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Status of National Spherical Torus Experiment Liquid Lithium Divertor

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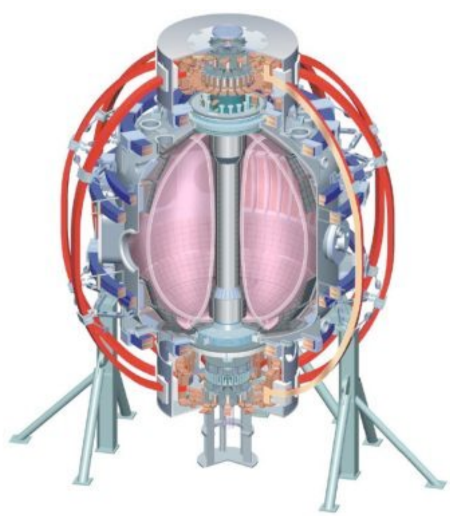
51st Meeting of the APS DPP
02-06 November 2009
Atlanta, Georgia



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Abstract

Recent NSTX high power divertor experiments have shown significant and recurring benefits of solid lithium coatings on plasma facing components to the performance of divertor plasmas in both L- and H-mode confinement regimes heated by high-power neutral beams. The next step in this work is the 2009 installation of a Liquid Lithium Divertor (LLD). The 20 cm wide LLD located on the lower outer divertor, consists of four 80−sections; each section is separated by a row of graphite diagnostic tiles. The temperature controlled LLD structure consists of a 0.165 mm layer of vacuum flame-sprayed 45% porous molybdenum, on top of 0.2 mm, 316-SS brazed to a 1.9 cm Cu base. The physics design of the LLD encompasses the desired plasma requirements, the experimental capabilities and conditions, power handling, radial location, pumping capability, operating temperature, lithium filling, MHD forces, and diagnostics for control and characterization.

Work supported by USDOE Contract DE-AC02-09CH11466.

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.
  - Plasma D efflux incident on Li forms LiD thereby reducing recycling
  - *Solid Li provides short pulse capability but has limited LiD capacity; 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 (capillary flow, swirl tubes, helium gas, 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-reaimed)
- 2 LITER: deposition on graphite divertor (2008)
- 2 LITER: deposition on graphite and LLD-1 (2009-2010)

III. Liquid Lithium Divertor [NSTX SNL Collaboration] (2010-2013)

- *LLD-1: Li evaporated on thin porus Mo/SS on Cu baseplate*
- *LLD-2: Li capillary flow to load a Mo mesh or foam surface over wider area*
- *LLD-3: long pulse (5s) power handling capillary surface with active cooling* (capillary flowing Li, swirl tubes, helium gas, hypervaportrons, evap cooling) *for 16 MW high power (10 MW NBI + 6 MW RF) ops*

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

- **LLD-1 (2010)**
  - *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 or foam
    - 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, helium gas, hypervaportrons, evaporative cooling) for 16 MW (2NBI + RF) operation*
    - Higher lithium fill rates (capillary flow replenishment planned for FTU)

The NSTX LLD-1 Design Includes the Experimental Physics Capabilities and Conditions for Achieving the Physics Design Goals

- **Elements of the LLD-1 Physics Design**
  - **Physics design goals**
    - Density control
    - Power handling
  - **Experimental physics capability**
    - Pumping capability
    - Radial Location
    - Lithium-filling method
    - Response to MHD
    - Operating temperature
    - Diagnostics for control and characterization

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 Ip = 700 kA
     - (15-25% n_e decrease from present exps)
   - highest non-inductive fraction discharges presently often evolve toward $n_e/n_{GW} \rightarrow 1$
   - initial tests of power handling with1 NBI (2 MW/m^2)

2) LLD-2: Enable n_e scan capability in long pulse H-mode (e.g.,~ x2) by varying lithium thickness and fueling
   - 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)

