NSTX

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NSTX Liquid Lithium Divertor (LLD) Design Status and Plans

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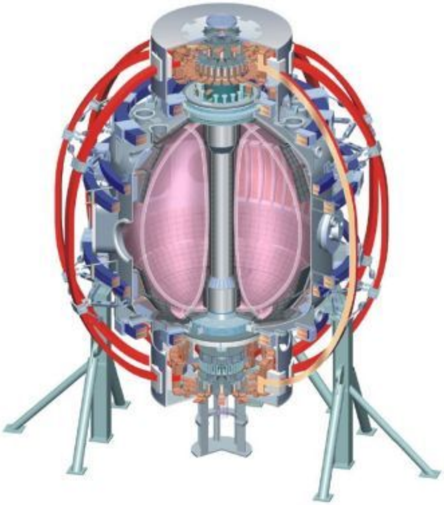
H. W. Kugel, PPPL

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Conference Room LSB-B318, PPPL
July 28-30, 2008



- Culham Sci Ctr
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- IPP, Jülich
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- U Quebec

Motivation for NSTX Lithium Research

- NSTX research with solid lithium is aimed initially towards using liquid lithium to control density, edge collisionality, impurity influxes, and eventually power handling.
  - *Solid Li provides short pulse capability but can saturate; liquid Li has much higher LiD capacity, and has potential for power handling and self healing.*

- Over the longer term, NSTX will investigate if liquid lithium can help integrate 4 important potential benefits for fusion
  a. Divertor pumping over large surface area compatible with high flux expansion solutions for power exhaust and low collisionality
  b. Improved confinement (reported in FY08)
  c. ELM reduction and elimination (reported in FY08)
  d. High-heat flux handling (via capillary flowing Li, swirl tubes, hypervaportrons, evaporative cooling)

NSTX Has a 3 Phase Lithium Plan

- The 3 Phase NSTX Lithium Plan for Particle Control and Power Handling is moving aggressively toward the 3rd Phase:

I. Lithium Injection Experiments (2005-2008)
  - Li pellet injection: 2-5 mg pellets, on graphite divertor (2005)
  - Li powder tests: 50 μm Li powder on graphite divertor (2007-2008)

II. Lithium Evaporator [LITER] (2006-2009)
  - 1 LITER: deposition on graphite divertor (2006-2007)
  - 2 LITER: deposition on graphite divertor (2008)
  - 2 LITER: deposition on graphite and LLD-1 (2009-2010)

III. Liquid Lithium Divertor [SNL - NSTX Collaboration] (2009-2013)
  - *LLD-1: Li evaporated on thin porus Mo/SS on Cu baseplate*
  - *LLD-2: Li capillary flow to load a Mo mesh surface over wider area*
  - *LLD-3: long pulse (5s) power handling capillary surface with active cooling* (via capillary flowing Li, swirl tubes, hypervaportrons, evaporative cooling) *for high-power 16 MW (10 MW NBI + 6 MW RF) operations*

Liquid Lithium Divertor Physics Design Goals

- Physics Design Goals

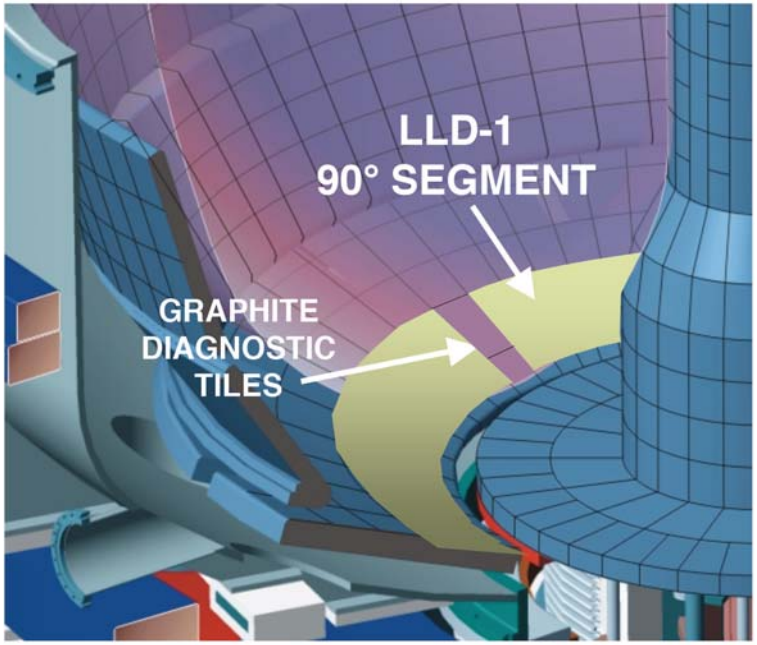
1) LLD-1: Achieve density control for increased neutral beam current drive capability in the range (from recent simulations):
   - $n_e \sim 5 \times 10^{19}$ m^{-3} at $I_P = 750$ kA
     - (15-25% n_e decrease from present exps)
   - highest non-inductive fraction discharges presently often evolve toward $n_e/n_{GW} \rightarrow 1$

2) LLD-2: Enable n_e scan capability in long pulse H-mode (e.g.,~ x2) by varying lithium thickness
   - Increase filling rate (e.g. capillary flow, powder dropper) to wider area mesh surface
   - Test ability to operate at significantly lower density
   - NHTX ($n_e/n_{GW} = 0.5$) and ST-CTF ($n_e/n_{GW} = 0.25$)

3) LLD-3: Investigate LLD with long-pulse (5s), high heat flux for 16 MW (10MW (2 NBI) + 6 MW RF) power handling capability

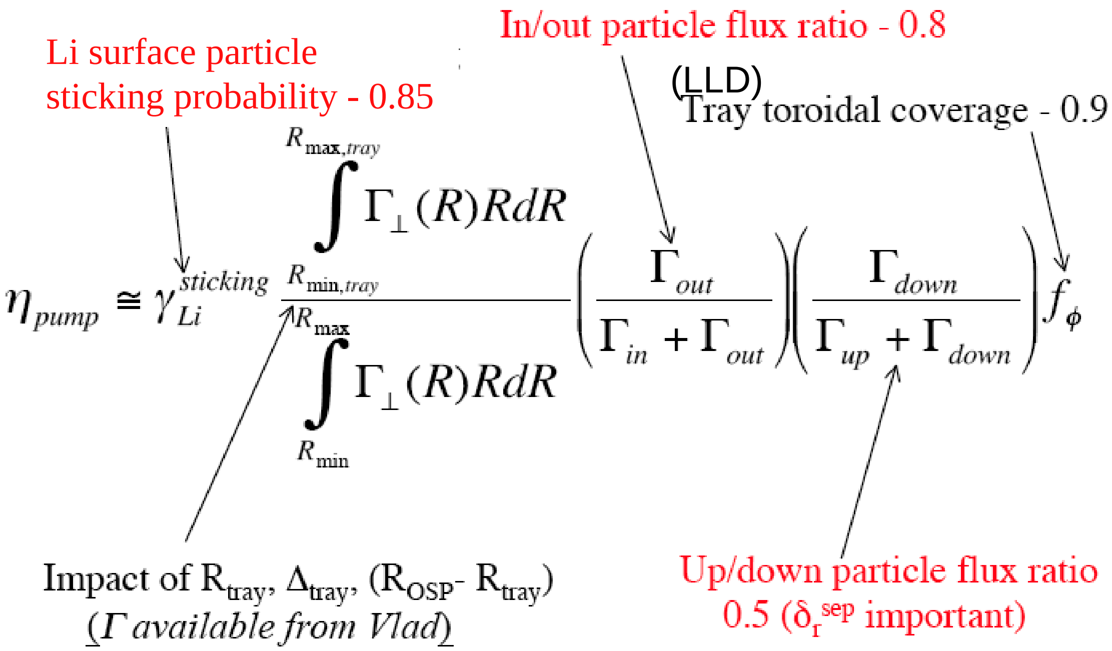
LLD-1 Plate Design With Thin Lithium Film on High-Z Bonded to Copper is Highest Confidence Approach

- Location - lower outer divertor in four 90° sections.
- Width - 20 cm starting 5 cm outboard of CHI gap.
- Shape - replaces present graphite tiles.
- Structure - 0.01cm Mo flame-sprayed on 0.02 cm SS brazed to 1.9 cm Cu. Resistive heaters and cooling lines maintain 200-400°C.
- Li Loading - 2 lithium evaporators.



