NSTX

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NSTX Plasma Operation with a Liquid Lithium Divertor (LLD)

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for the NSTX Research Team

Plasma Facing Components Meeting

August 10-12, 2011, ORNL, Oak Ridge TN

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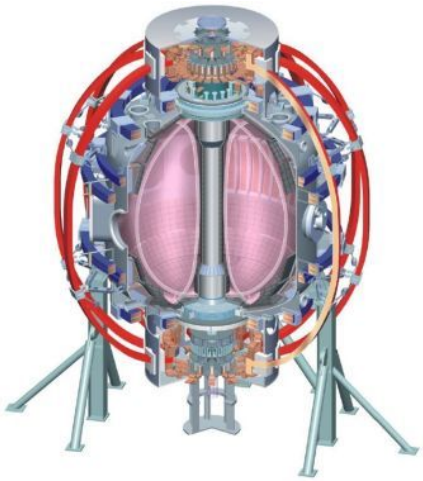

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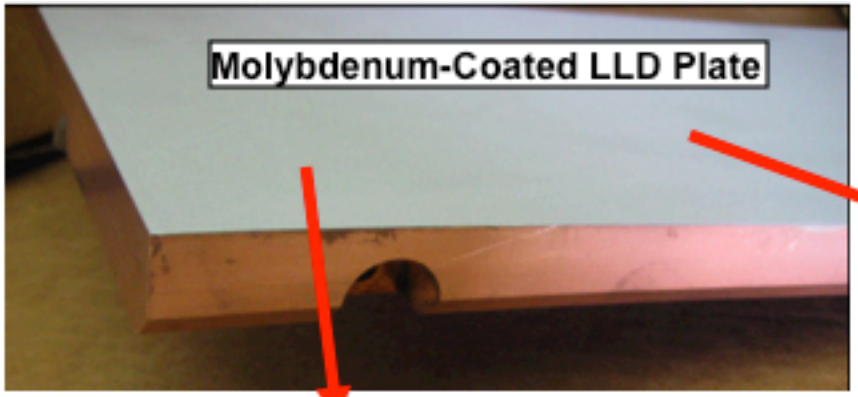
NSTX Plasma Improvements with Solid Lithium Coatings 2005-2009 Motivated the 2010 Installation of a Liquid Lithium Divertor

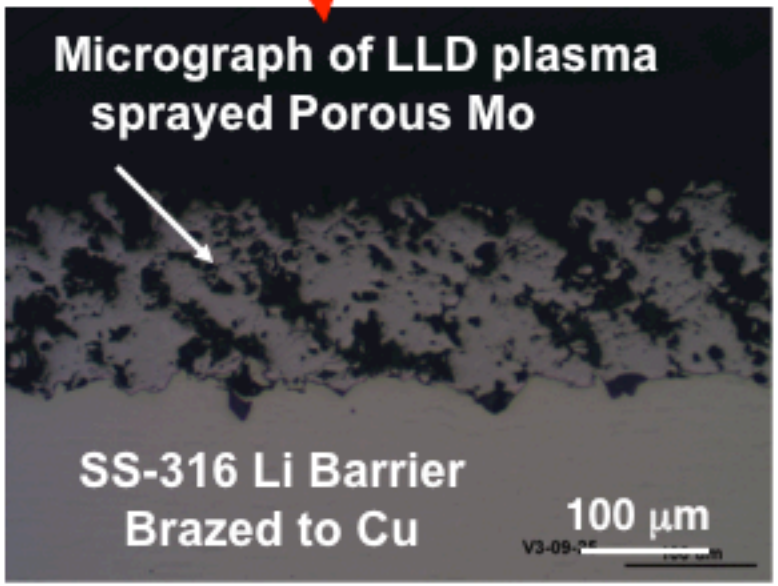
- In NSTX *edge recycling of D fuel is reduced* as the plasma D efflux is retained in lithium and lithium compounds:
  - Solid lithium coatings provide short pulse capability but have limited capacity to absorb D and getter impurities and must be renewed between discharges
  - Liquid lithium has much higher capacity for absorbing D, and has potential for power handling and self healing walls

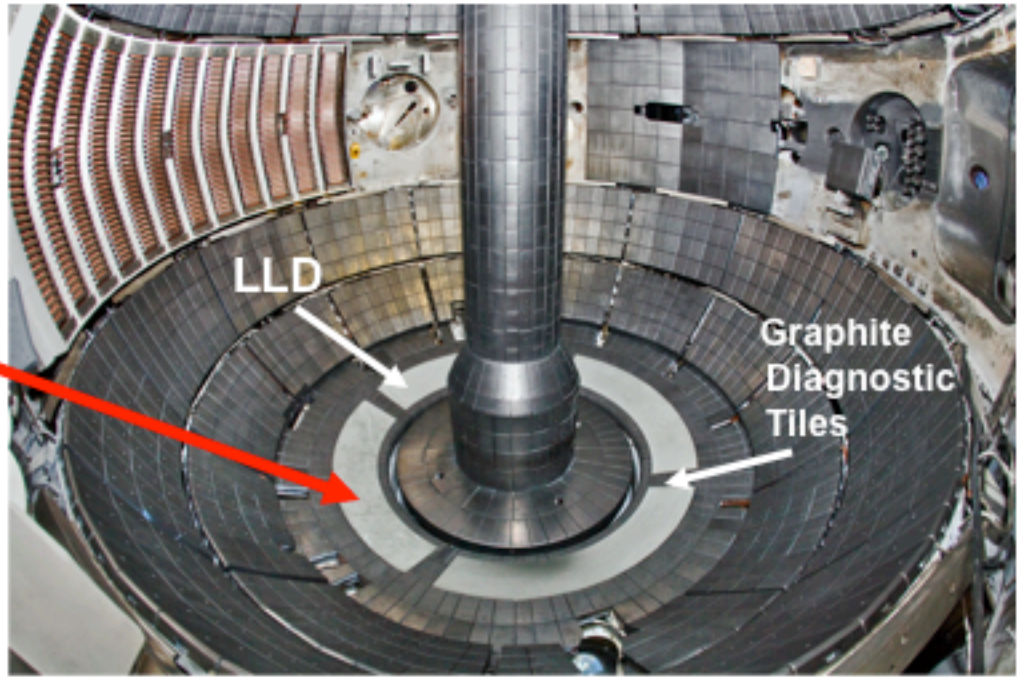
- NSTX 2010 installation and operation of the liquid lithium divertor (LLD) was designed to test:
  - A molybdenum substrate compatible with liquid lithium and able to withstand high heat loads.
  - *An approximation to the lithium surface purity achievable with a flowing liquid lithium system* using a static porous system replenished by fresh deposition from evaporators.