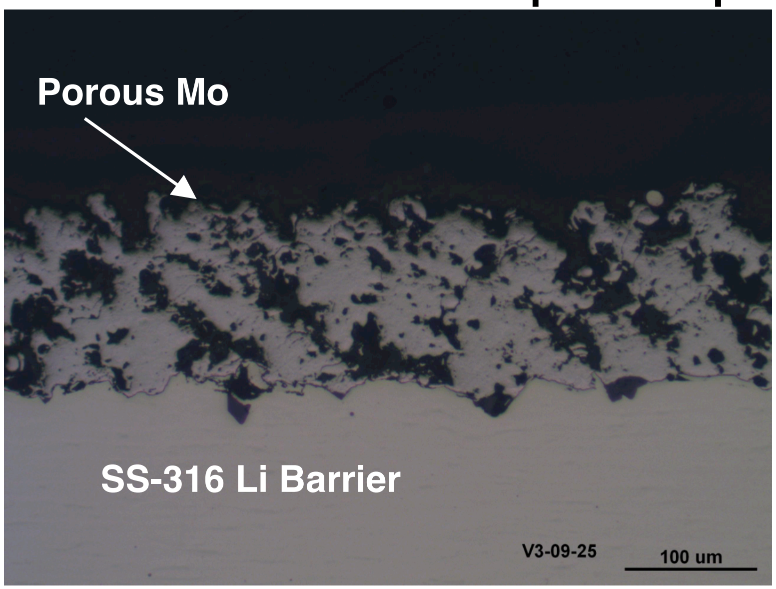
3) LLD-3: Investigate LLD with long-pulse (5s), high heat flux for 16 MW (10 MW, 2NBI + 6 MW RF) power handling capability

LLD-1 Lithium-bearing Surface is Thin Porous Molybdenum

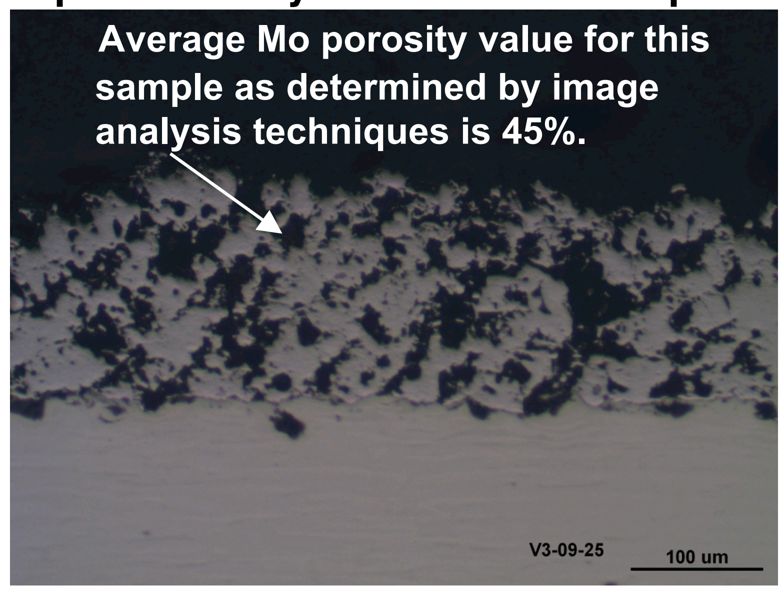
- **Key properties of an acceptable LLD-1 lithium surface**
  - sufficient surface tension to hold Li in presence of JxB forces
  - ability of liquid Li to flow across metal surface (wetting capability)
  - minimize temperature rate of rise of Li --> rapid heat transfer from Li to base

- Thin plasma sprayed porous Mo, on a thin SS-316 Li barrier, on thick Cu baseplate thermal sink is highest confidence initial approach