- Each toroidal section electrically grounded to vessel at one mid-segment location to control eddy currents
- Each toroidal section fastened at 4 corners to divertor copper baseplate with fasteners providing structural support, electrical isolation, and accommodating thermal expansion (design adopted from JET PPPL collaboration)
- Narrow graphite tile transition regions between sections contain thermocouples, an array of Langmuir probes, and magnetic & current sensors

Particle Balance and Recycling Model Used to Estimate 0-D LLD-1 Pumping Projections and Sensitivities



Li surface particle sticking probability - 0.85

In/out particle flux ratio - 0.8

(LLD) Tray toroidal coverage - 0.9

$$\eta_{pump} \cong \gamma_{Li}^{sticking} \frac{\int_{R_{\min,tray}}^{R_{\max,tray}} \Gamma_{\perp}(R)RdR}{\int_{R_{\min}}^{R_{\max}} \Gamma_{\perp}(R)RdR} \left(\frac{\Gamma_{out}}{\Gamma_{in}+\Gamma_{out}}\right)\left(\frac{\Gamma_{down}}{\Gamma_{up}+\Gamma_{down}}\right) f_{\phi}$$

Impact of R_{tray}, Δ_{tray}, $(R_{OSP} - R_{tray})$
(*Γ available from Vlad*)

Up/down particle flux ratio 0.5 (δ_r^{sep} important)

* Red items estimated from CCD camera data

(V. Soukhanovskii, LLNL)

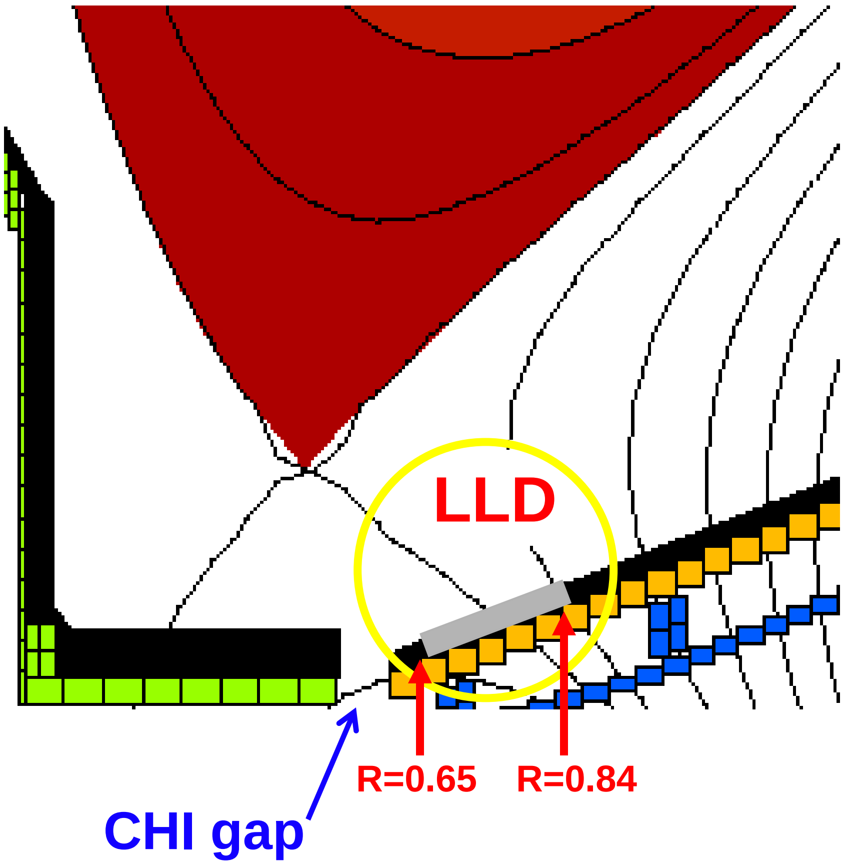
Iterative Procedure

- Convert measured Dα luminosity to particle flux using 20 ionizations per photon
- Estimate LLD-1 flux intercept fraction from candidate discharge data for a given time slice
- Vary R_{LLD} in steps of 1 cm
- Repeat for different W_{LLD}, R_P η_{CORE} and other input parameters

R.Maingi, ORNL

NSTX Data Used to Enable Analysis of Expected Performance of LLD-1 for Low δ Plasmas

Low δ : reduce n_e by 50%



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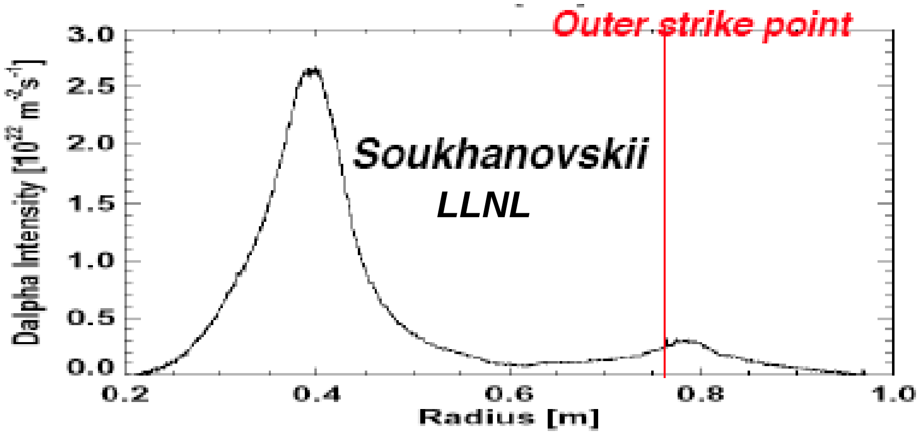
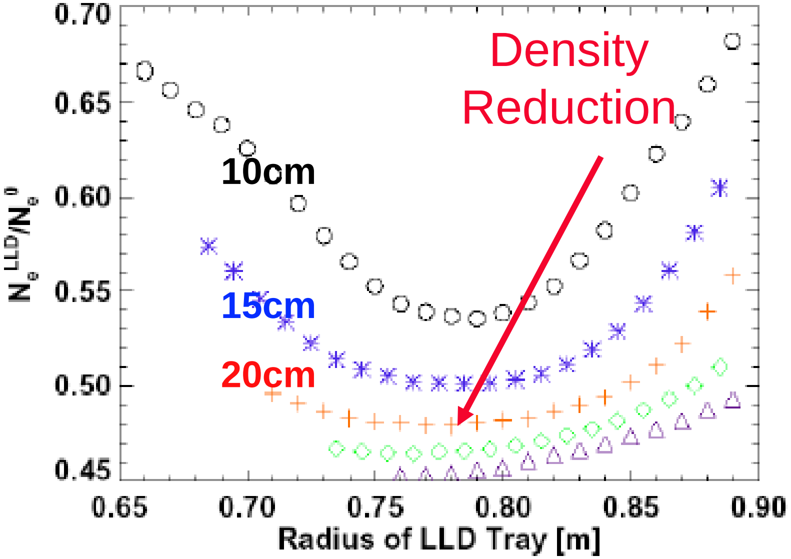