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.

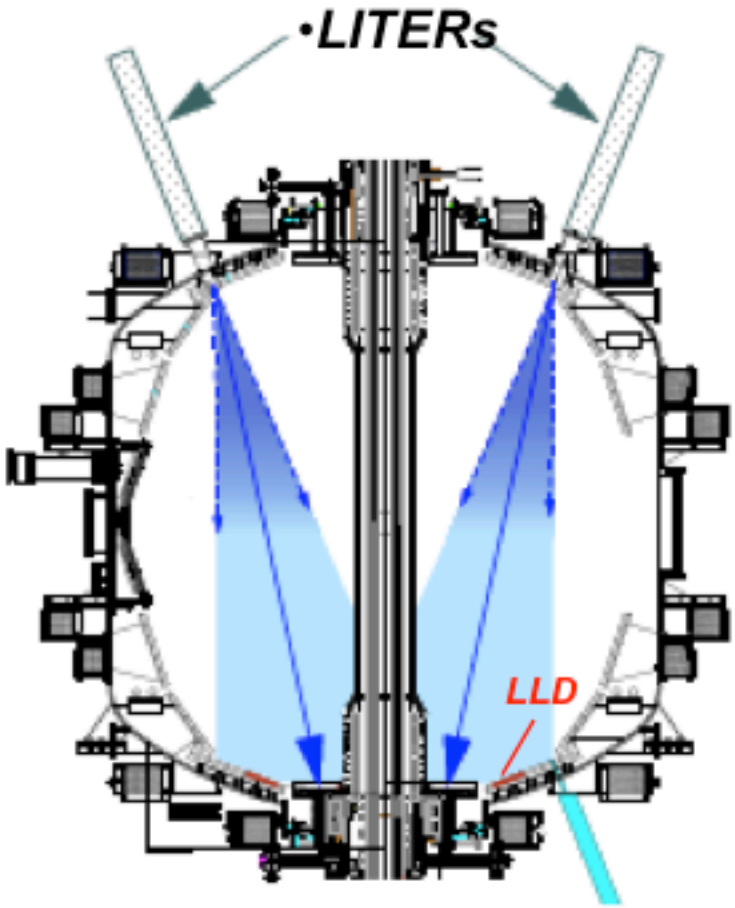






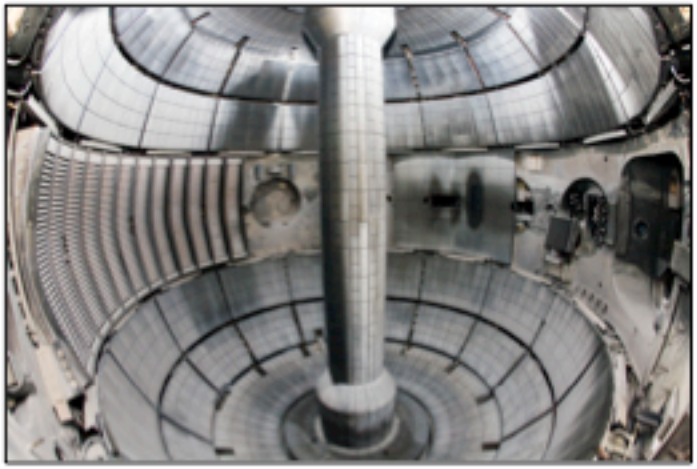
- 4 heated plates (80°each) separated by graphite diagnostic tiles. Each section electrically grounded at one location to control disruption induced currents
- LLD loaded by LITER evaporation
  - LLD has 37g Li capacity (100% full)
  - 2010 tests with LLD up to 200% full
  - 5% of LITER output reaches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

Since 2008, Dual Lithium Evaporators (LITERs) Are Used To Deposit Lithium Coatings On NSTX Lower Divertor for 10 minutes Between About 90% of Discharges



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

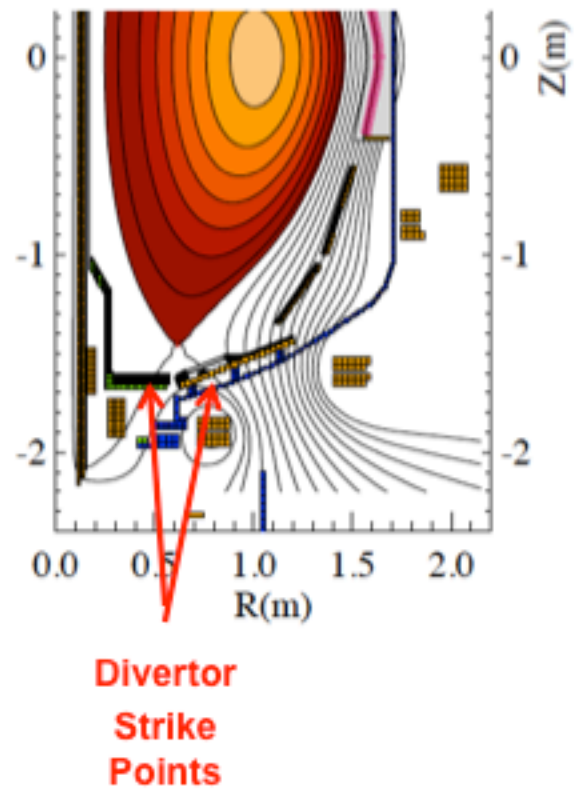
- Lithium transported over broad area by wings of LITER distribution and plasma migration.