Cross sectional views of plasma sprayed porous molybdenum LLD sample



Longitudinal



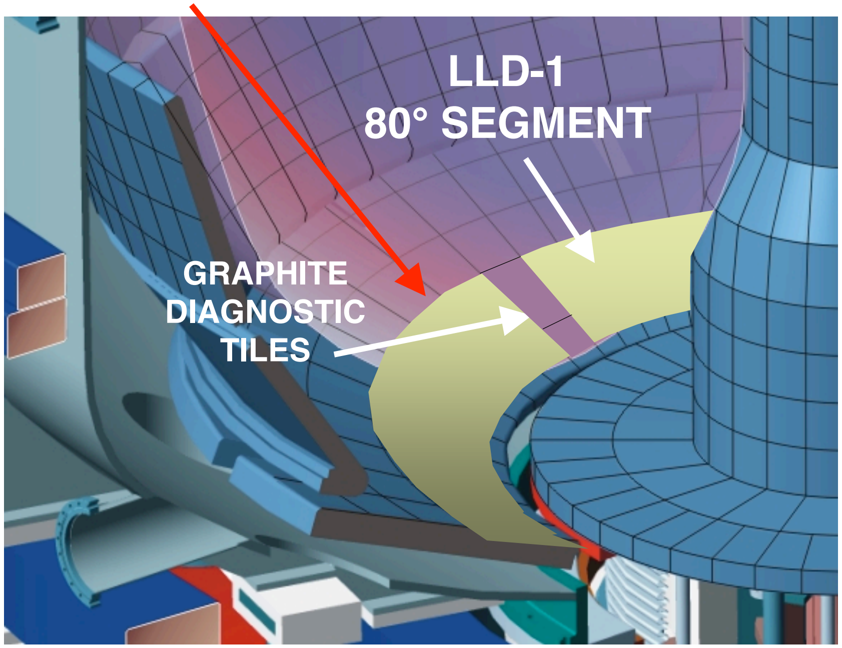
Transverse

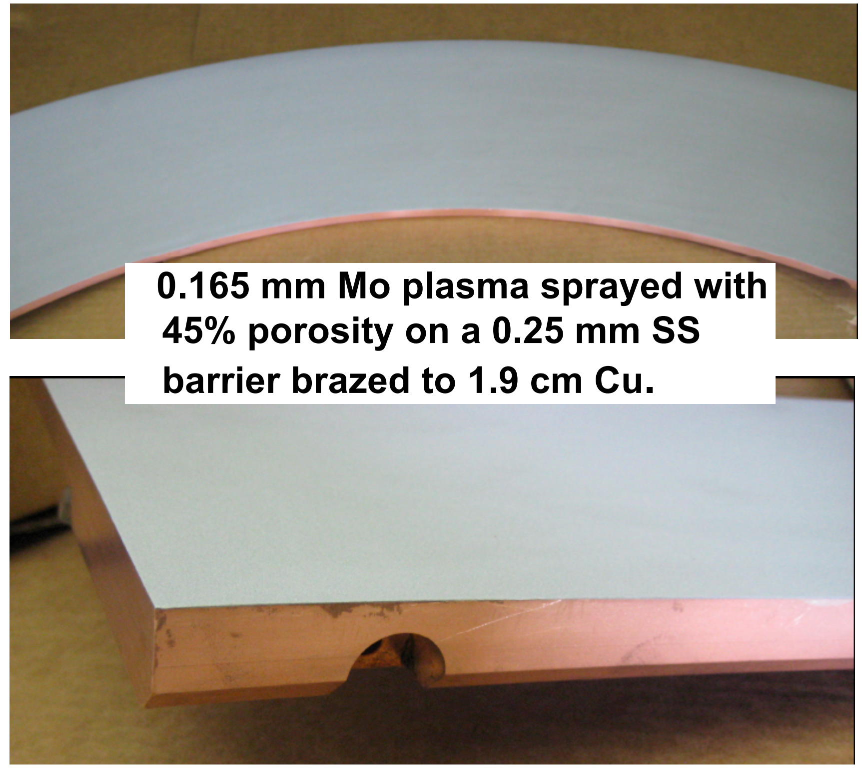
- The average thickness of the deposit on this sample was 0.006” (0.152 mm)