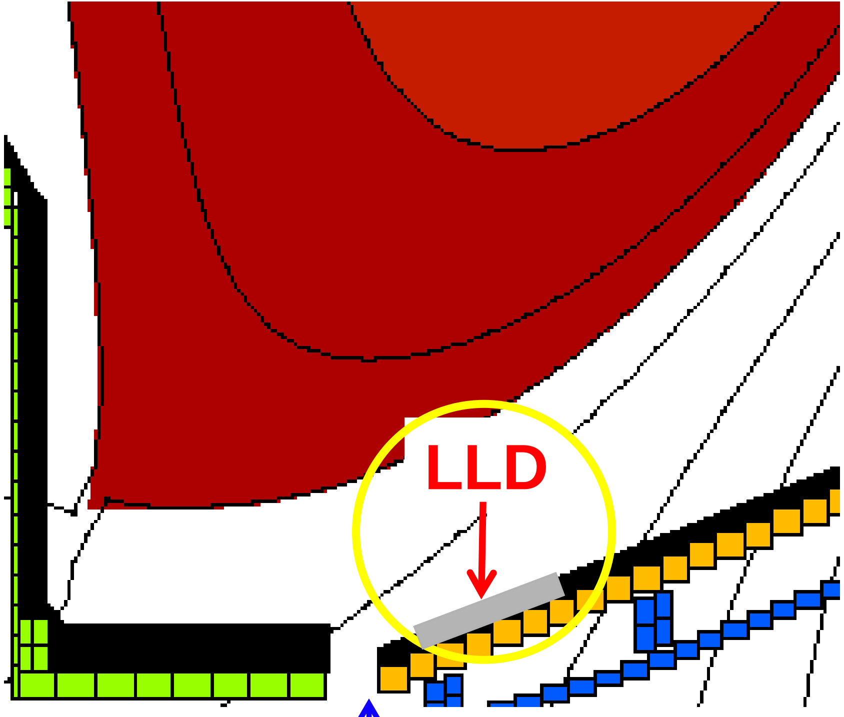


Shown for different LLD-1 widths

Pumping by LLD-1 20 cm Wide on Outer Divertor Will Provide Density Control for Inner Divertor Broad SOL Dα Profile High δ Plasmas

- Density reduction will depend on proximity of outer strike point to LLD-1

High δ : reduce n_e by 25%



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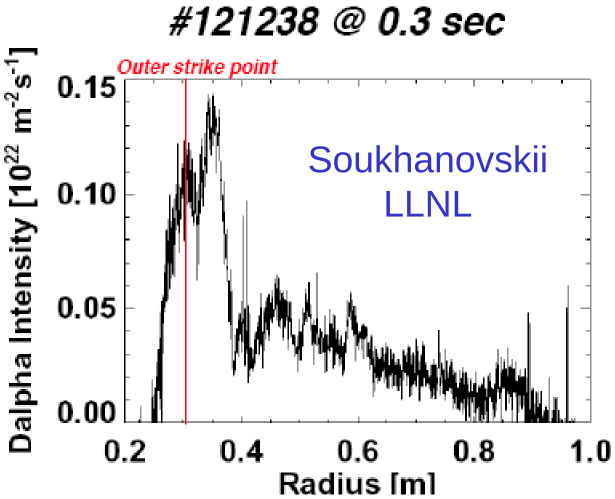
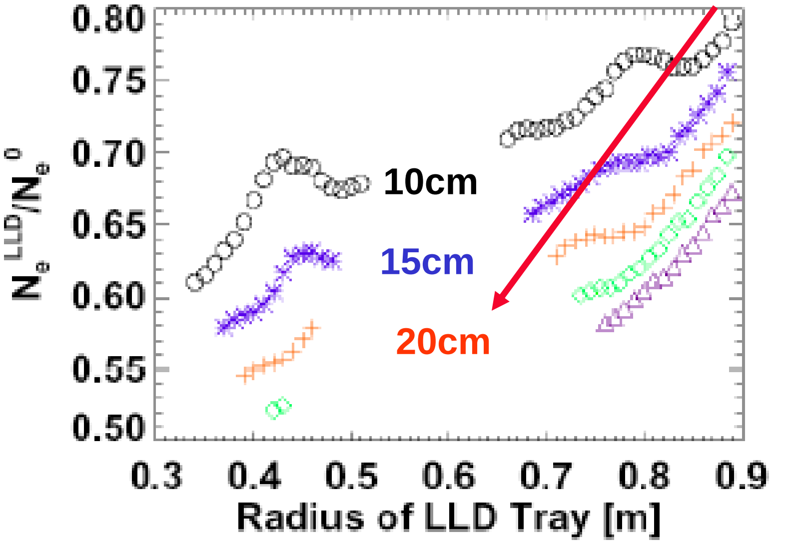




Shown for different LLD-1 widths

LLD-1 Design Derives from Extensive International Liquid Lithium R&D

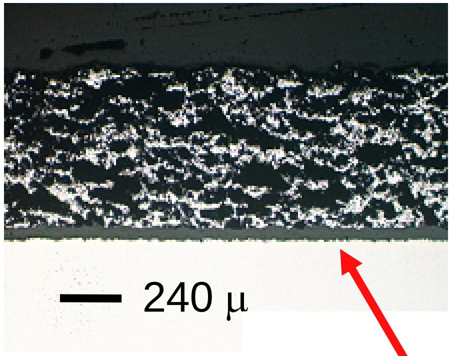
- Lithium surface tension forces in capillary media (metal wire meshes, metal felts, sintered metals, flame-sprayed porous metals) have been shown to form, control, confine, and redistribute liquid Li uniformly over plasma-wetted surface in presence of JxB forces, gravity, and thermal gradients.
  - No thermal induced cracking in lithium filled medium
  - No fatigue
  - No radiation swelling
  - Exiting flows can remove codeposition
  - Continuous flow provides replenishment during erosion
  - *Provides recycling control*
  - *Provides impurity control*
  - *Provides low collisionality edge conditions*
  - *Maximum allowable incident heat fluxes >*$100MW/m^2$
    - Examples: Mo wire meshes [T-11, FTU], flame-sprayed porous Mo [LTX]

- LLD-1 design and plans are following an integrated R&D approach

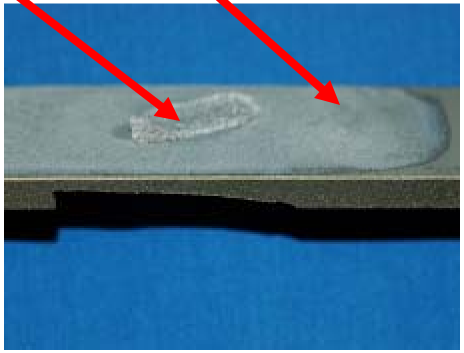
Integrated Approach: LTX R&D Aiding in Performance Projections and Design of NSTX LLD-1

- LTX is preparing to begin lithium operations
  - Recycling on liquid Li at more relevant edge parameters than CDX-U
  - Test plasma fueling w/ gas puffing, jets when recycling particle source is small
  - Examine Li sputtering w/ hotter edge

- ***Solid Li melting***
- ***Liquid Li flowing over porous Mo***



Micrograph of highly porous moly



Successful lithium wetting test on porous moly

- LLD-1 relevant lithium wall implementations developed for LTX
  - NSTX & LTX have been working closely with Sandia to determine LLD-1 design for operations in FY09
  - Flame-sprayed porous Mo adopted for NSTX LLD-1 capillary surface

- Candidate LLD-1 porous molybdenum surface -
  - Originally developed for 2nd LTX shell (Phase II SBIR w/ Plasma Processes, Inc.)

