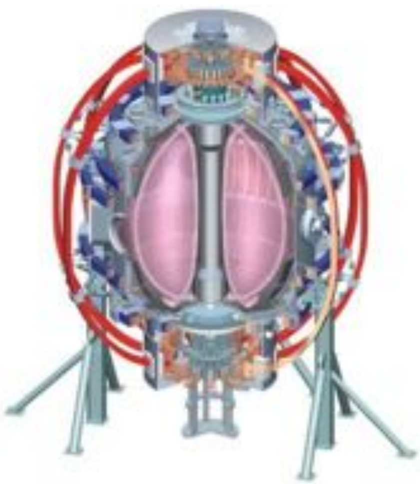
for the NSTX Research Team

The 2nd International Symposium on Lithium Applications for Fusion Devices
PPPL, April 27-29, 2011



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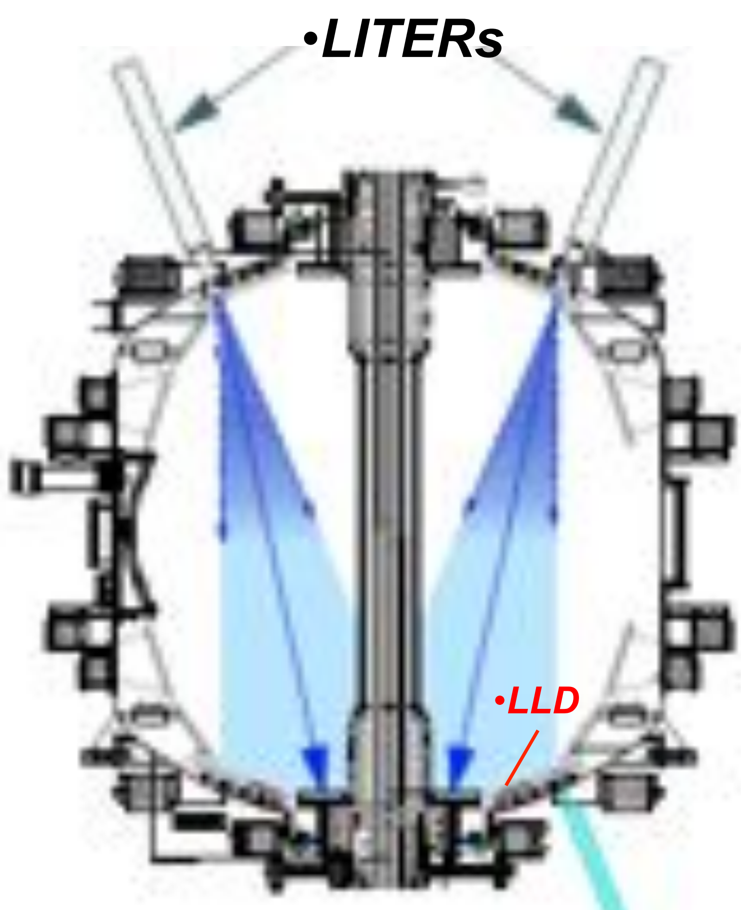
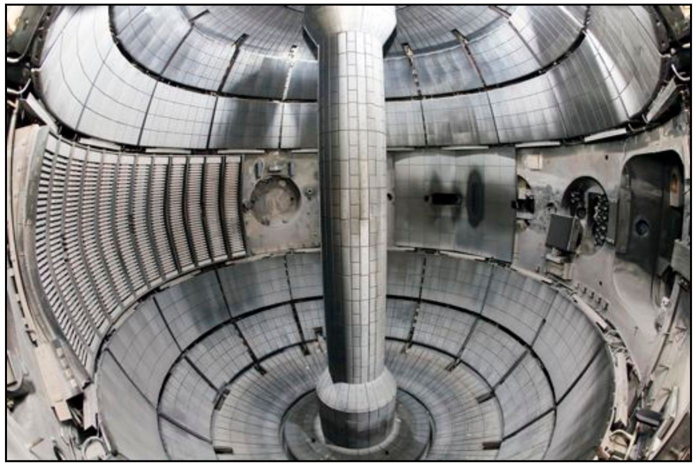
Since 2008, Dual Lithium Evaporators (LITERs) Are Used To Deposit Lithium Coatings On NSTX Lower Divertor for 10 minutes Between About 80% of Discharges



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

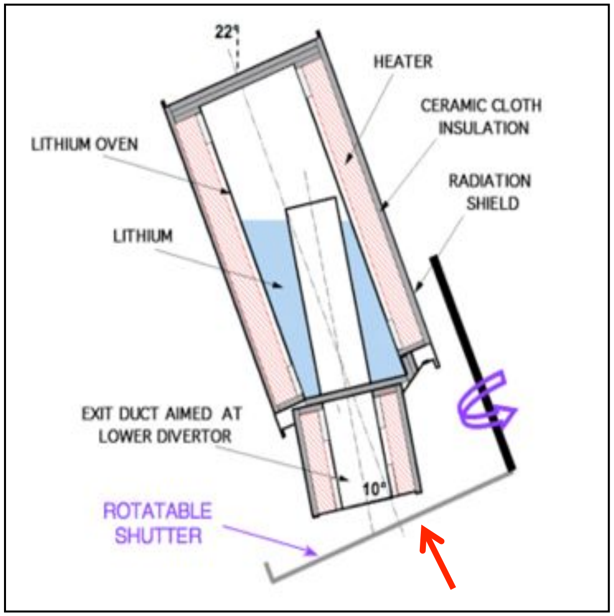
- Lithium transported over broad area by wings of LITER distribution and plasma migration.



- 2009 Photo: After exposure to air, 600g Li deposition converts to white lithium carbonate (Li_2CO_3)
  - Li_2CO_3 removed prior to evacuation with 5% solution of acetic acid (vinegar) (CH_3COOH) to convert Li_2CO_3 to water soluble lithium acetate ($LiC_2H_3O_2$)

Enabling Technologies Have Been Developed to Support NSTX Lithium Deposition

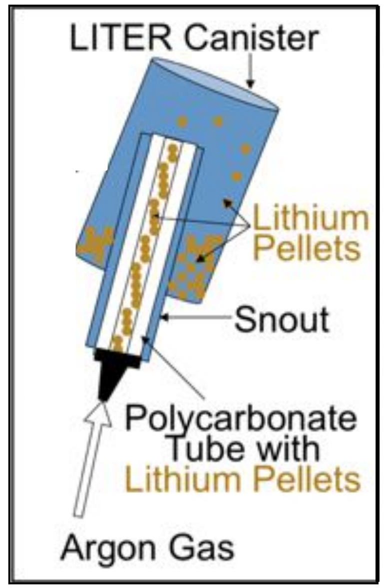
LITER Oven on 1.6m Probe



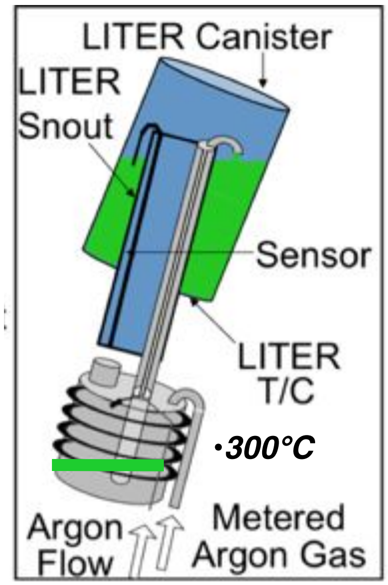
- Rotatable shutter stops lithium when diagnostic window shutters open.

- 4 LITER Units:
  - 2 mounted on vessel
  - 2 for reloading
  - replaced every~2 wks.

Initially, LITERs filled using solid Li pellets injected with Ar (40g max).



In 2010, LITERs filled using liquid lithium injected with Ar (80g max), less impurities.