Liquid Lithium Divertor to Test Pumping Effectiveness

• LLD-1 Plates To Operate at Lithium Melting Temperature (200 - 400 °C)

Liquid Lithium Divertor (LLD-1)



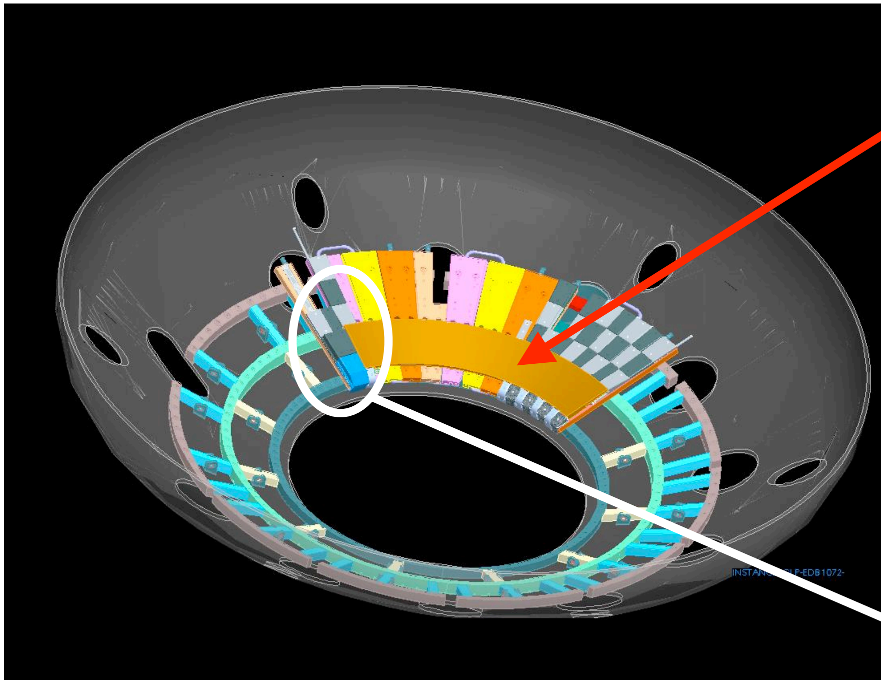


Moly-Coated LLD Plate

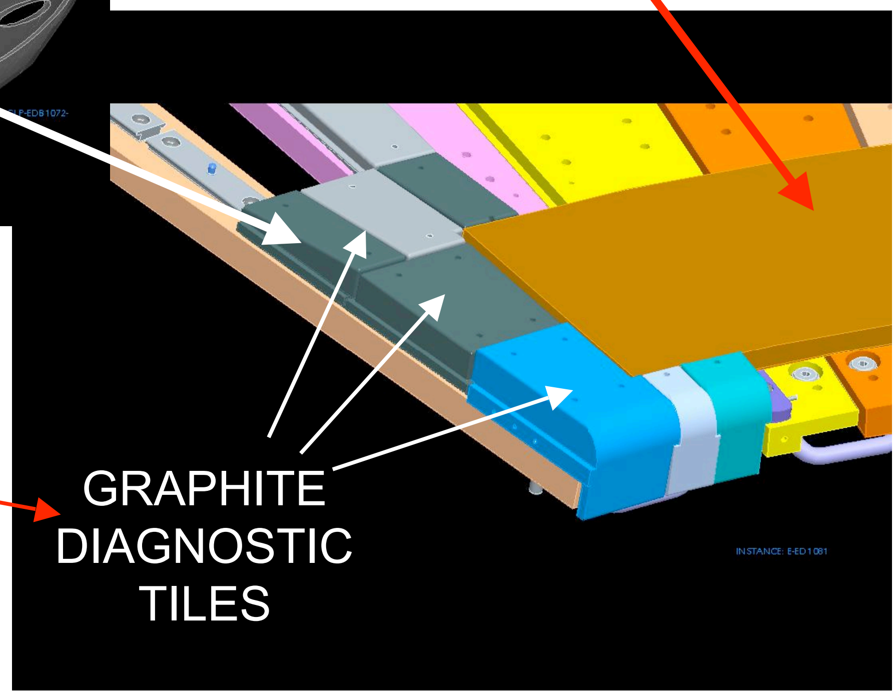
- Each toroidal section fastened at 4 corners to divertor copper baseplate with fasteners providing structural support, electrical isolation, thermal expansion