R. Majeski, R.Kaita

NSTX-SNL Collaboration Has Considered Two Candidate Surfaces for LLD-1

- Two candidate Li surfaces have been under investigation

1) Thin flame sprayed porous Mo, on thin SS on thick Cu baseplate is highest confidence initial approach

   - LTX style plate (tested offline)
     (prepared by Plasma Processes Inc.)

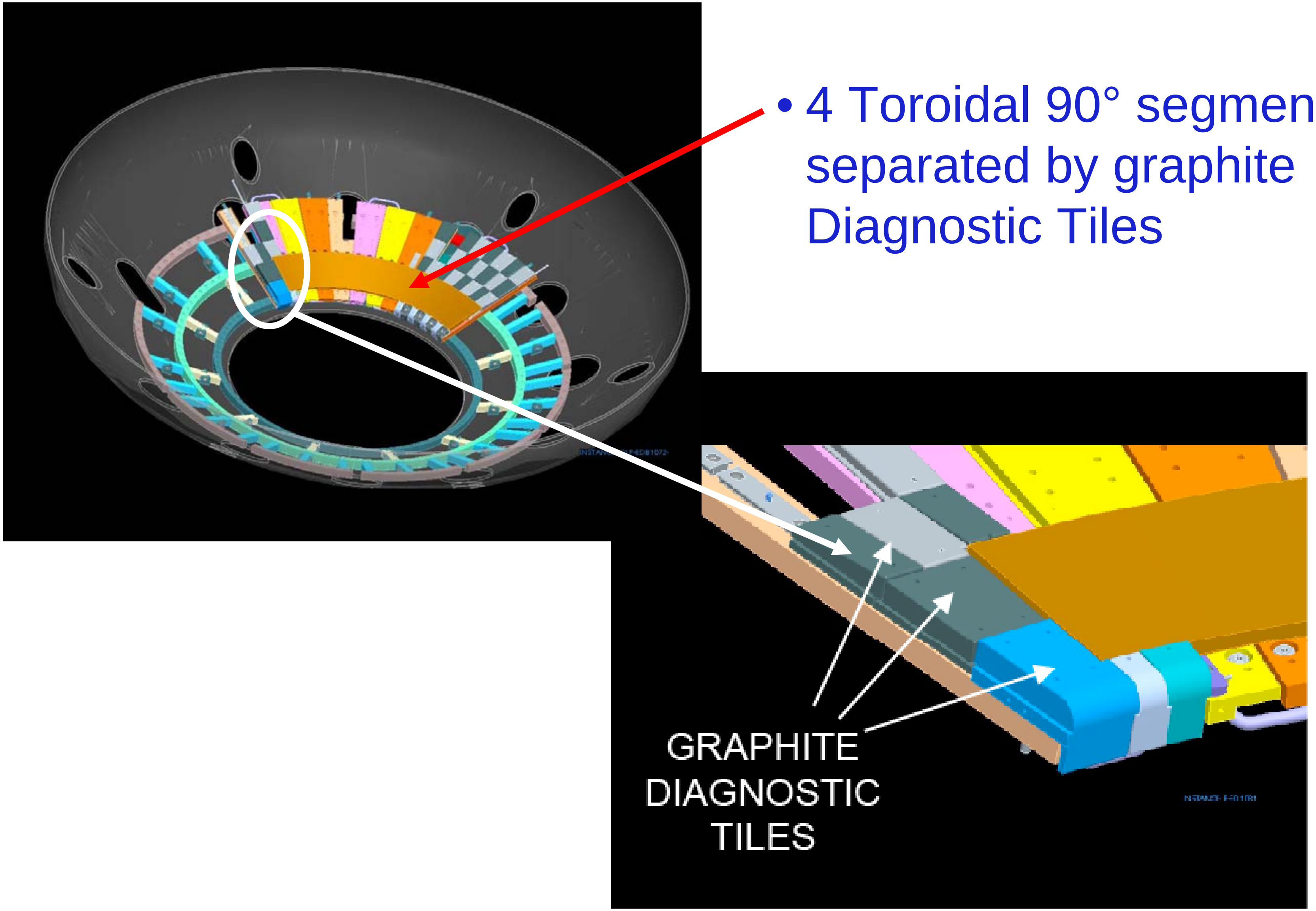
     - Experiments and simulations of LLD-1 behavior (porousity, gravity, thermal, JxB forces) in progress (N. Morley, UCLA)

2) Chemical vapor deposited Mo on vitreous carbon mesh

   - under investigation at SNL (not tested; testing planned)
     (prepared by Ultramet Inc.)

- Key properties for an acceptable LLD-1 lithium surface
  - ability of liquid Li to flow across a metal surface (wetting capability)
  - minimize temperature rate of rise of Li → rapid heat transfer from Li to baseplate

Plasma Facing Views of the Basic LLD-1 Copper Plate Substrate



- 4 Toroidal 90° segments separated by graphite Diagnostic Tiles

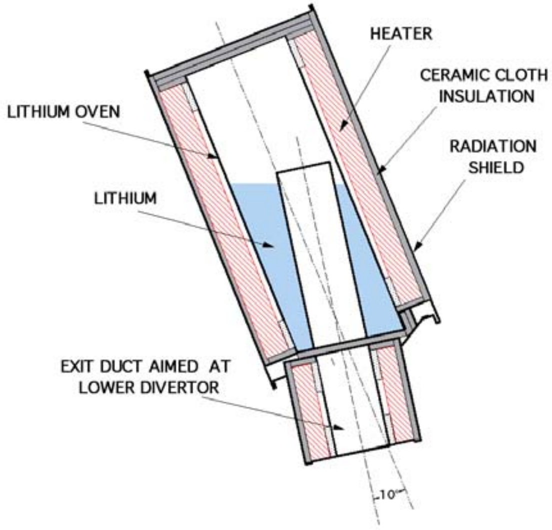
LLD-1 Operation Requires Additional Diagnostics for NSTX Control and Characterization for Step Devices

- *Each LLD-1 90° segment has control and monitoring sensors:*
  - 12 thermocouples embedded in the heaters for monitoring heater limits
  - 12 thermocouples embedded in copper baseplate for monitoring heat transfer
  - 2 strips of 4 thermocouples each for torodial and radial temperature variations
  - 1 center post halo current Rogowski for monitoring JxB effects

- *Each set of inter-segment graphite tiles has diagnostic sensors:*
  - Bay H: existing 2D magnetic sensor array and 2 thermocouples
  - Bay B: 120 LP array with some UIUC signal conditioners for triple probes
  - Bay E and Bay K: 2 biased electrodes, 5 LP, 1 thermocouples