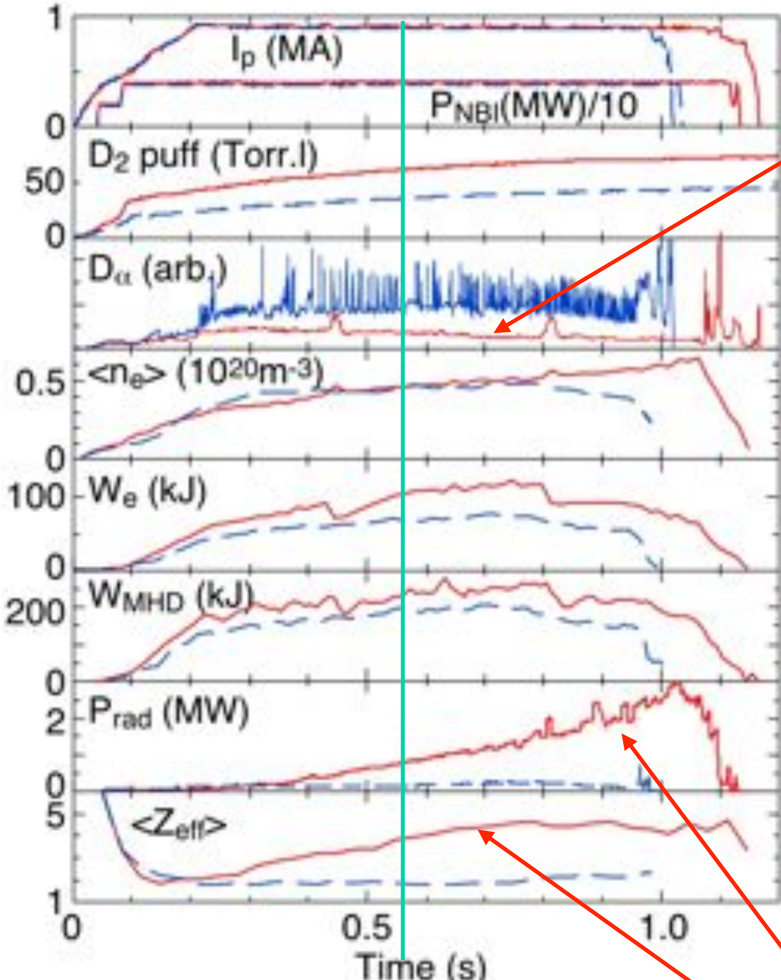


- After Li filling, prior to installation on NSTX, LITERs are outgassed in vacuum to 600°C to remove any argon and dissolved gases.

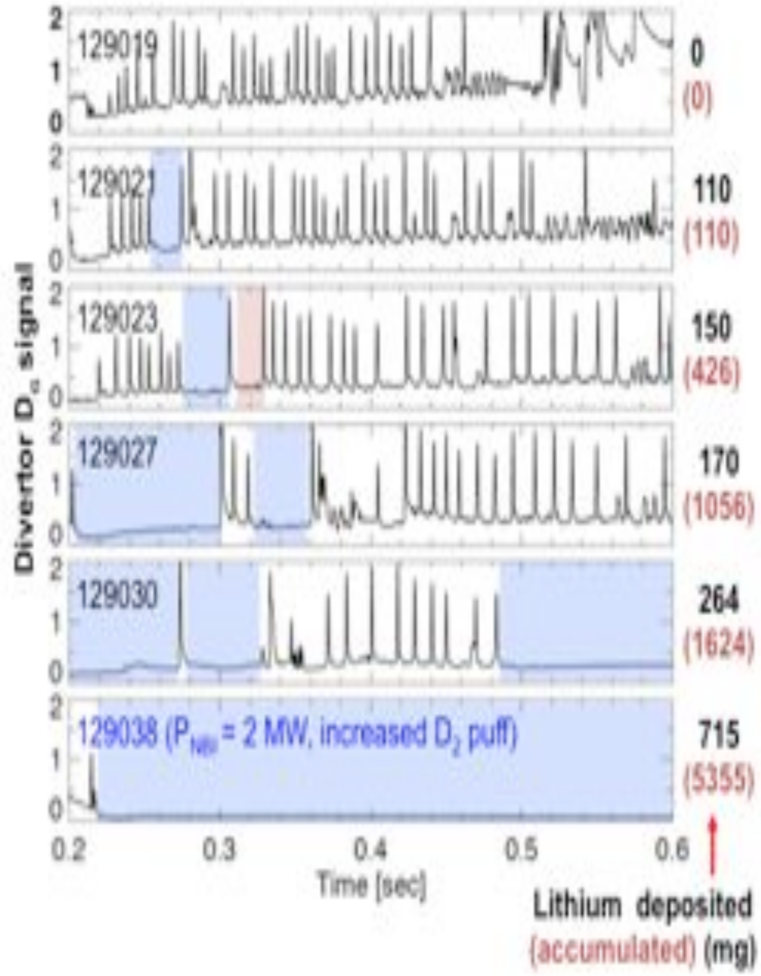
Poster : J. Timberlake

Solid Li Coating Reduces D-recycling, Reduces H-mode Power Threshold, Broadens Te Profiles, Decreases Electron Thermal Diffusivity, Suppresses ELMs, Improves Confinement

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



- ELMS reduced as lithium increases



- Without ELMs, impurity accumulation increases radiated power and Z_{eff}

NSTX Solid Lithium Surfaces Must Be Renewed Between Discharges
- Evaporative Deposition Cannot Provide Lithium PFC Conditions for Long Pulse, High Power Divertors

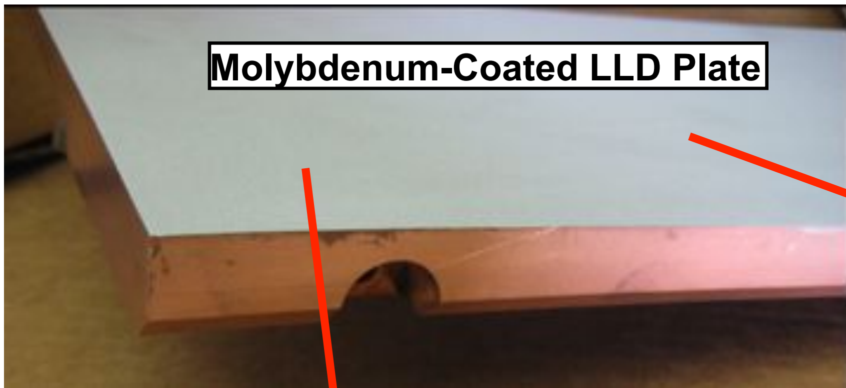
- Flowing liquid lithium provides a scheme for avoiding limitations of evaporative lithium coatings (erosion, evaporation, saturation…). 2010 implementation of Liquid Lithium Divertor (LLD) designed to test two key issues:
  - Substrate compatible with liquid lithium and able to withstand high heat loads
  - Performance of static liquid lithium relative to flowing liquid lithium

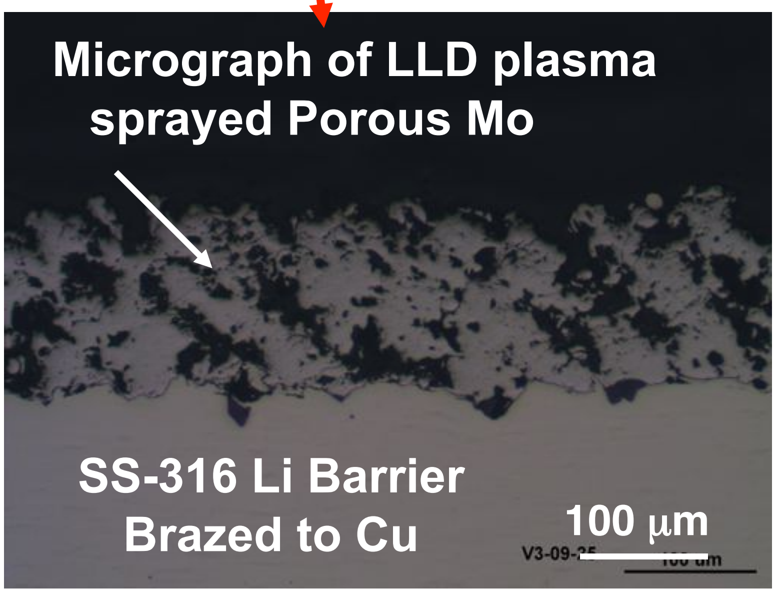
- LLD operation successfully demonstrated with the divertor strike points on lithium-filled surface
  - Design incorporated plasma-sprayed molybdenum surface, on thin stainless steel liner, brazed to thick copper baseplate
  - Longterm thermal response dominated by thermal mass of the copper
  - No macroscopic evidence of surface damage by lithium or heating

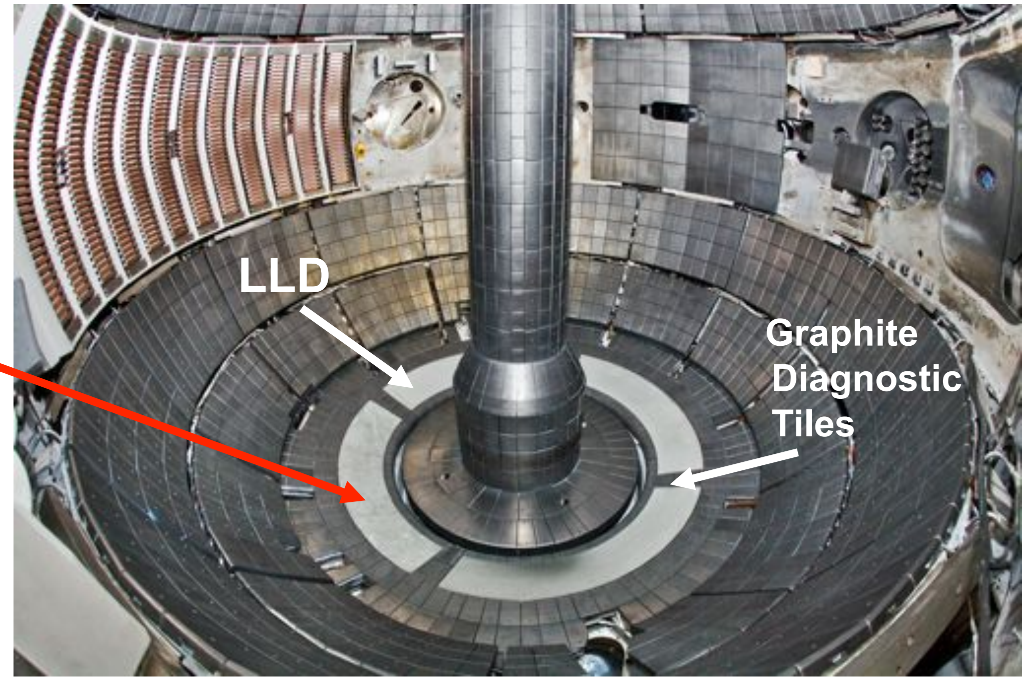
- LLD in its effects on plasma performance did not clearly differ from those of evaporative lithium coatings
  - LLD temperatures exceeded melting point of lithium
  - Lithium compounds from impurities remain undissolved on surface

2010 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.