- 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 ($LiC_2H_3O_2$)

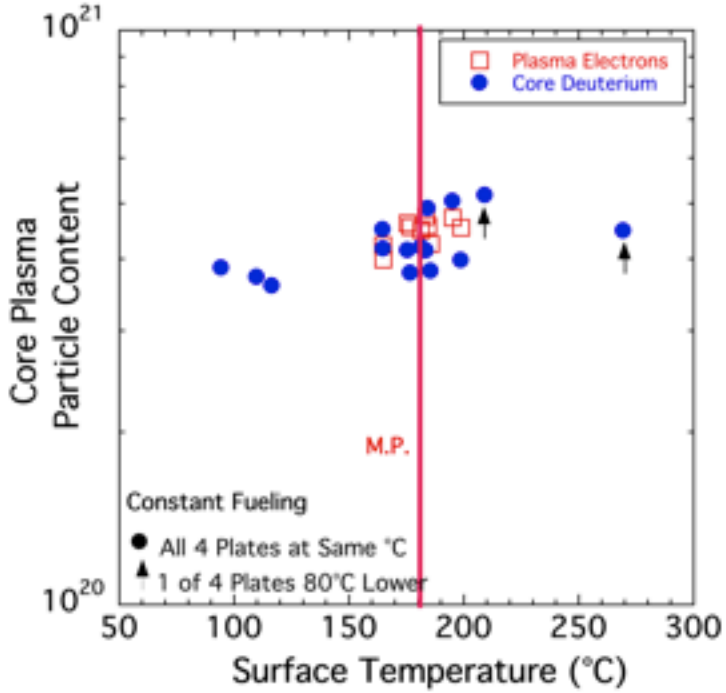
NSTX 2010 Liquid Lithium Divertor (LLD) Results

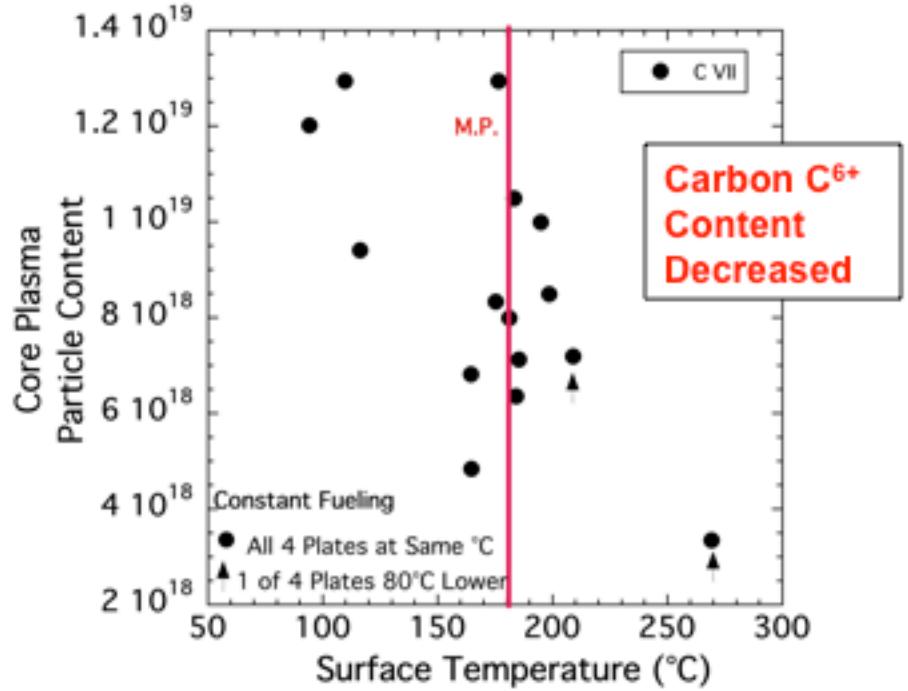
- LLD in its effects on plasma performance did not clearly differ from those of lithium evaporated on graphite (lithiated graphite)
  - LLD temperatures exceeded melting point of lithium
  - Indications of thick lithium impurities on the LLD surface
- Using divertor strike points on lithium-filled LLD surface successfully demonstrated:
  - Long-term thermal response dominated by thermal mass of the copper
  - No macroscopic evidence of surface damage by lithium or heating