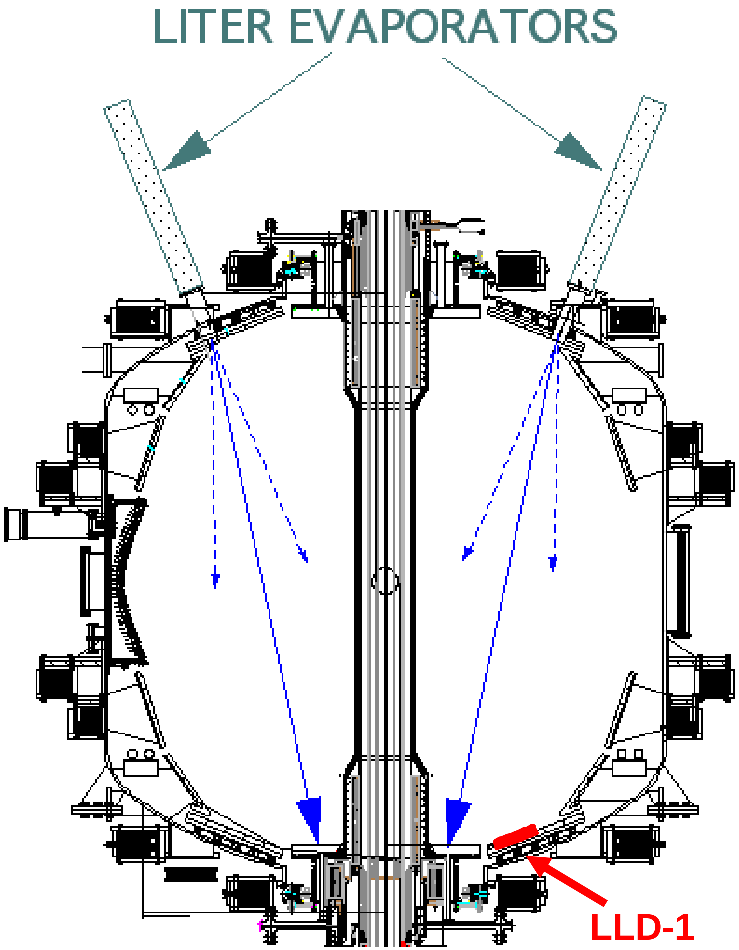
- *External Diagnostics:*
  - Bay H: Slow IR camera, Bay E: Fast IR camera
  - Bay G: Lyman-α Diode Array for recycling measurements at the LLD-1 highly reflective liquid lithium surface

LLD-1 Li Surface Will Be Supplied Using the 2 LITER Units



- Design of LIThium EvaporatoR (LITER) Shown in Operating Orientation

- **Photo of LITER on probe & loaded with Li under argon**

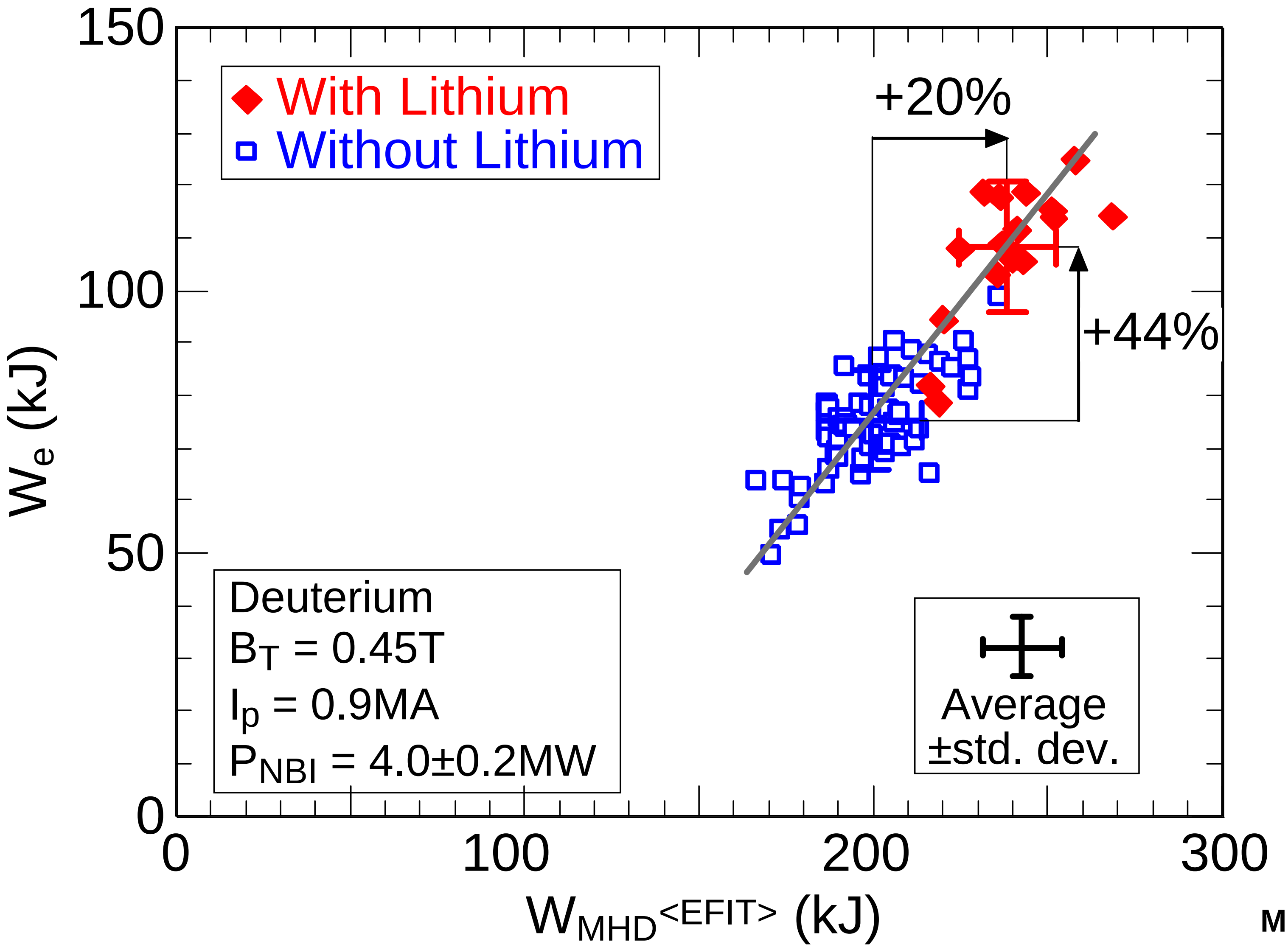


- **LITER central aiming axis to graphite divertor and gaussian angle at 1/e (dashed)**

Dual LITER System Used Routinely as a New Operational Capability for Establishing Lithium Wall Conditions

- In recent experiments, the dual LIThium EvaporatoR (LITER) evaporated 120g of Li into NSTX (+60 g on LITER shutters)
  - The LITERs deposited lithium on the lower divertor target for 10 min, at combined rates of 10-70 mg/min
  - Prior to each discharge, the LITERs were withdrawn behind shutters
  - If HeGDC was applied, the shutters remained closed
  - The shutters were then reopened as soon as the diagnostic window shutters closed, and the deposition cycle repeated
  - Became routine operational tool used to establish lithium wall conditions
    - used for many FY08 experiments; the next slides show some of the initial results.

Stored Energy (W_{MHD}) Increases After Li Deposition Mostly Through Increase in Electron Stored Energy (W_e)