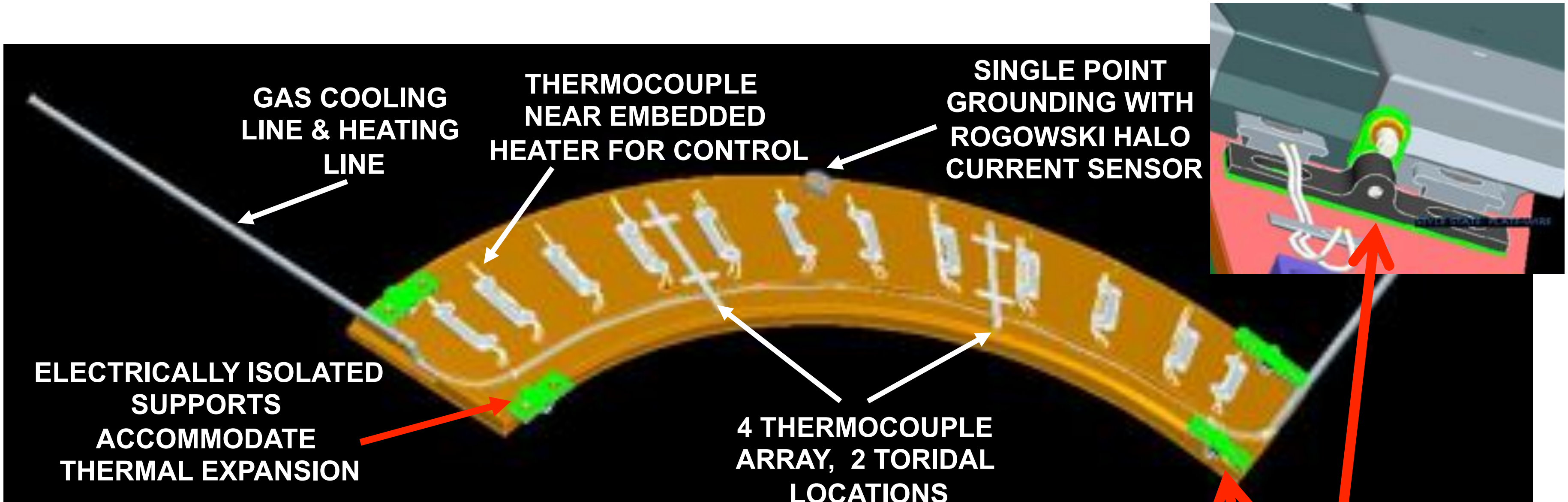




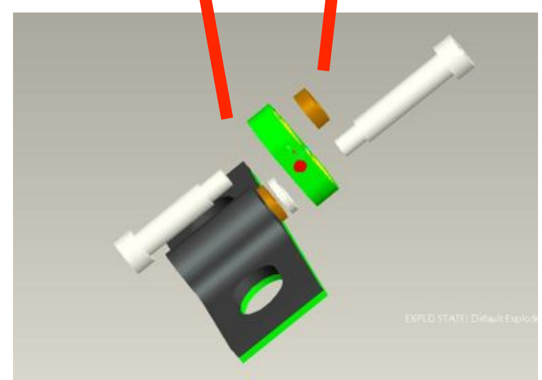


- 4 heated plates (80°each) separated by graphite diagnostic tiles. Each section electrically grounded at one location to control disruption induced currents
- LLD loaded by LITER evaporation
  - 5% of LITER output reaches LLD
  - LLD has 37g Li capacity (100% full)
  - 2010 tests with LLD up to 200% full

Bottom View of LLD-2010 Copper Substrate Plate Showing Heating, and Cooling Components, and Thermocouples, and Induced Current Sensor



- 12 heaters (240v) each with embedded TC for monitoring heater limits.
- 12 TC embedded in copper baseplate for monitoring heat transfer.
- 2 strips of 4 TC each for monitoring torodial and radial temperature variations.
- 1 Center post Rogowski coil for monitoring currents during disruptions of the plasma current.
- Dedicated computer control system.



- Mechanical Support
- Thermal Isolation
- Electrical Isolation

Changing LLD Experimental Conditions During the 2010 Campaign May Have Accelerated LLD Impurity Accumulation

- LLD on outer divertor, was partially heated only during special experiments and cold or not actively heated at other times.
  - Surface was re-melted many times
    (each remelt may have changed surface impurity concentrations)

- Electrical heaters on one unit failed due to an insulation failure between heater cables and vessel wall. Air heater failure on one unit occurred outside the vessel.

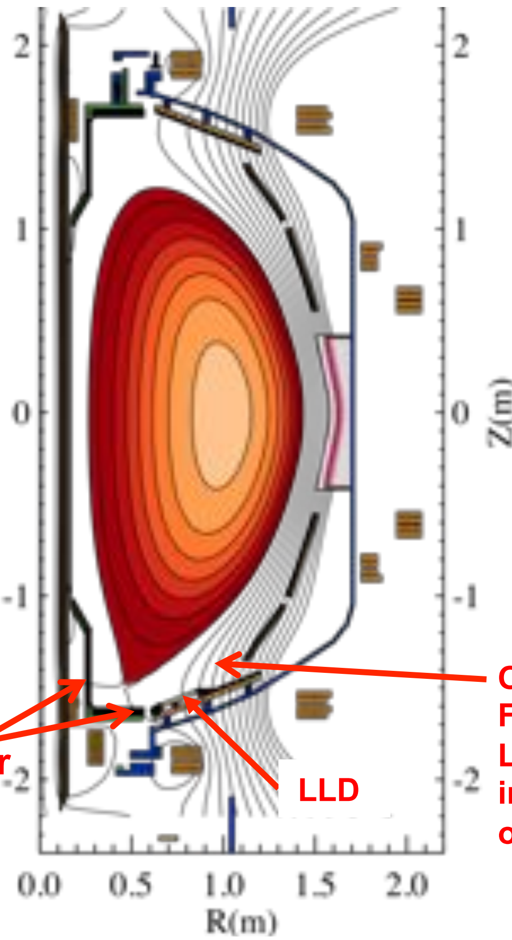
- LLD endured 5 argon vents (possible increased air impurity interactions), and continual redeposition of sputtered C and Li from other experiments.

- Continual lithium deposition 10-40mg/min for 10 mins between discharges, or up to 260g (3 days) for special experiments.

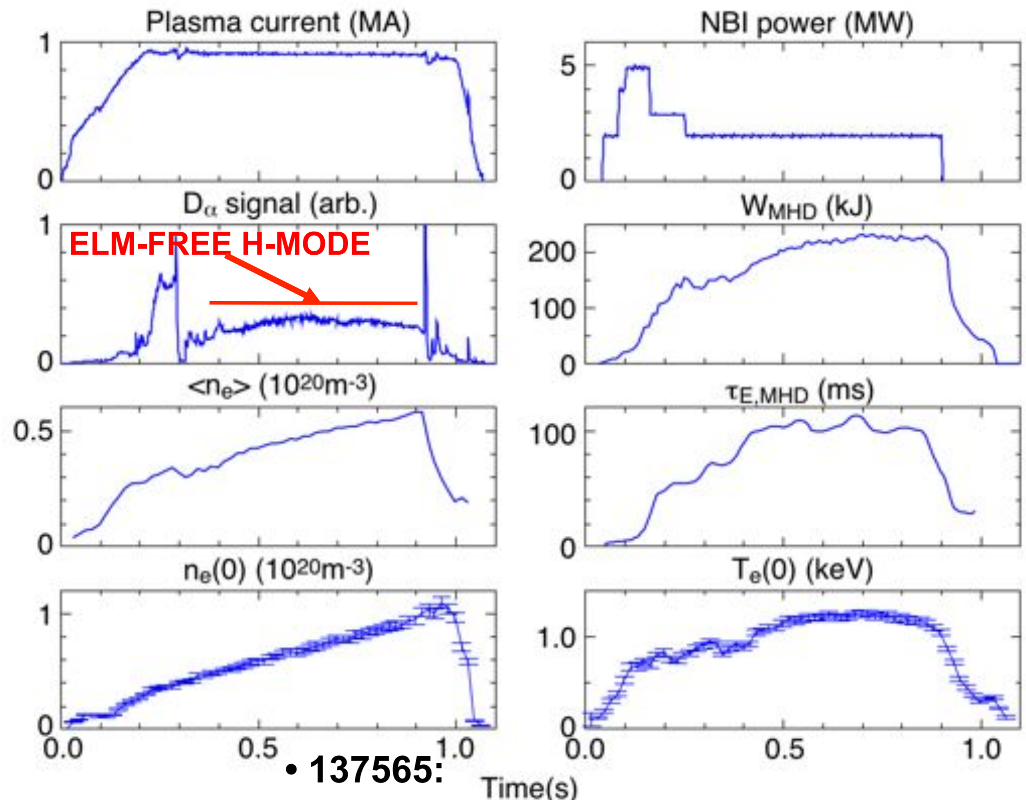
- Evidence of significant buildup of D, and Li-C complexes on the surface of LLD.