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

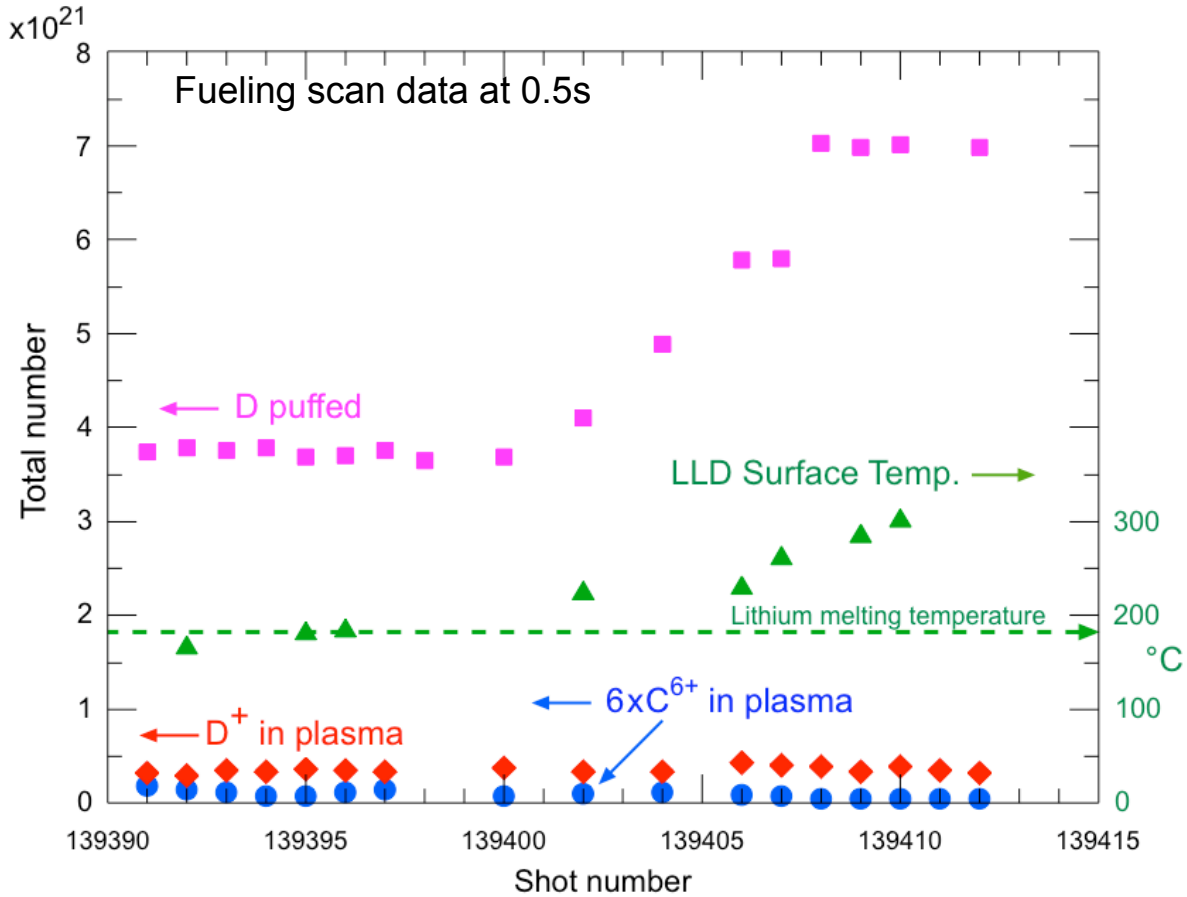




- Indicates that D absorption of the solid and liquid lithium were about the same under NSTX 2010 conditions.
- Noteworthy decrease in core carbon may be due to LLD pumping and/or due to less quiescent edge conditions.

The Difference Between the D Gas Input and the Plasma D Content Reached High Values In This Scan Without Disrupting the Plasma, but There Was Little Change in the Plasma Deuterium Content.

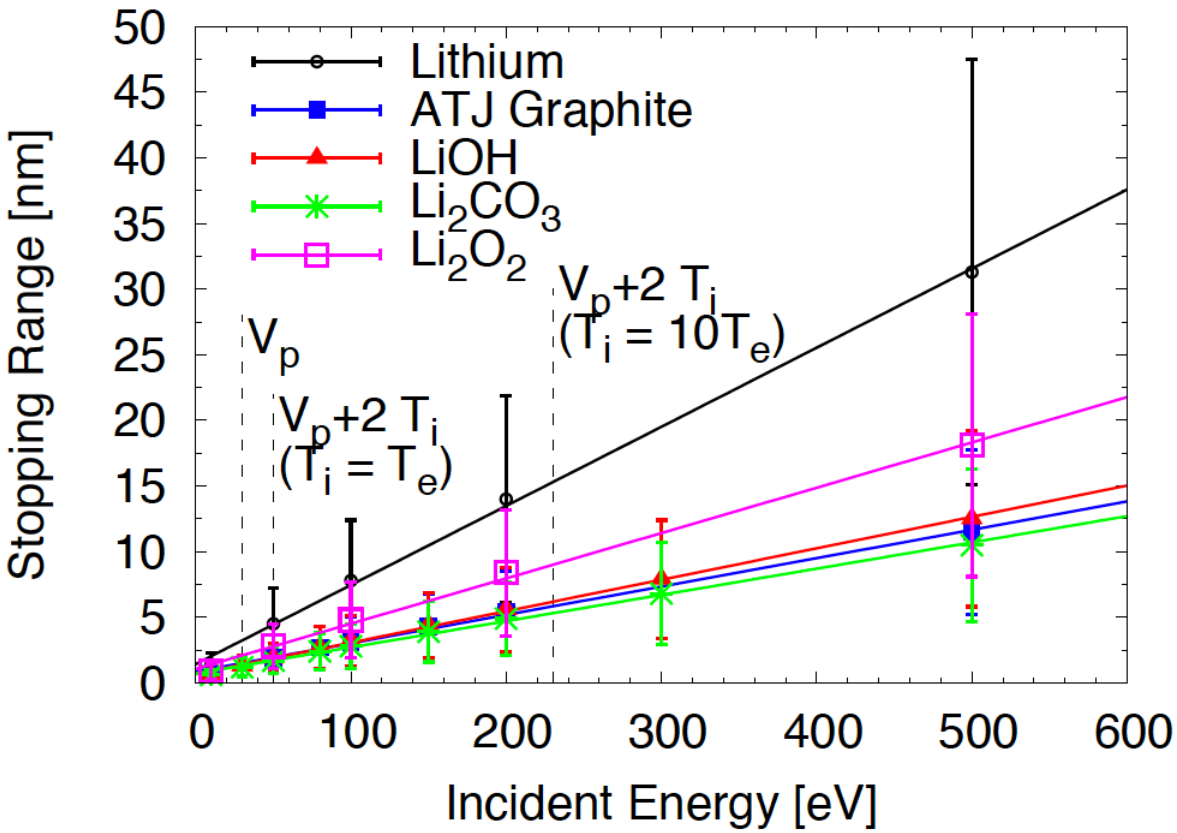
- Total number of D particles puffed (gas fueling), and the resultant D and C^{6+} plasma content versus LLD surface temperature during the plasma.



- Need to investigate if the added D, after becoming ionized in the SOL open field-lines, flowed to the divertor, and was absorbed by the liquid lithium rather than increasing the plasma density.

D Incident on LLD at Diverted Strike Point Stopping in Lithium Compounds on LLD Surface

- Static liquid lithium on LLD, getters NSTX Vacuum partial pressures (H_2O, CO, CO_2)
- Divertor LP array (NSTX/UIUC) and midplane CHERS indicate D ion energies of ~50eV incident on the resulting LLD surface of lithium impurity compounds