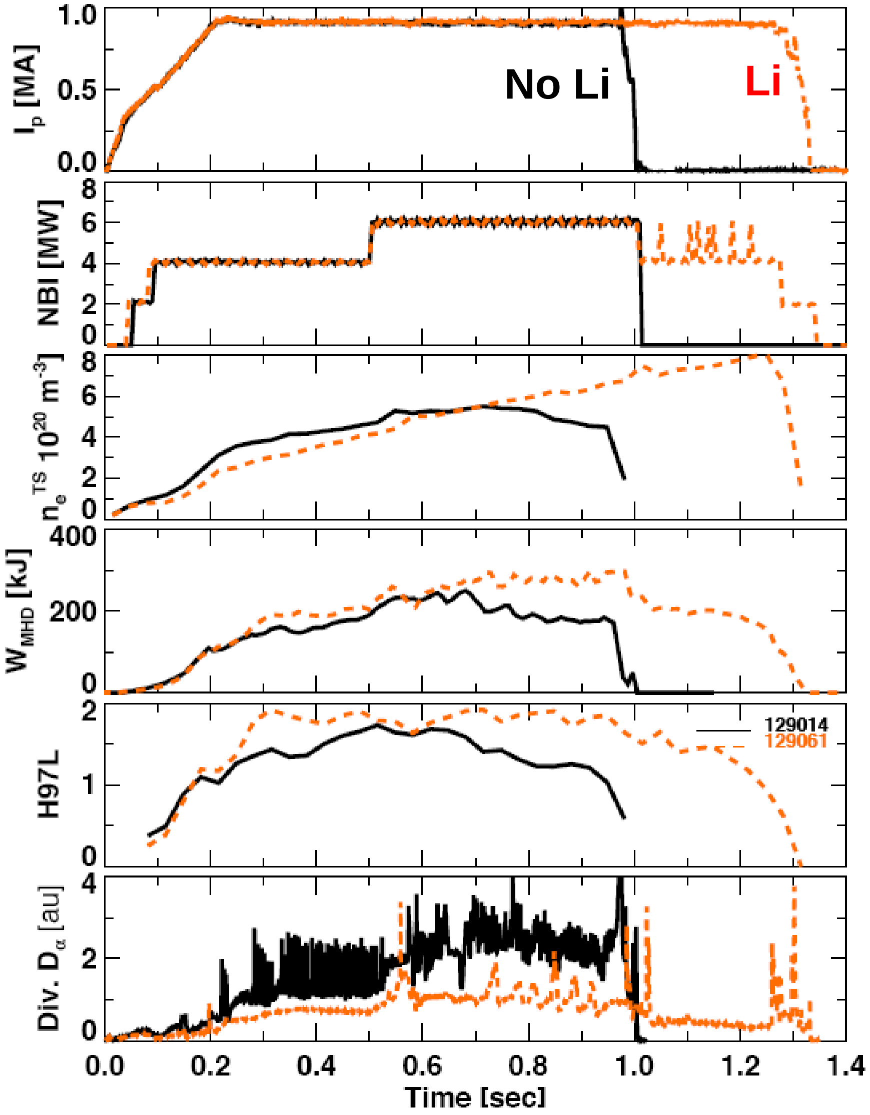
M. G. Bell

Solid Lithium Surface Coatings
Increase Confinement, Stored Energy, and Pulse Length

- Comparison for pre-Li and post-Li reference shots with constant NBI, constant external gas, etc.

- Lithium (188 mg) reduced density in initial period up to 0.6s
  - pre-Li discharge was ELMy
  - ELMs were absent on Li shot

- In time, the lack of ELMs causes the density in the discharge with Li to overtake the shot without Li.

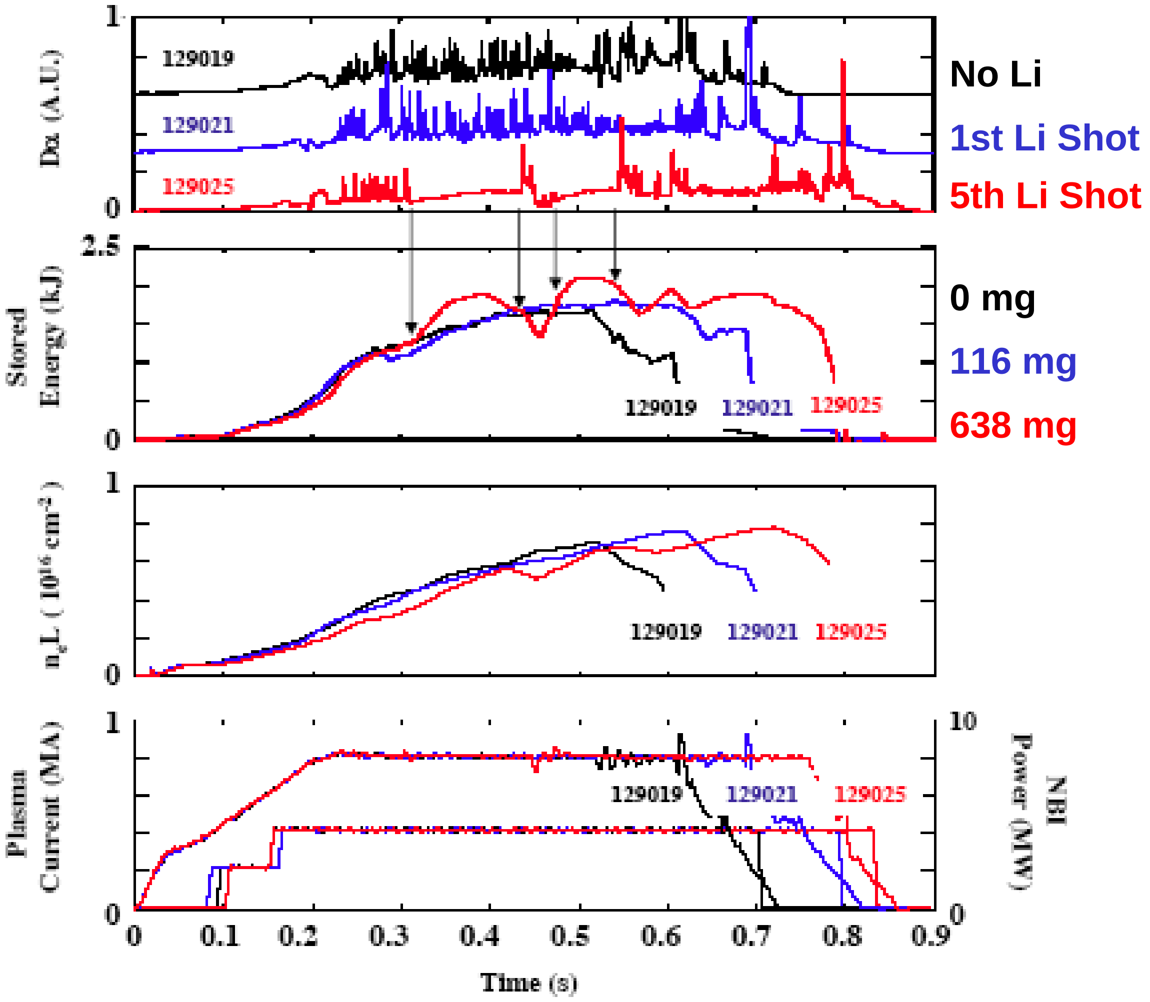


R. Maingi, ORNL

ELM Suppression by 5th Discharge With Li
No ELMs ⇒ Immediate Increase in Stored Energy