- LLD plates became electrically floating early in the campaign due to damage during disruptions in the plasma current, possibly resulting in intermittent biasing.

Early 2010 Campaign: Thin Li Deposition and Only Open Field Lines on LLD Yielded Divertor Discharges Similar to Lithiated Graphite



TYPICAL DISCHARGE OBTAINED WITH LITHIUM WALL CONDITIONS



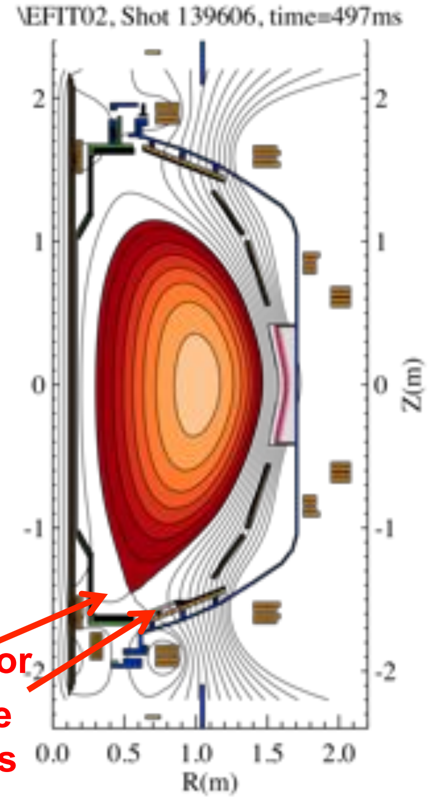
- **137565:**
  - **OSP=0.50m on graphite with open field lines on LLD with Li fill <5%**
  - **LLD T_0 = 319°C, LITER 21mg/min**

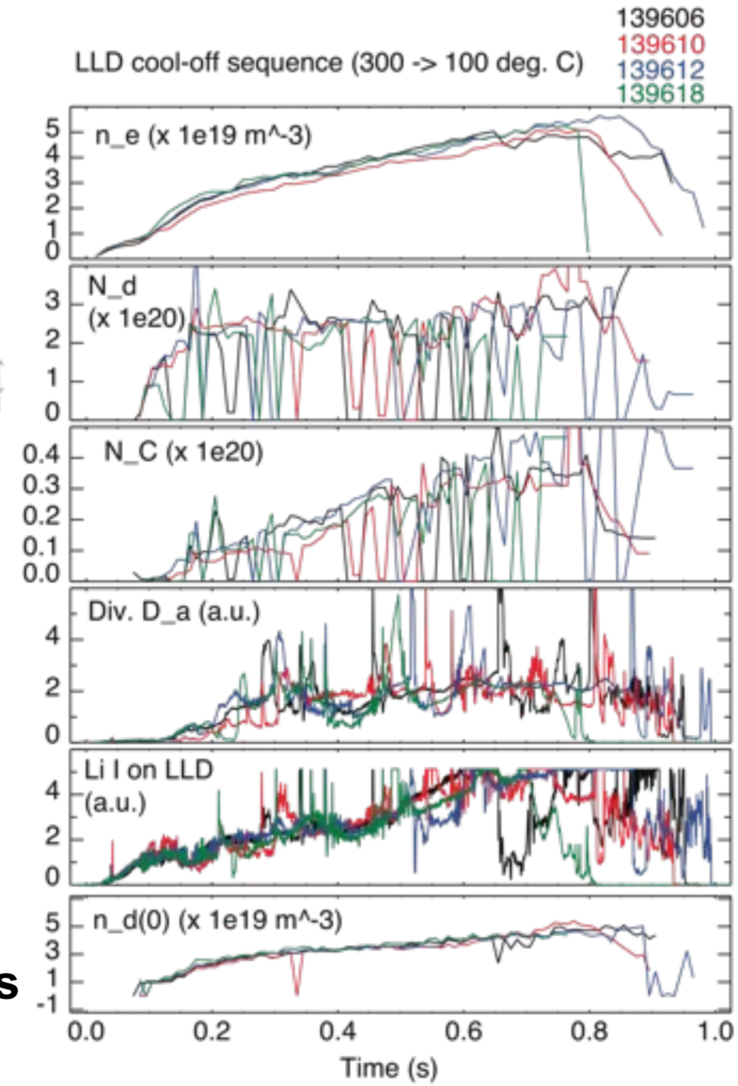
- **The required fueling and resultant edge conditions were about the same as when using lithiated graphite over entire lower divertor**

Mid 2010 Campaign: LLD Operation After 75 Hour Li Evaporation (260 g) on Lower Divertor Area (50% LLD Fill), Pumping With Otr StkPt on LLD Was Comparable to Typical Lithiated Graphite Pumping Rates

- **Diverted operation LLD did not require more fueling.**
- Deuteron core densities and inventories similar regardless of LLD T(°C)
- Core carbon inventories similar to regular LITER discharges
- Less quiescent edge (from Dα measurements)

Divertor Strike Points

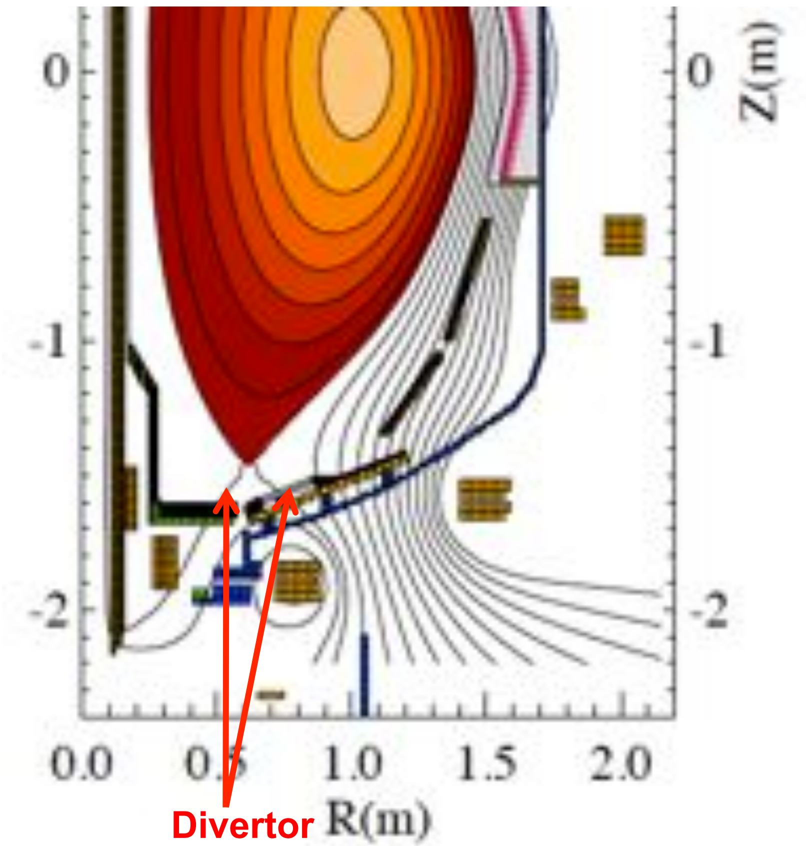




- **First time since 2005, sufficient Li was deposited sufficiently fast to allow at least 30 discharges on the LLD, and then 150 discharges on the lithiated graphite without needing LITER between discharges.**

<u>End of 2010 Campaign</u>: Diverted, Discharges Run With Outer Strike Point in Middle of Liquid Lithium Divertor