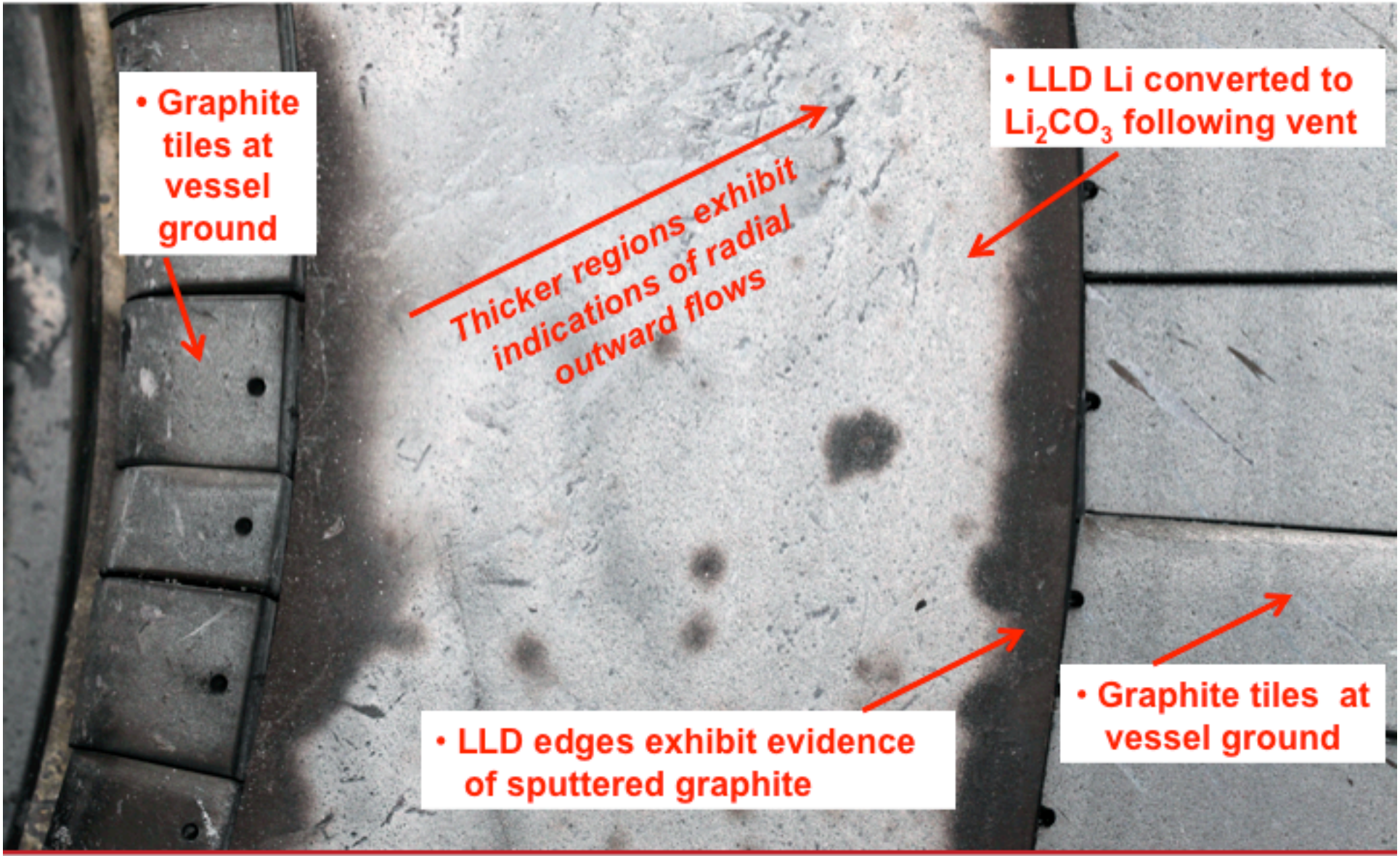


Reference TRIM Stopping Range Calculation
-M. Jaworski

- Work is in progress to investigate if D-Li-O-C complexes on lithiated graphite and static liquid lithium surfaces exhibit similar D retention.

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

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

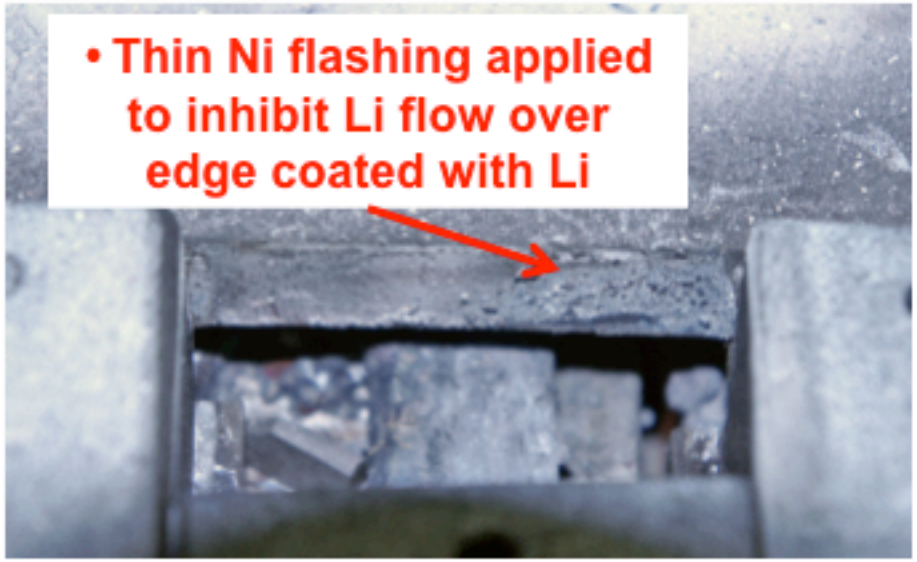


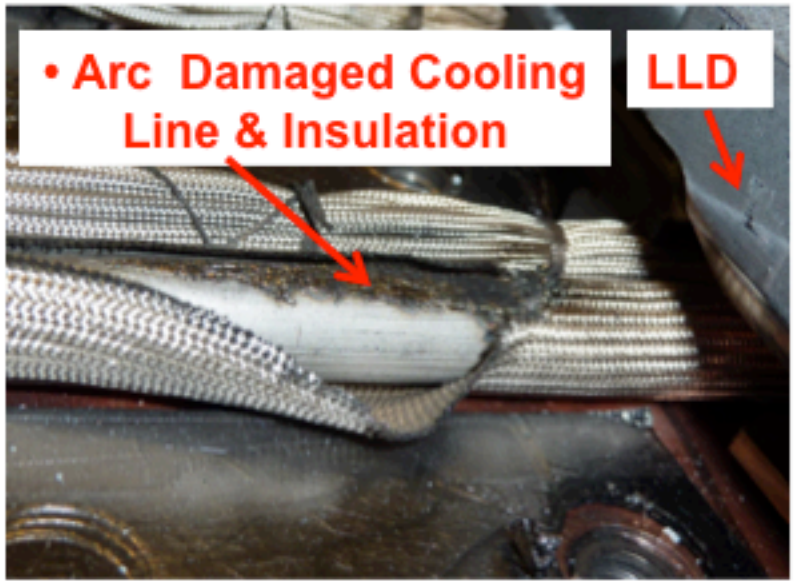
LLD Damaged by Magnetic Forces Induced by Plasma Current Disruptions