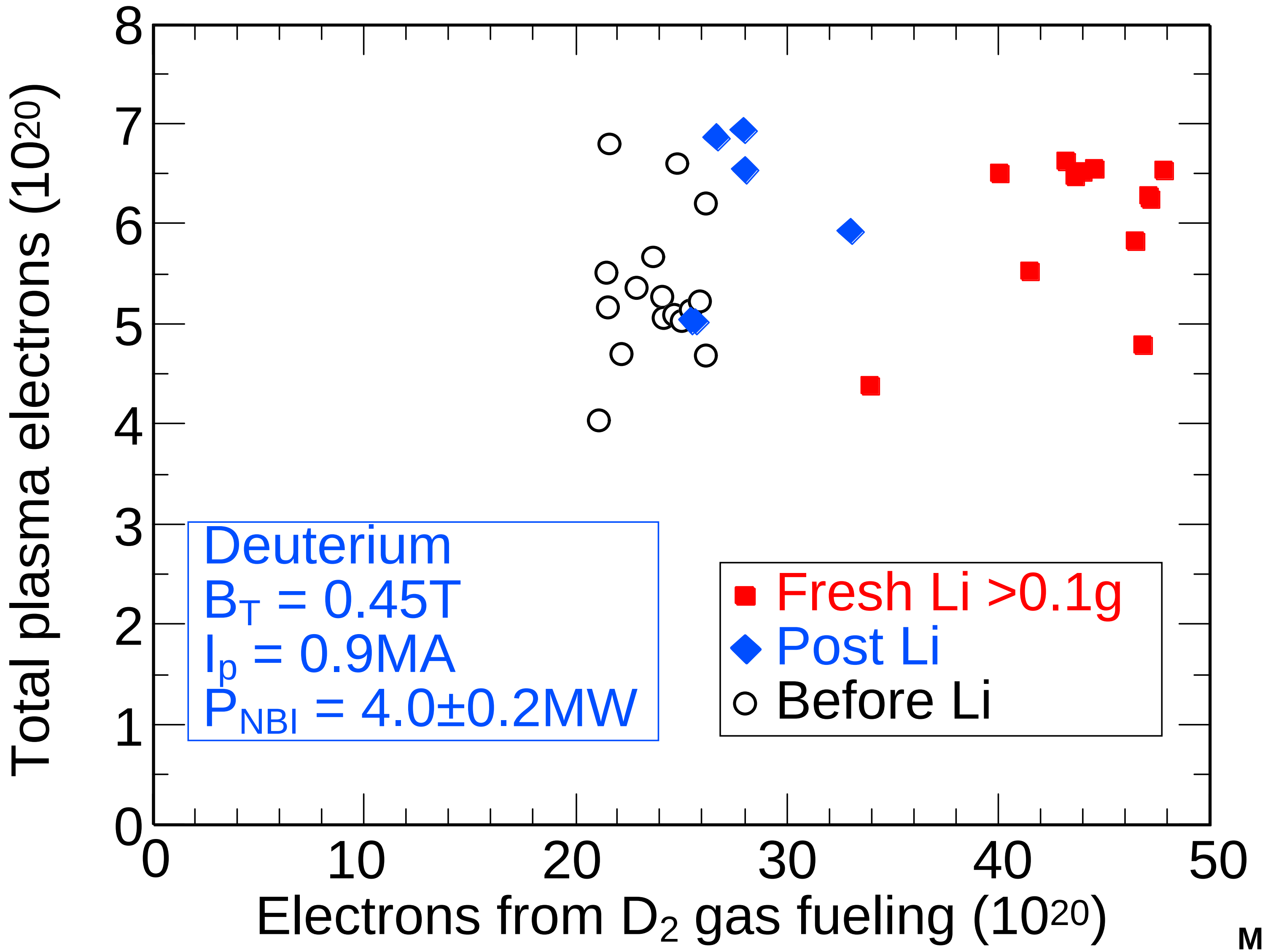
- As Li increases
  - ELMs decrease
  - Stored energy increases
  - Pulse lengthens

- At higher Li evaporation rates and higher PFC accumulations, complete ELM suppression occurs
  ⇒ higher confinement*



*** D. Mansfield, PSI08, O-28**

Lithium Edge Conditions Require Large Fueling Increases to Maintain Density

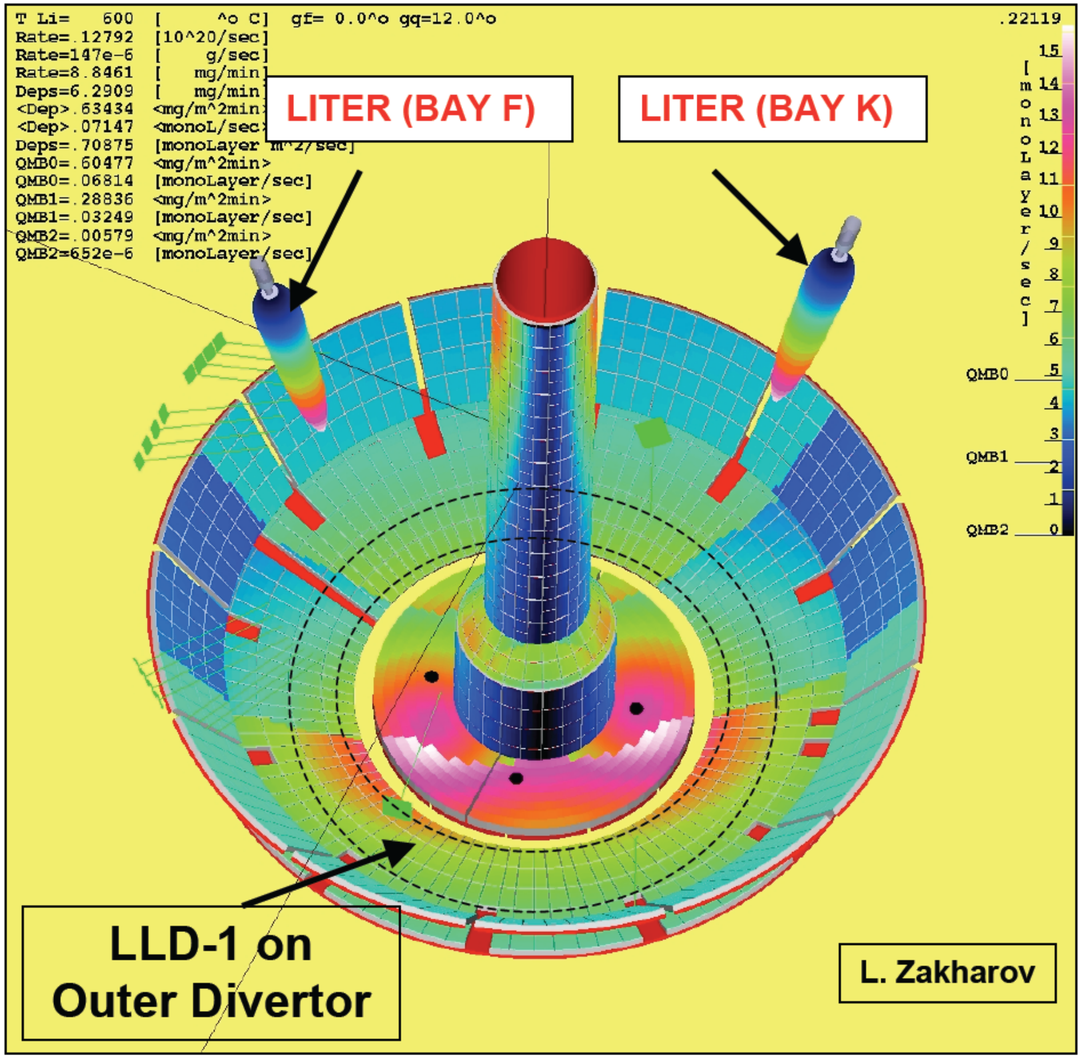


M. G. Bell

LITER Technical Success Demonstrated by Initial Results of Evaporated Lithium Surface Coatings

- The effects of the active lithium surface coatings on standard discharge scenarios include:
  1. Reduced plasma density in the early phase of the discharge
  2. Suppression of ELMs
  3. Improved energy confinement
  4. Reduced flux consumption and increased pulse length for standard, high-triangularity discharges
  5. Reduced HeGDC time between discharges to maintain the H-mode
  6. Increased pedestal electron and ion temperature
  7. Reduced SOL plasma density and edge neutral density
  8. Discharges after lithium also benefited from n=1 and n=3 mode control by the external non-axisymmetric coils to reduce deleterious MHD activity.

LLD-1 Will Be Loaded With Lithium Using LITER



```
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]
```

LITER (BAY F)

LITER (BAY K)

LLD-1 on Outer Divertor

L. Zakharov

- <u>LITER Deposition Capability</u>

- for LLD-1 to pump NSTX plasma from 7x10^{13} cm^{-3} --> 5 x10^{13} cm^{-3} will require the absorption of 2.4 x 10^{20} D particles, every particle confinement time (~ 50 ms), for 1000 ms, for a total of 4.8 x 10^{21} D particles absorbed.