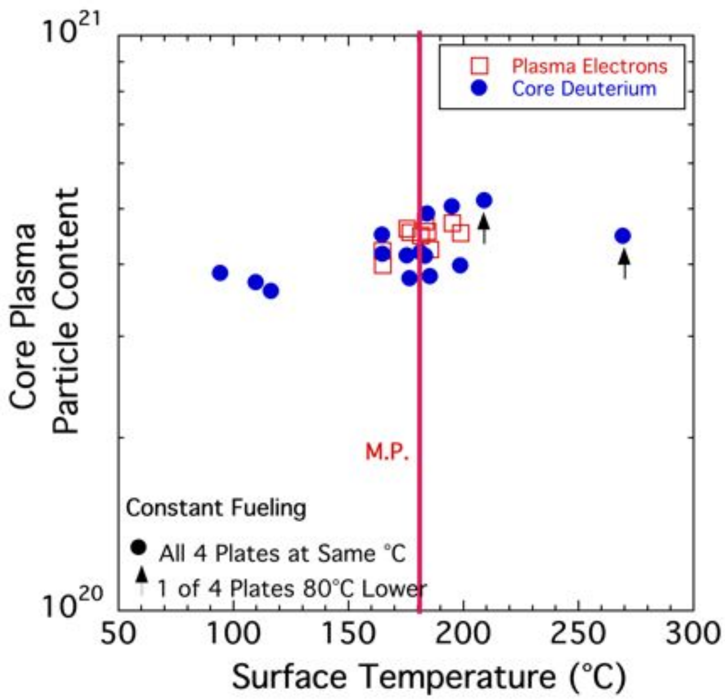
- Discharge
  - I_p = 0.8MA,
  - P_{NB} = 4.0MW
    B_T = 0.48T
    R_{OSP} = 0.78m

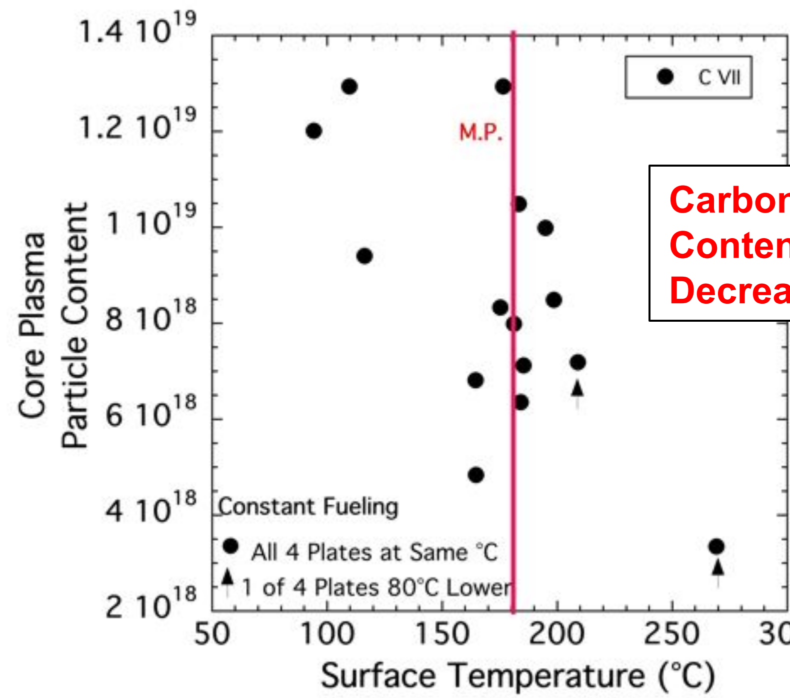


- LLD Lithium Content
  - LLD fill ~200% (67g)
  - Sequence preceded by 7g LITER deposition.
  - No LITER between discharges

End of 2010 Campaign: As LLD Plate Surface Temperature Transitioned from Solid to Liquid Li, Core Plasma Electron Density and Core D Content Remained Relatively Constant, but Core C^{6+} Content Decreased

- **Same Fueling for Each Discharge**
  - **-no additional fueling required to maintain reference discharges**



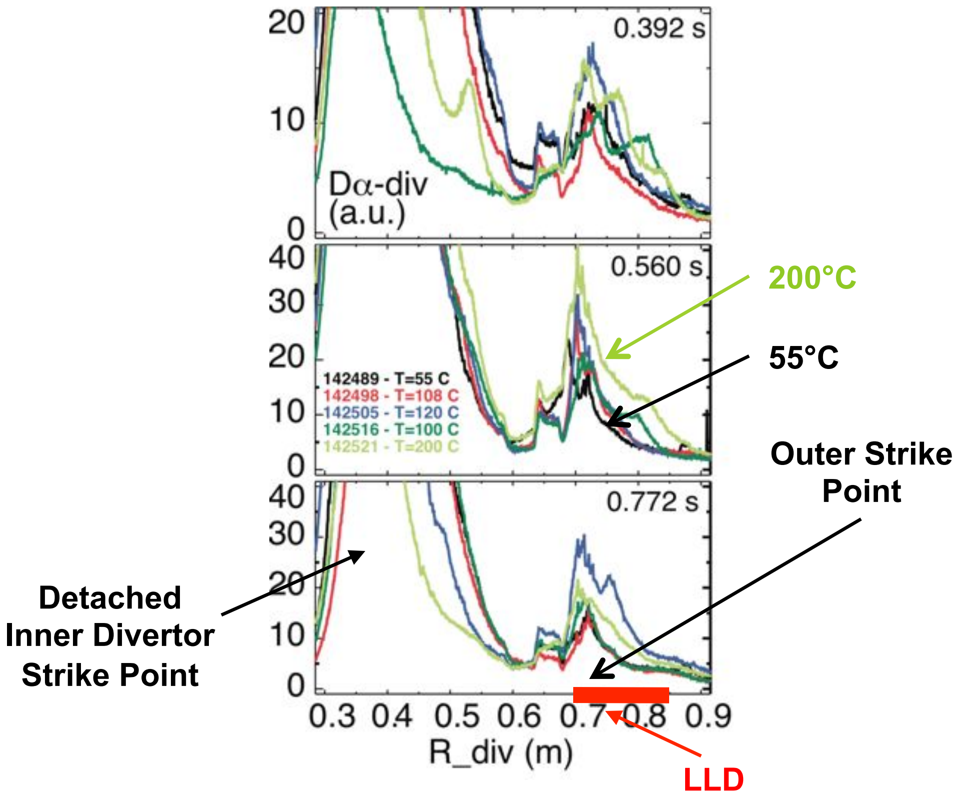


Carbon C^{6+} Content Decreased

- Indicates that D absorption of the solid and liquid lithium were about the same under NSTX 2010 conditions.
- Noteworthy decrease in core carbon may be due to LLD pumping and/or due to less quiescent edge conditions.

End of 2010 Campaign: No Systematic Trend In The Outer Strike Point Divertor Edge D-alpha Luminosity Profile Measured Over The LLD As Its Temperature Was Increased By Plasma Heating

•Dα radial profile for thick solid lithium on graphite tiles & LLD 200% filled. No LITER between discharges.



• Radial profile of edge Dα luminosity exhibited recycling or desorption from LLD.

• Although, at this point in the campaign, the LLD cumulative Li fill was 200%, this was insufficient overcome the cumulative LLD impurities, without LITER between discharges.

2010 LLD Results Based On Required Fueling for Stable Discharges Imply Comparable Solid and Liquid Li Pumping Under NSTX Conditions

- **Early work by McCracken, Erents, and others found fast D retention in clean solid lithium and liquid lithium to be close to unity *for clean surfaces*.**

Vertical scale dependent on surface impurities

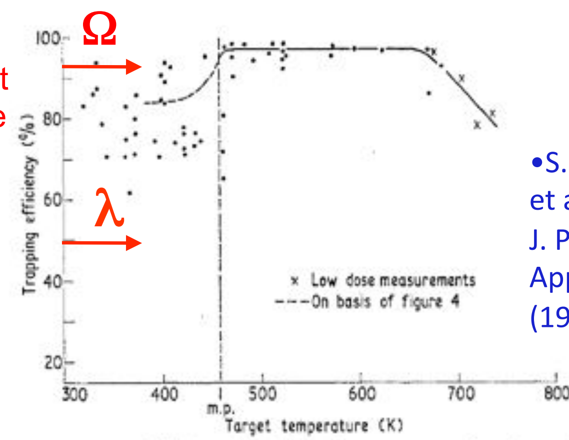


Figure 3. Trapping efficiency of lithium for 18 keV deuterons as a function of temperature for constant dose of 5×10^{17} ions/cm^2.

•S. K. Erents, et al., J. Phys. D., Appl. Phys. 6 (1971) 672.