- Each toroidal section electrically grounded to vessel at one mid-segment location to control eddy currents

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

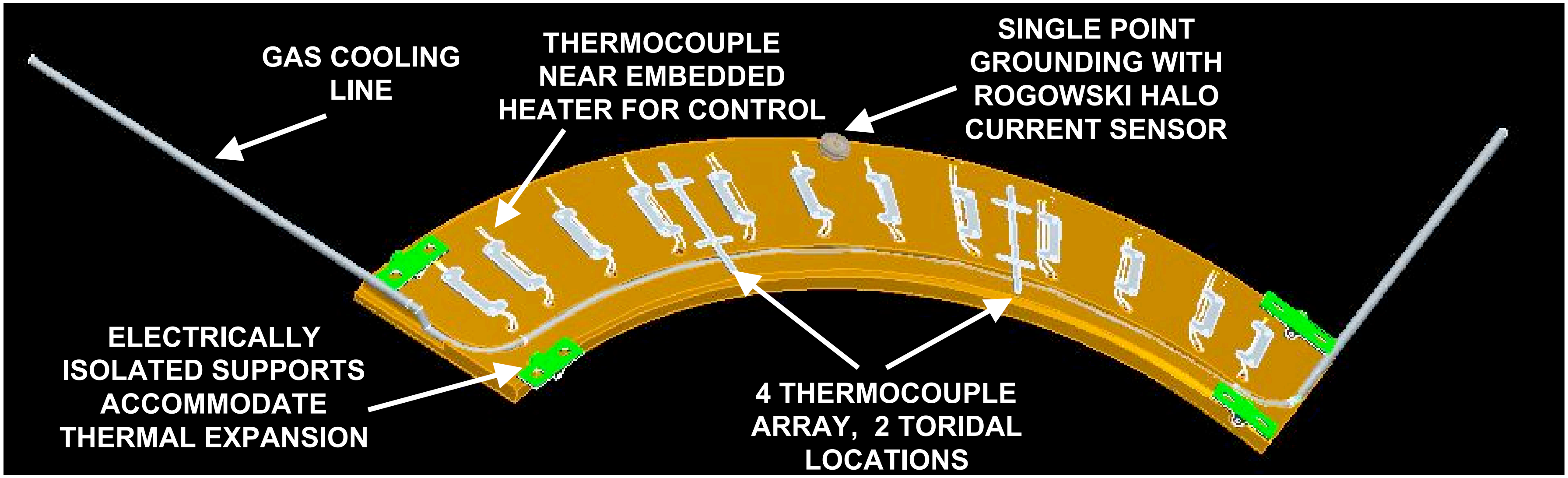


- 4 Toroidal 80° segments separated by graphite Diagnostic Tiles
- Each copper substrate segment is clad with a thin stainless steel barrier with a front face of porous flame sprayed Mo



- **Diagnostic Tiles**
  - **- Mirnov Coils**
  - **- Thermocouples**
  - **- Langmuir Probe Arrays**
  - **- Bias Electrodes**

Bottom View of LLD-1 Copper Substrate Plate Showing Heating, and Cooling Components, and Thermocouples, and Induced Current Sensor