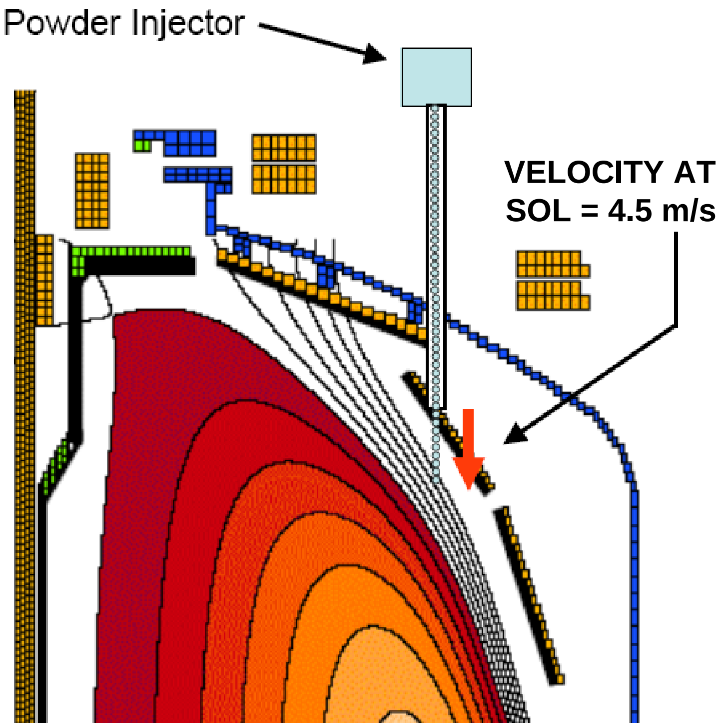
- for a 1:1 D/Li ratio requires at least 5.5x10^{-2} g of lithium (2 μm).

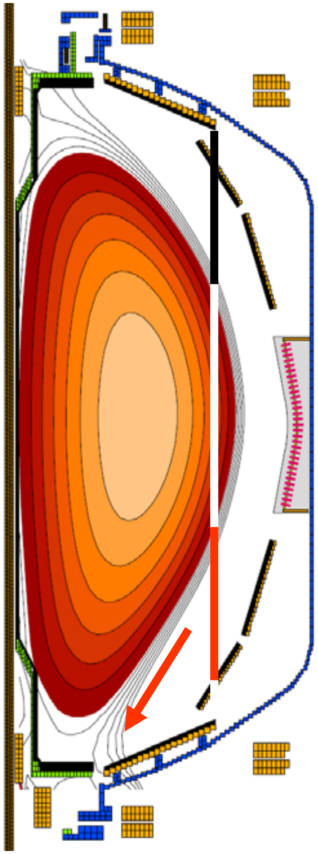
- present LITER deposition efficiency on to LLD ~ 7% of it total output, then the total lithium need is 0.79 g.

- using two evaporators at 30 mg /min (FY07 typ) will require about 13 min to coat the LLD-1.

- if lower concentration ratio 0.1D/Li is required, then need 7.9 g of lithium (20 μm), or 4 g per LITER, operating at 100 mg/min for 40 min.

New Li Powder Injection Capability Will Be Tested Offline for Potential for Reloading LLD-1 Prior to Discharges





- Li powder injected during breakdown and early in discharge reaches lower divertor
- Recent initial results indicate Li powder (50 μm) injected early in discharge yielded higher, and broader temperature profiles earlier in the discharge

D. Mansfield DPP, APS, 2008

- Laboratory experiments are planned to test if this new capability for present discharges can be used to reload the LLD-1 <u>prior to a series of discharges</u>

NSTX Will Test the Potential Benefits of Liquid Lithium Divertor for Integrating High Plasma and PSI Performance

- LLD-1
  - *The Outer Divertor is the initial lowest technical and programmatic risk location for LLD-1 to the high performance, high δ, ST research program*
  - LLD-1, 20 cm wide pumping on Outer Divertor provides reduction in density for increased neutral beam current drive capability

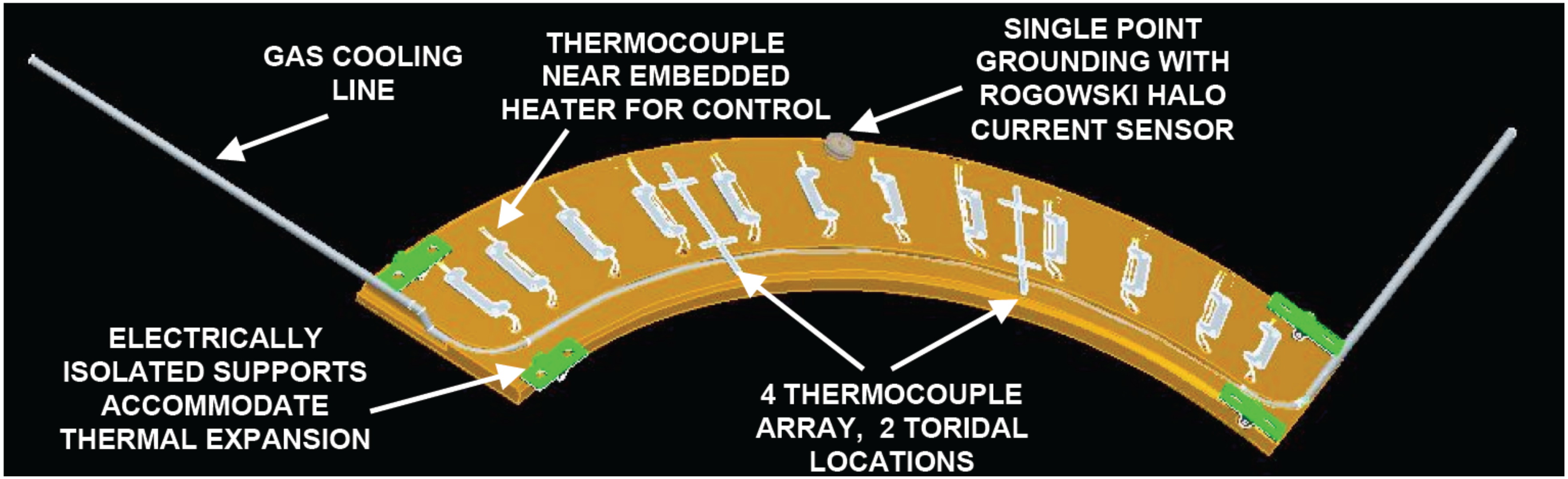
- LLD-2
  - Enable n_e scan capability in long pulse H-mode
    - Increase filling rate (powder, capillary) to wider area Mo mesh surface
    - Test ability to operate at significantly lower density (NHTX, CTF)

- LLD-3
  - Investigate power handling for long-pulse with high heat-flux
    - *long pulse (5s) power handling surface with active cooling (capillary flows,swirl tubes, hypervaportrons, evaporative cooling) for 16 MW (2NBI + RF) operation*
    - Higher lithium fill rates (capillary flow replenishment planned for FTU)

- LLD-1 Status
  - Final Design Review successful. Final drawings submitted by SNL for procurement.
  - Successful CDR for LLD-1 Diagnostics. LLD Controls FDR scheduled for Sept.
  - Planning to complete installation in 2008 for FY09 operation.

Backup

Bottom View of LLD-1 Copper Substrate Plate Showing Controls and Sensors



- 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 halo current Rogowski coil for monitoring JxB effects