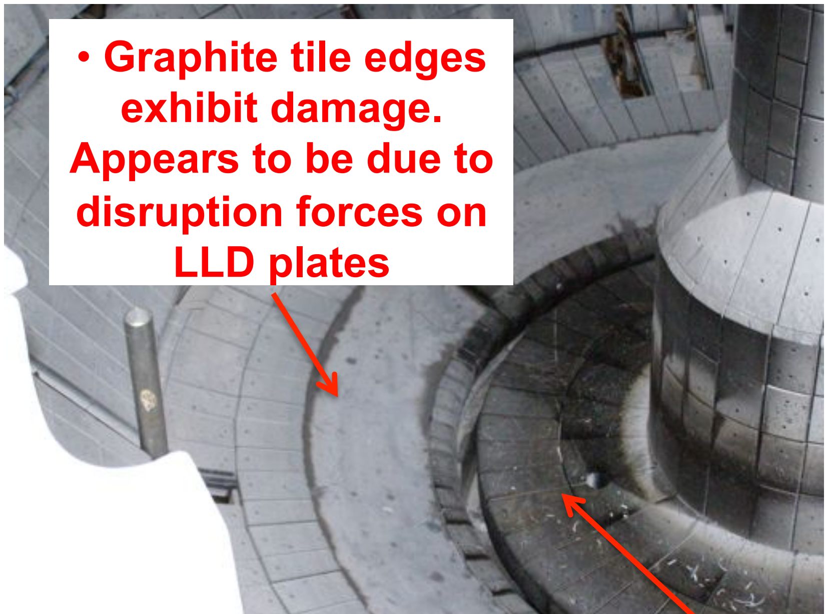
- Laboratory studies for solid Li on graphite, suggested that the retention of D in solid NSTX Li is less than unity due to:
(1) Li intercalation in graphite,
(2) Li interactions with impurities in graphite,
(3) Li reactions with residual gases,
(4) D saturation of the Li surface layers (<250nm),

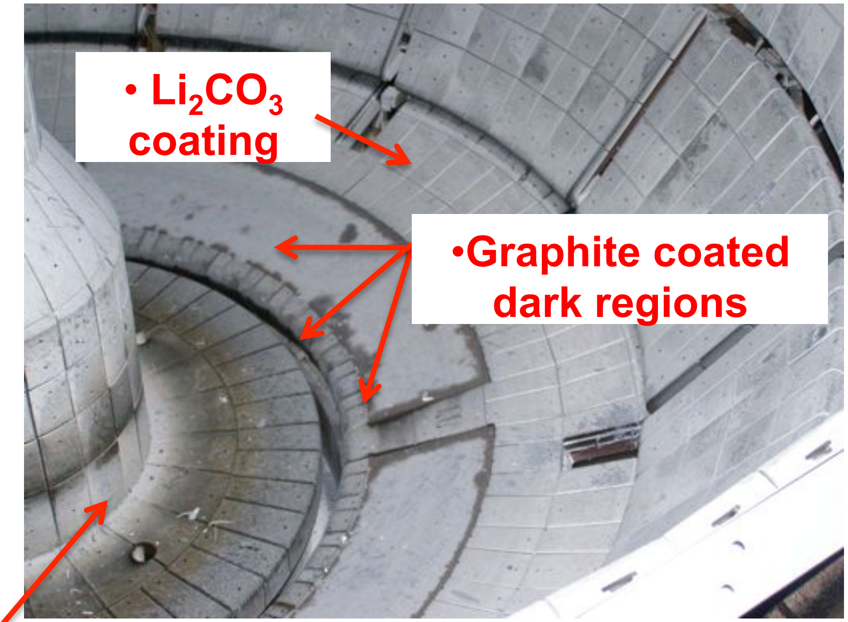
The 2010 LLD measurements tested if liquid Li in the LLD would provide more D-retention, and for longer durations.

- Question: Given the NSTX 2010 results, are the D-retention efficiencies in solid Li and static liquid Li both near unity (Ω), or both much less than unity (λ)?
  - and how did the D-retentions change during the 2010 Campaign?

2010 Photo of NSTX Interior Following 1.3 kg Lithium Deposition Applied During 2010 Experimental Campaign Indicates Extensive Lithium Coverage Due to Direct Evaporation and Plasma Transport

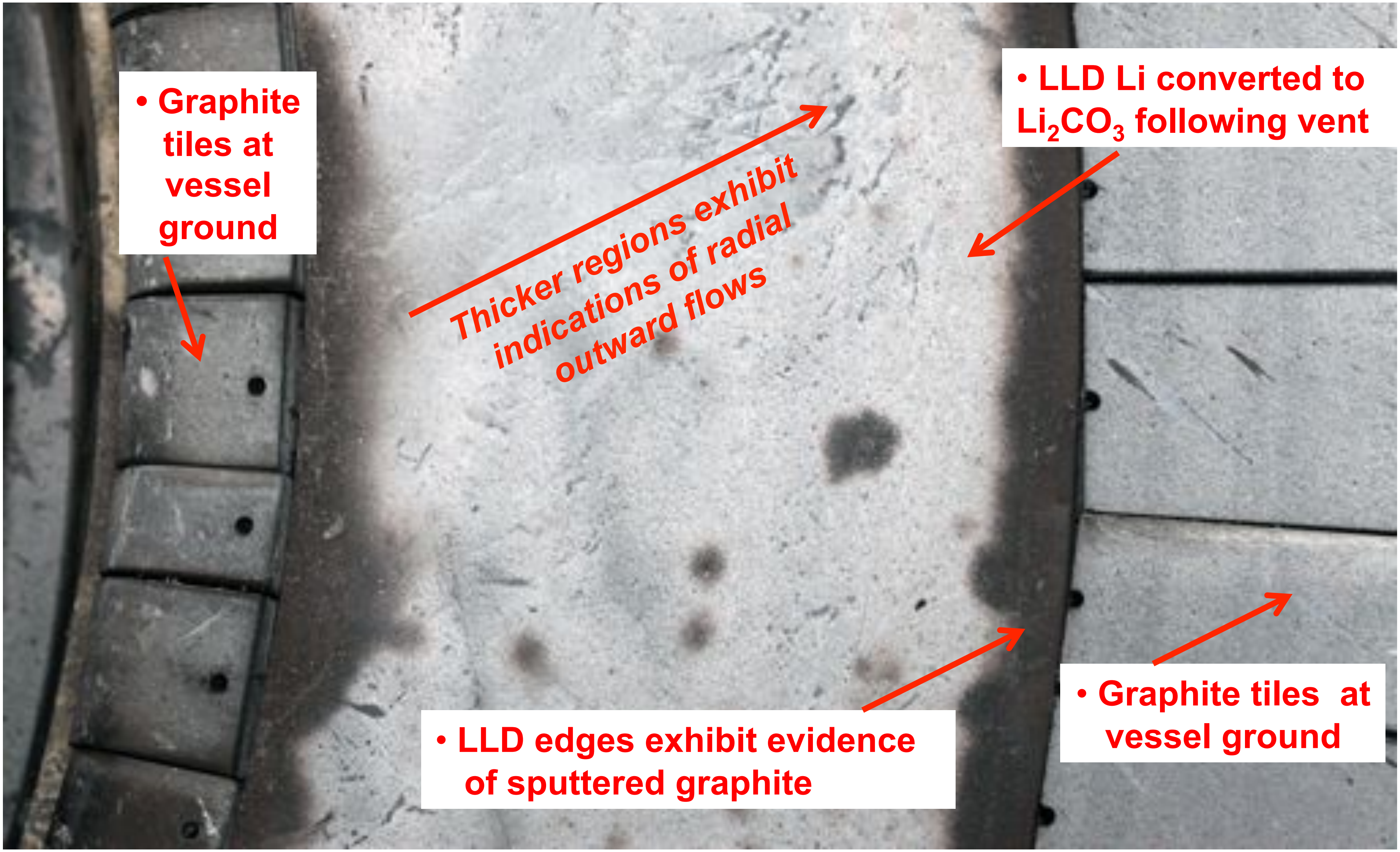
Closer Views of NSTX Interior Following 1.3 kg Lithium Deposition Applied During 2010 Experimental Campaign





• Less lithium on inner divertor where power is usually deposited

Close-up Photo of LLD Plate and Edge Graphite Tiles After 2010 Campaign Using 1.347 Kg Li Deposition