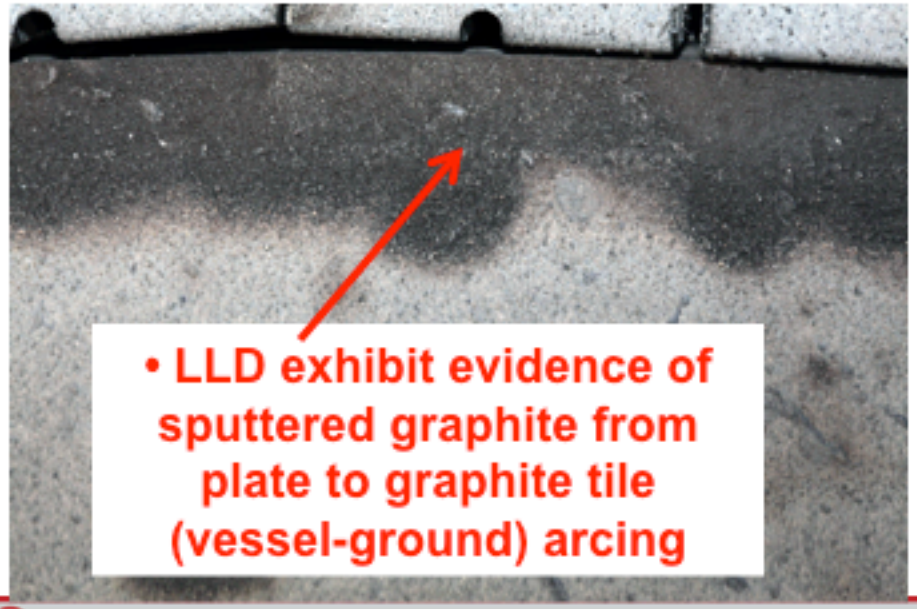
- The underside of the LLD plates exhibited mechanical and electrical damage attributed to MHD forces during plasma current disruptions that exerted upward and radial outward forces on the plates.

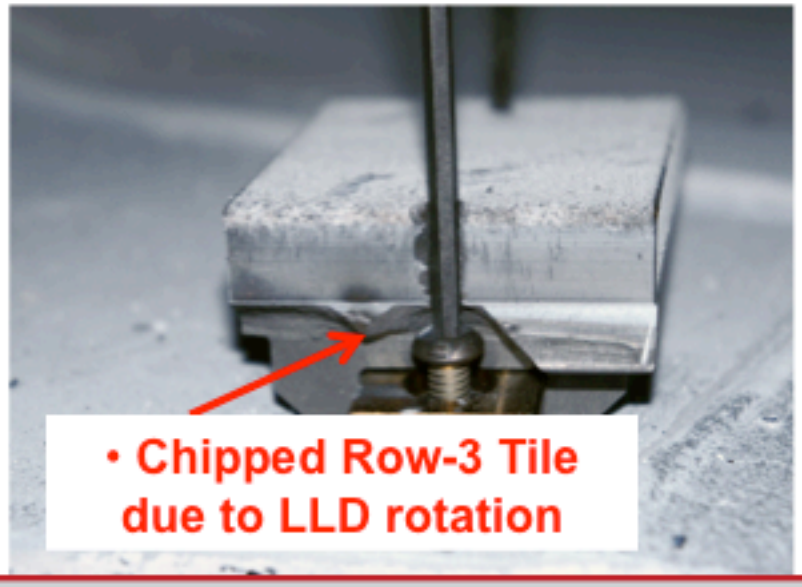
- LLD plate damage:
  - Heater insulation damage prior to start of plasma operations at vessel outer wall may have compromised plate isolation
  - Small, rapid irregular shift of the plates about their locating plug-grounding point resulting in cracked graphite tiles around the edges of the plates, and 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