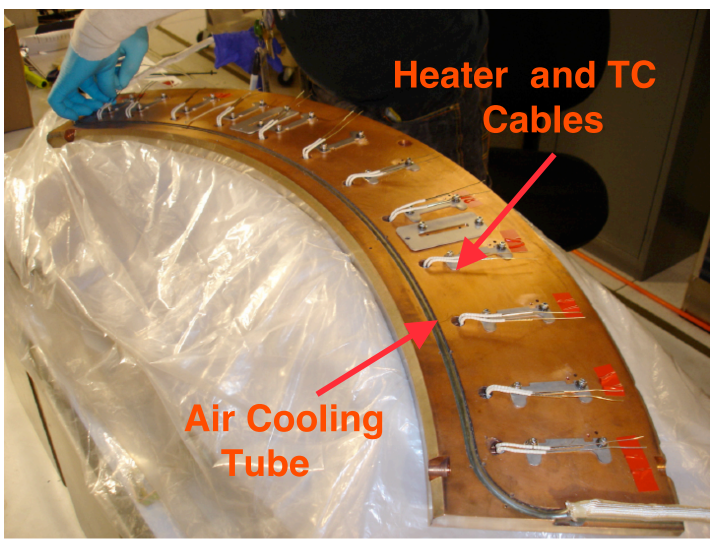


- **12 heaters (240v) each with embedded TC for monitoring heater limits**
- **12 TC embedded in copper baseplate for monitoring heat transfer**
- **2 strips of 4 TC each for monitoring torodial and radial temperature variations**
- **1 Center post halo current Rogowski coil for monitoring induced halo currents**

LLD-1 Installation Proceeding on Schedule

1st LLD-1 Plate
Installed in NSTX

LLD-1 Control Being
Tested Off-Line



All Heater and TC
elements installed in
all 4 LLD-1 Plates

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

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

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

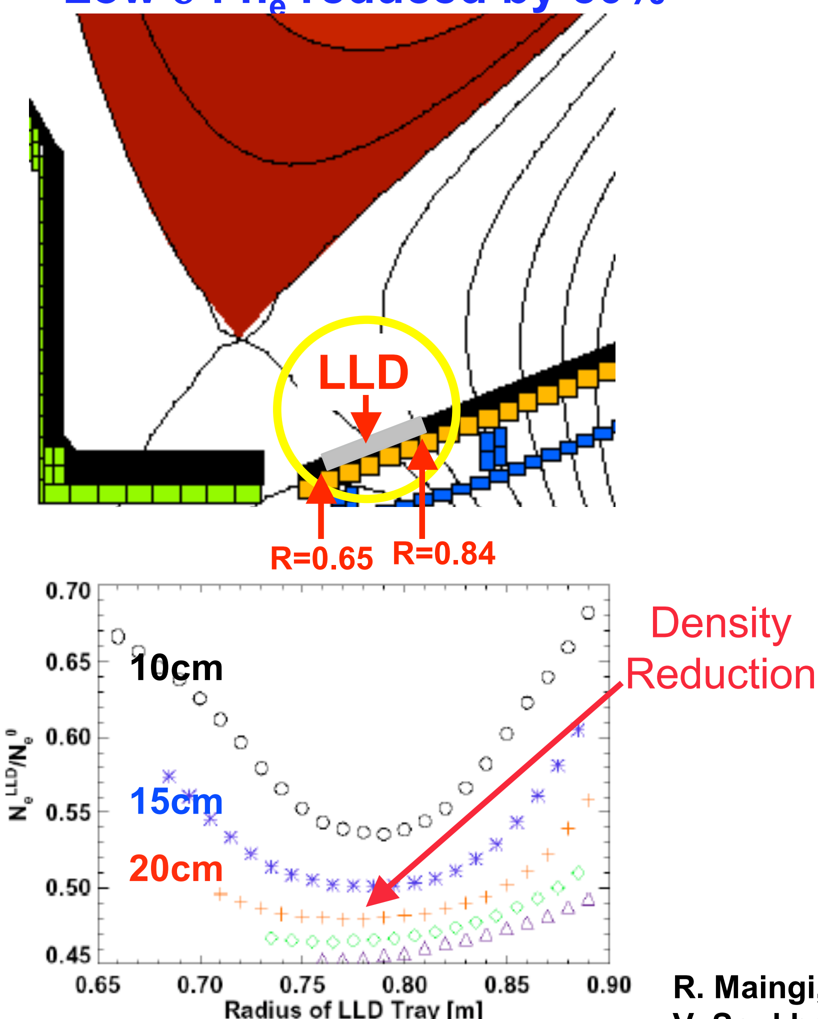
- Convert measured Dα luminosity to particle flux using 20 ionizations per photon
- Estimate LLD-1 flux intercept fraction from candidate discharge data for a given time slice
- Vary R_{LLD} in steps of 1 cm
- Repeat for different W_{LLD}, R_P, η_{CORE} and other input parameters