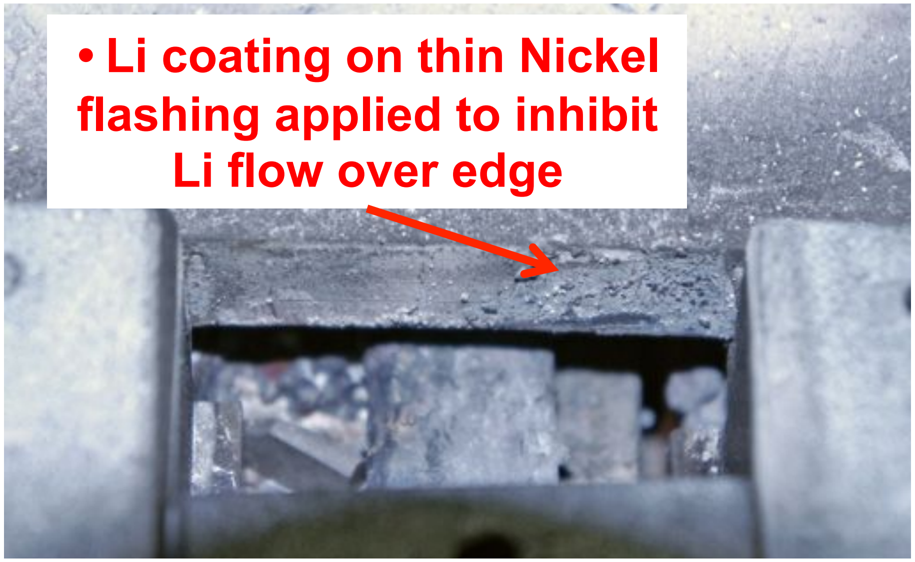


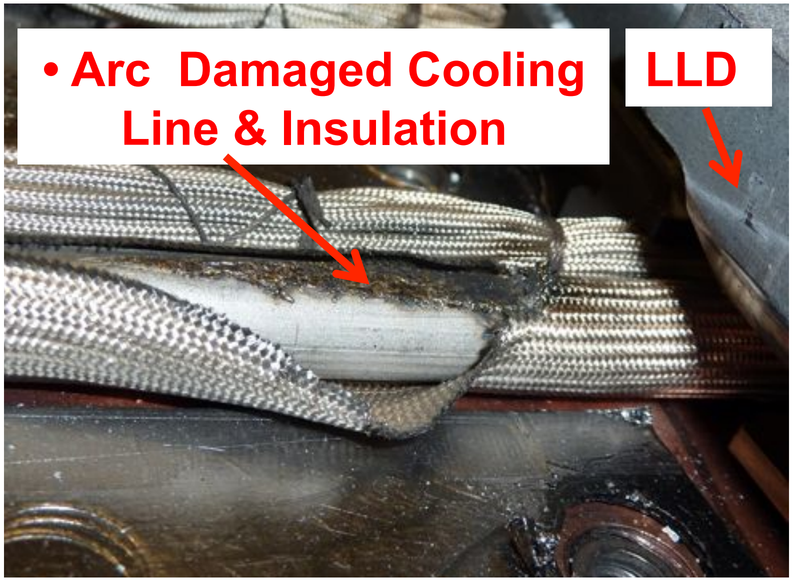
LLD Damaged by Magnetic Forces Induced by Plasma Current Disruptions

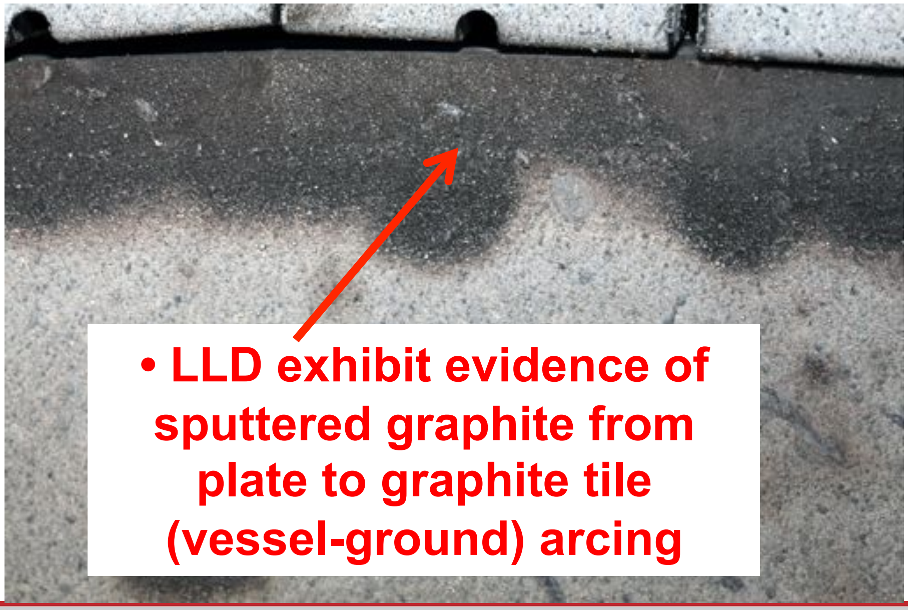
- **The underside of the LLD plates (opposite the plasma facing side) exhibited mechanical and electrical damage attributed to MHD forces during plasma current disruptions that exerted upward and radial outward forces on the plates.**

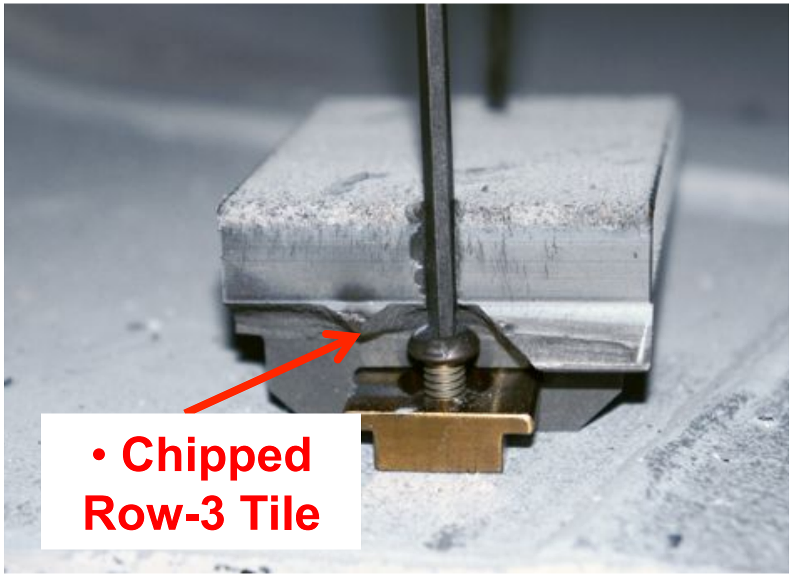
- **LLD plate damage:**
  - **Heater insulation damage prior to start of plasma operations at vessel outer wall, may have compromised plate isolation**
  - **Small, rapid irregular shift of the plates about their locating plug-grounding point resulting in cracked graphite tiles around the edges of the plates, and plate cooling/heating tube abrasion**
  - **Damage to the plate corner supports exhibited as 3 broken support screw pins, deformed copper support holes, and arcing to surrounding structure**
  - **Heavy arcing damage to the electrical ground post**