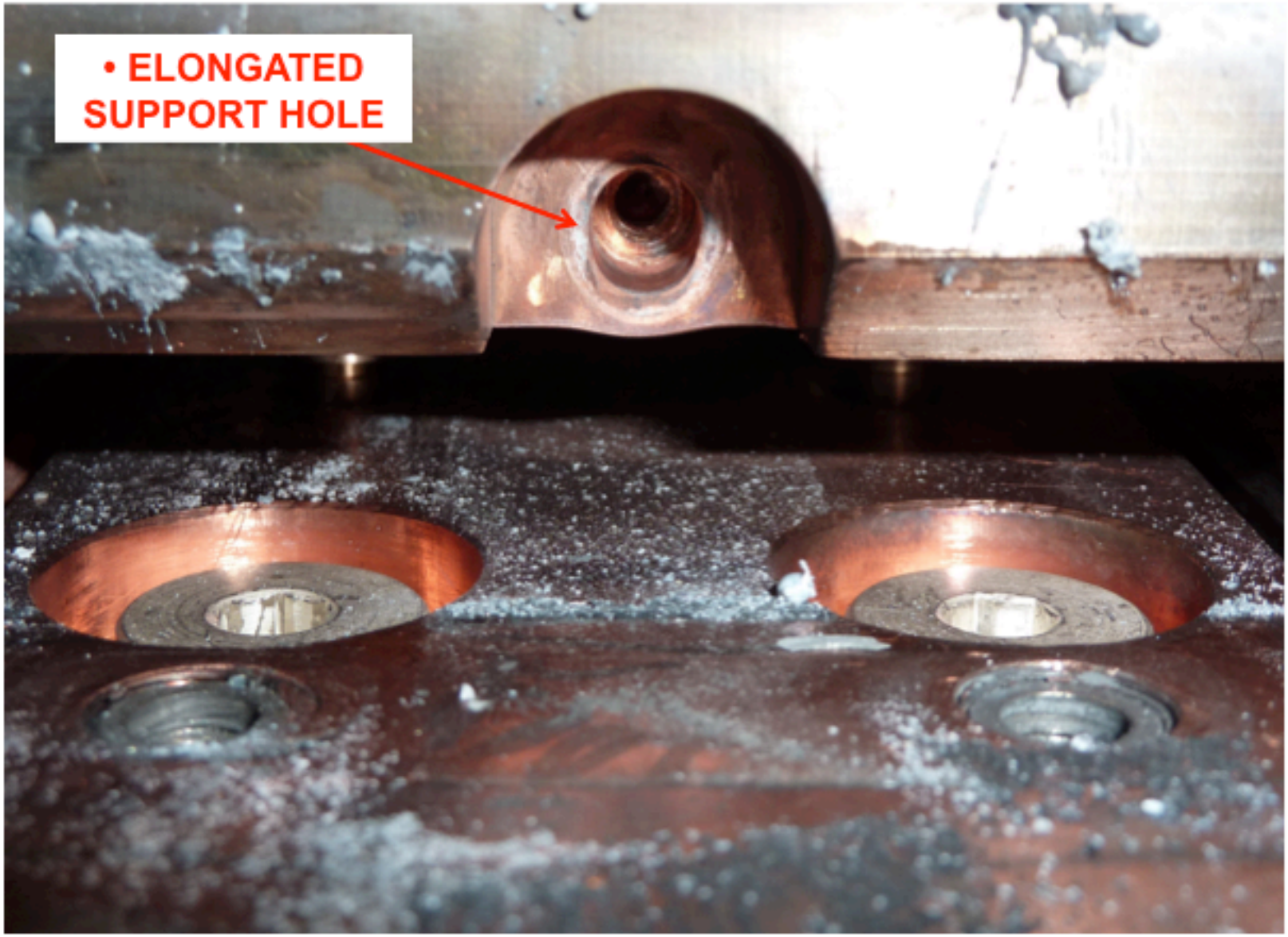








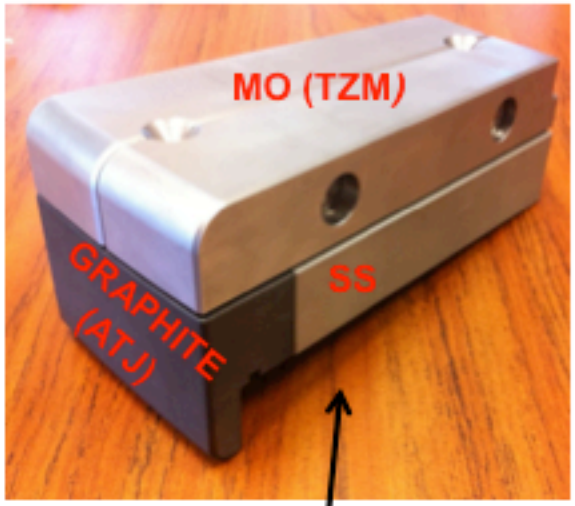
LLD Plate Corner Support Hole Elongated By Disruption Forces

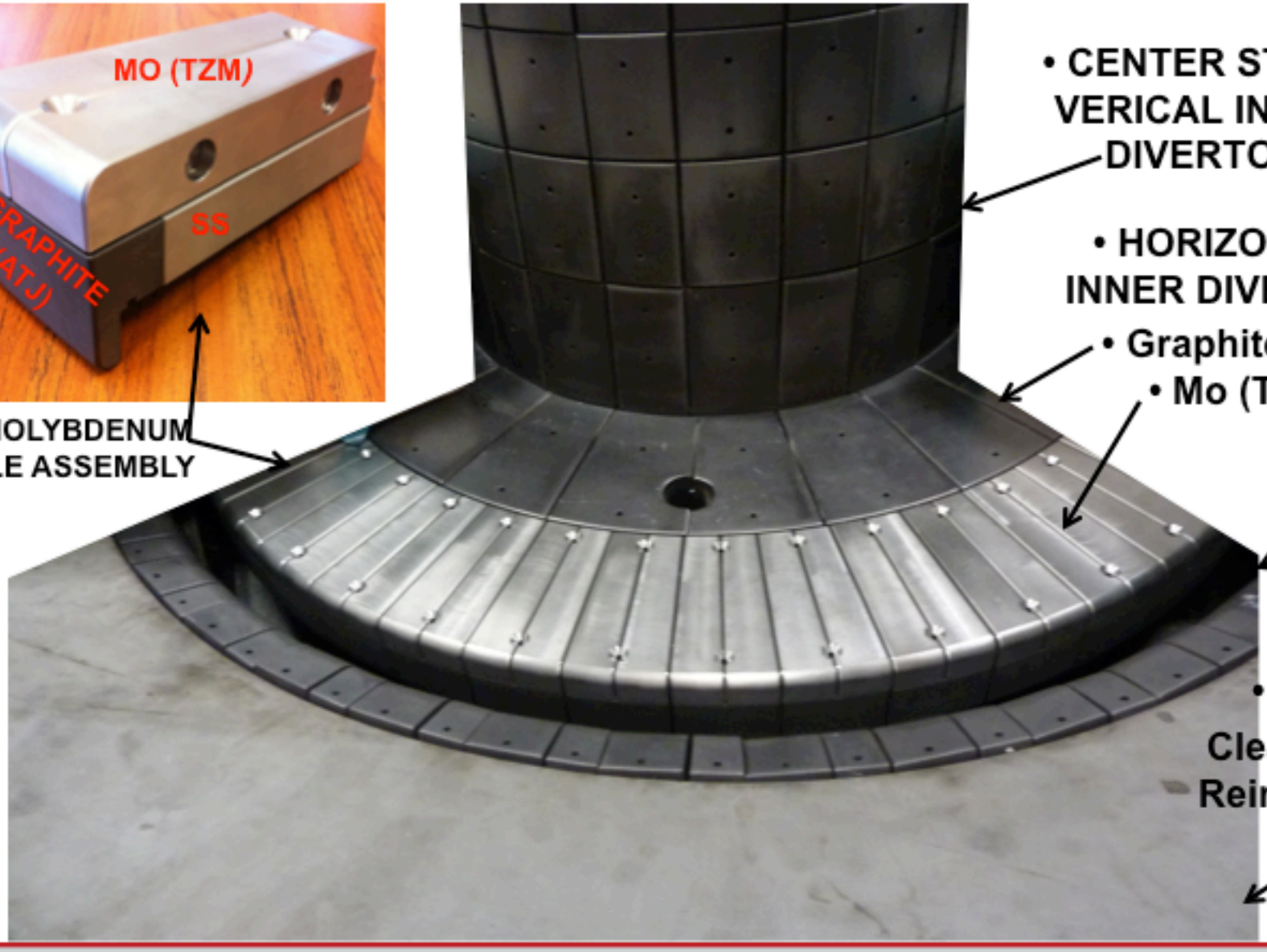


April 2011 Installation Photo of LLD and Molybdenum Tiles

- Both Inner and Outer Strike Points can Be Placed on Molybdenum

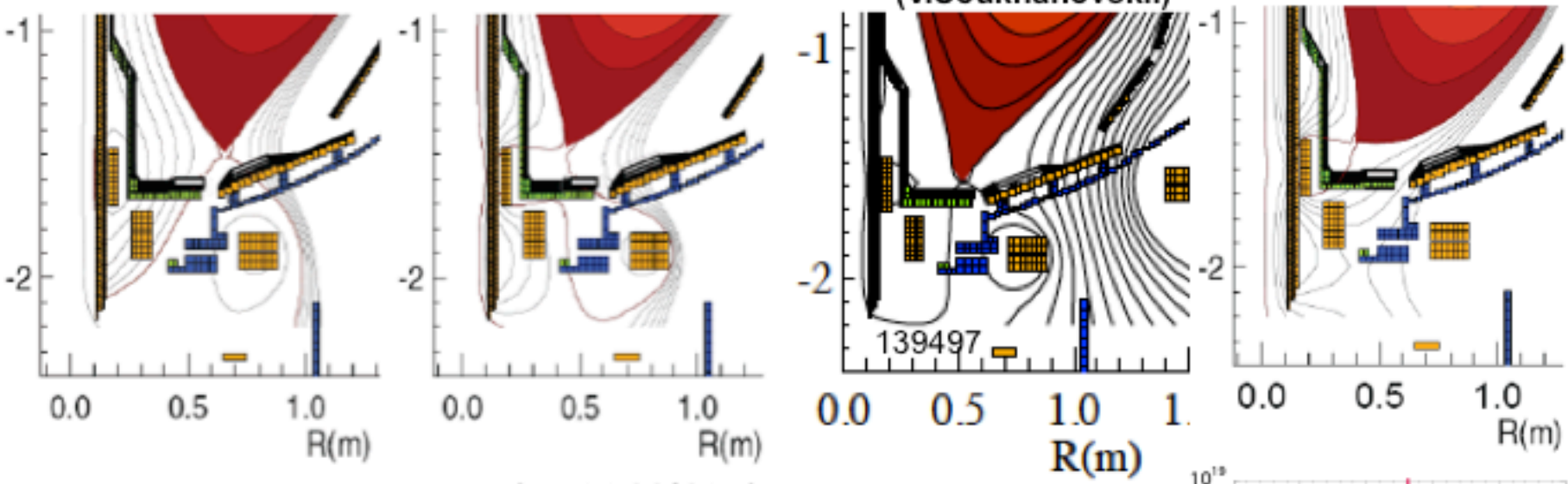
- Divertor Carbon Sputtering Source Term Can be Varied by Moving the Discharge



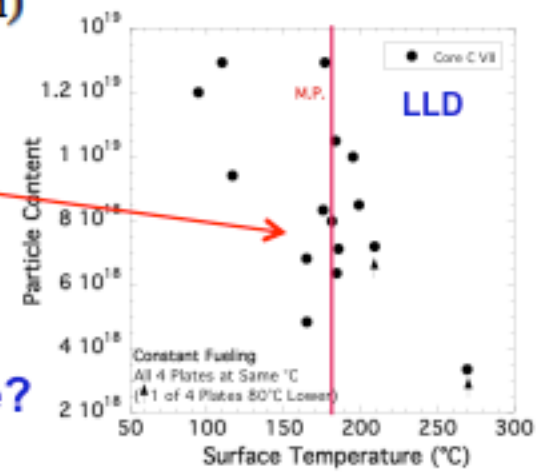


2012 Plan is to Compare 4 Plasmas Incident on Lithiated-Mo and Lithiated-Graphite Divertor

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)
  - Long-term 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 impurity compounds may have covered surface

- Issues of lithium vacuum chemistry need investigation for both analysis of the static liquid lithium results, and the design of flowing liquid lithium system for NSTX-U.
  - 0.1 mm thick liquid lithium moving at~1 cm/s, is sufficient
    - for impurity control and to test Zakharov fusion wall regime (2nd ISLAPD)
  - Need suitable lithium substrate for power handing
    - 5 sec, 25-38 MW/m^2 (max Ip - max Ip & pwr)

BACKUP

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*.**

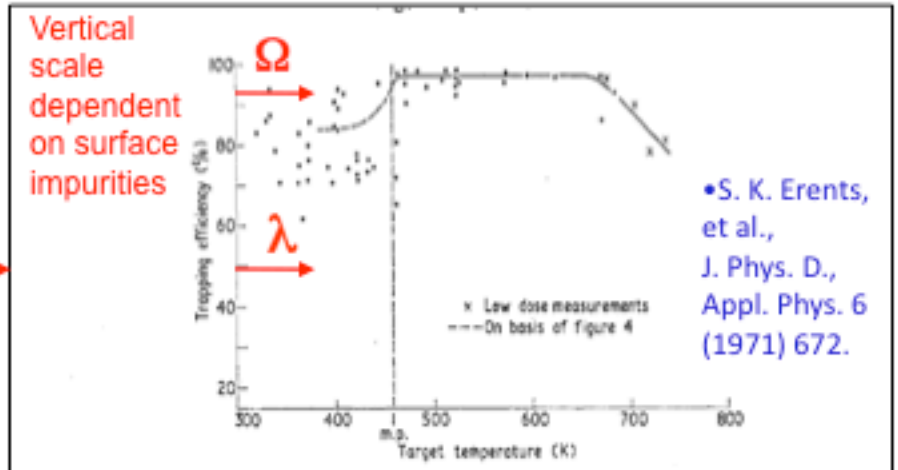


Figure 3. Trapping efficiency of lithium for 18 keV deuterons as a function of temperature for constant dose of 5×10^{17} ions/cm^2.

•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?