Photos of LLD 2010 Damage and Lithium Features

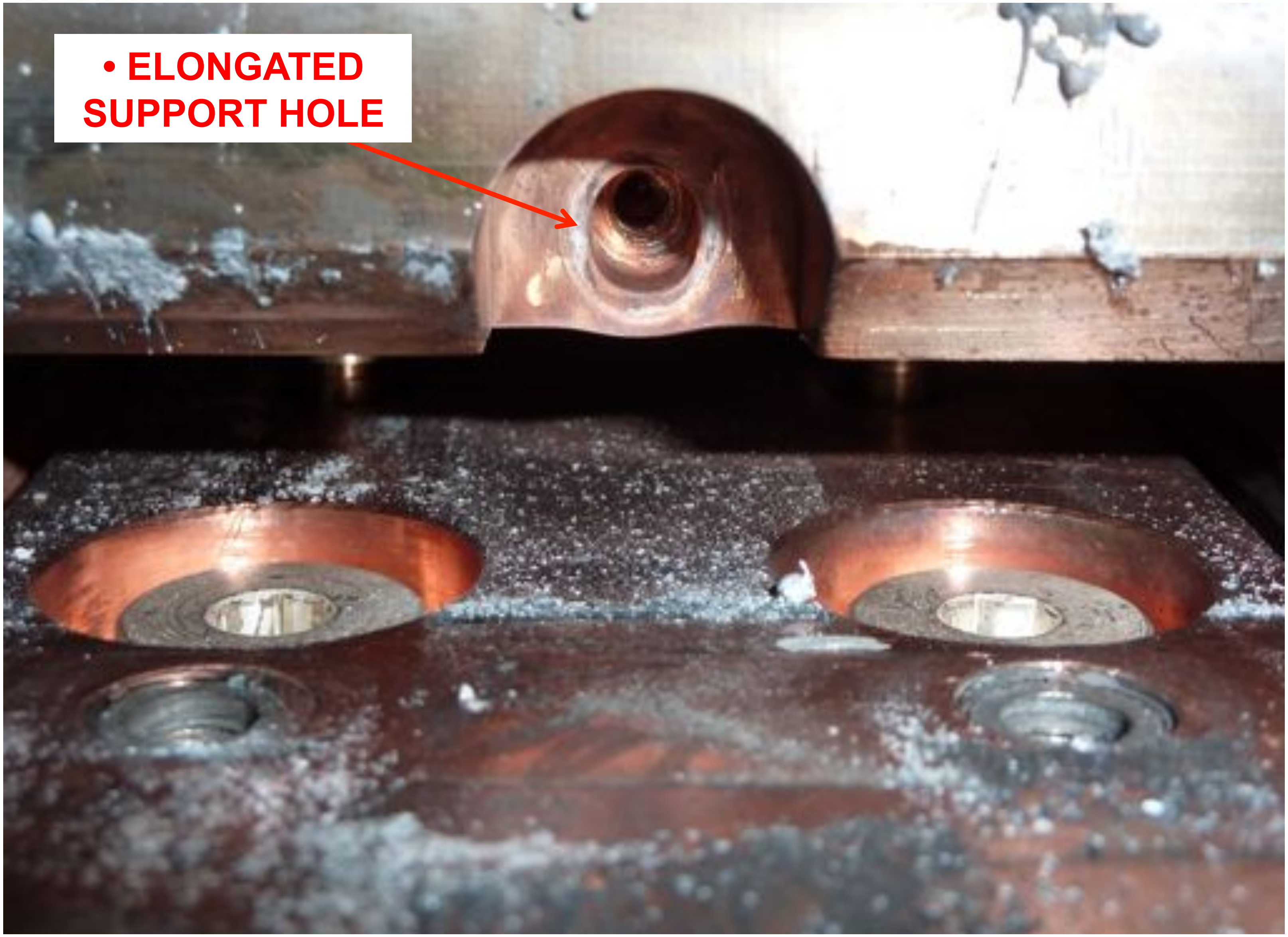




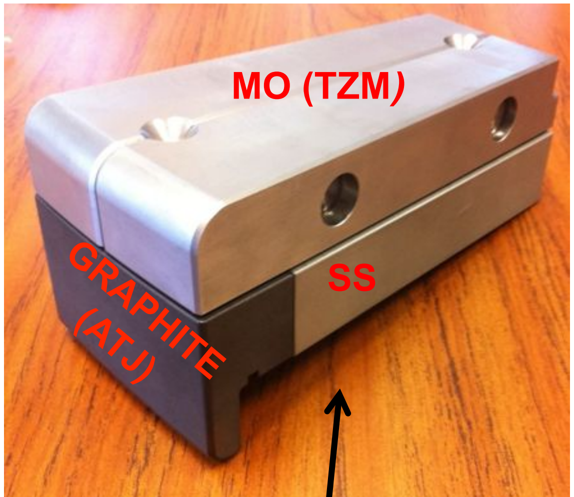




LLD Plate Corner Support Hole Elongated By Disruption Forces



April 2011 Installation Photo of LLD and Molybdenum Tiles
- Both Inner and Outer Strike Points can Be Placed on Molybdenum
- Divertor Carbon Sputtering Source Term Can be Varied by Moving the Discharge



MOLYBDENUM TILE ASSEMBLY

CENTER STACK VERICAL INNER DIVERTOR

HORIZONTAL INNER DIVERTOR
- Graphite (ATJ)
- Mo (TZM)

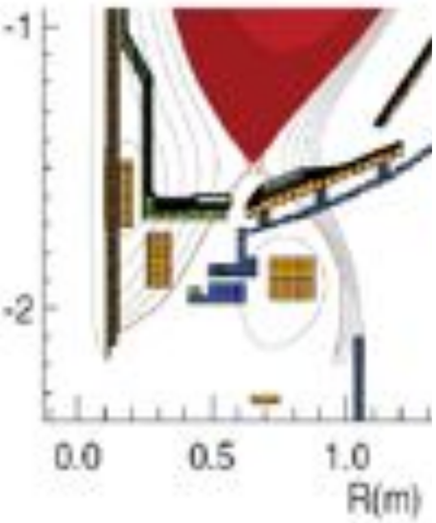
CHI GAP

LLD

Cleaned & Reinstalled

2011 LLD Experiments: Begin with Both LSN Strike Points on Mo-LLD and Mo- Inboard tile

- Flux plot showing both diverted strike points on Mo tile and Mo-LLD



- Measurement Plan (30 discharges)
  - Early in campaign, LITER 20 mg/min, constant fueling
  - Let LLD plasma auto-heat 10°C per shot
  - As LLD transitions through Li melting (180°C) measure:
    - Waveform of Core D and C^{6+} particle content
    - Electron density rate of rise
    - Li, CII, OII, Mo, Prad waveforms
    - Fast IR front face temperature waveforms
    - LP array and edge turbulence measurements
    - ELM characteristics
    - Global wall pumping characteristics
- Scan fueling to determine effect of inboard divertor strike point detachment

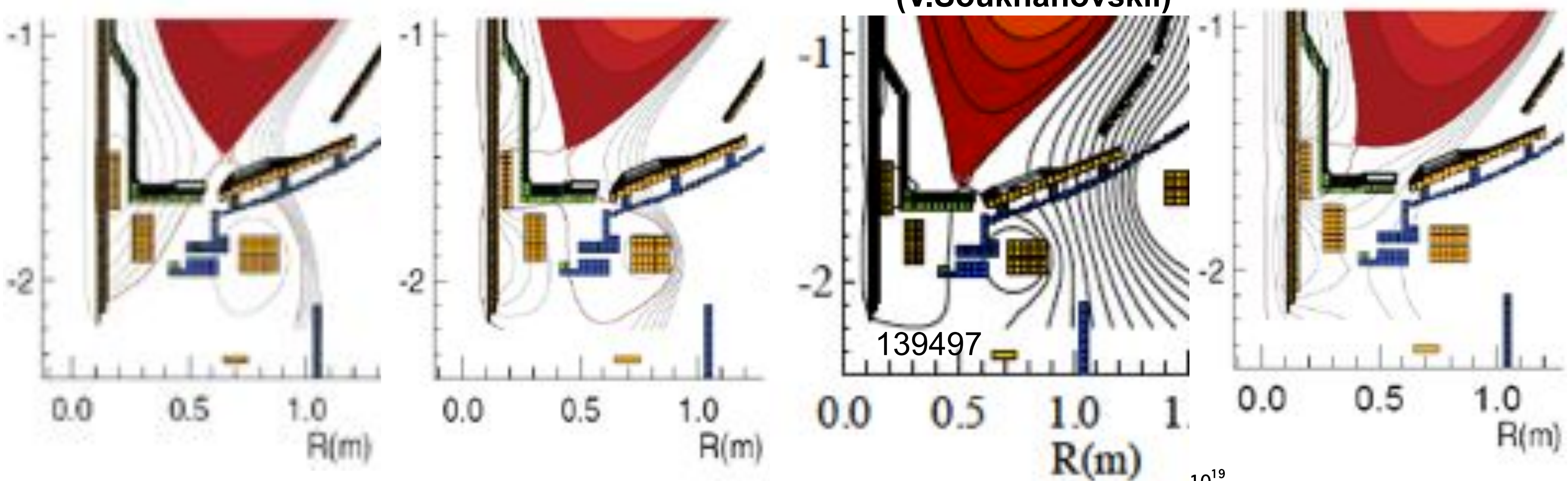
After Step 1, Will Compare 4 Plasmas Incident on Lithiated-Mo and Lithiated-Graphite Divertor

1. Str Pt: Mo-LLD & Mo tile

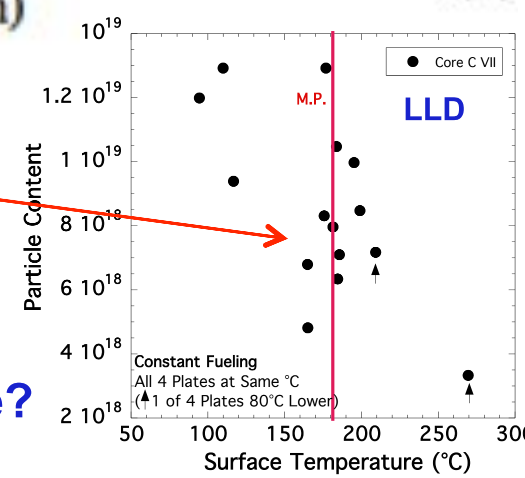
2. Otr Str Pt: Mo-tile Inr Str Pt: Graphite

3. Snowflake-minus Otr Str Pt: Mo tile. (V.Soukhanovskii)

4. Both Str Pts on Graphite



- **Experimental questions for 2011/12 Campaign:**
  - **How does core C^{6+} change?**
  - **How does core D^{+} change?**
  - **How does electron density rise change?**
  - **How does edge C source term change, Prad?**
  - **How do edge conditions (ELMs, quiesence) change?**



Summary and Conclusions

- LLD operation successfully demonstrated with strike point on lithium-filled surface (required for NSTX-U to have full power, long pulse Li PFC conditions)
    - Longterm thermal response dominated by thermal mass of the copper
    - No macroscopic evidence of surface damage by lithium or heating

- LLD in its effect on plasma performance did not clearly differ from evaporative lithium coatings
    - LLD static lithium surface exhibited a degradation due to D and impurity buildup during a 19 wk, 3700 discharge, experimental campaign.
    - LLD temperatures exceeded melting point of lithium but lithium compounds from impurities remained undissolved on surface

- For the first time, sufficient lithium was deposited, sufficiently fast, to allow at least 30 discharges on the LLD, and then 150 discharges on the lithiated graphite without LITER needed between discharges (can be extended for longer pulses)

- Issues of lithium vacuum chemistry need investigation for both static liquid lithium analysis, and the design of flowing lithium system for NSTX-U.