R.Maingi, ORNL

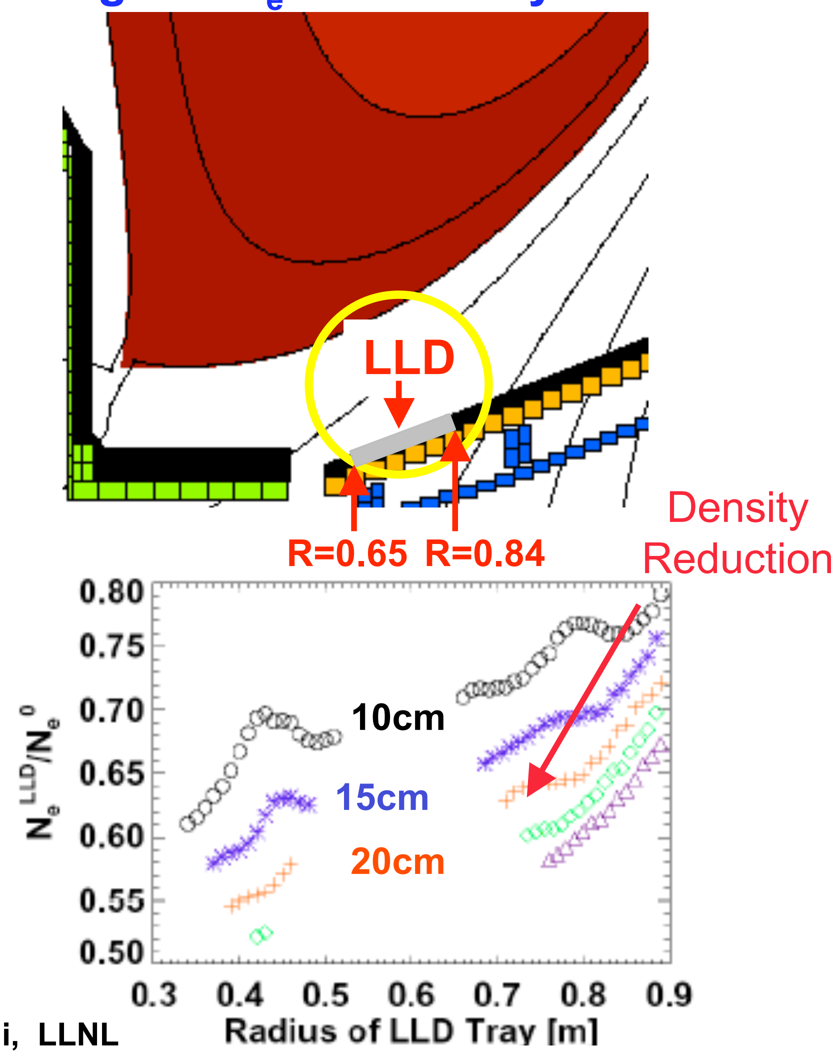
Due to High Flux Expansion, Pumping by 20 cm Wide LLD-1 on Outer Divertor Will Provide Density Control for Both High and Low δ Plasmas

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

Low δ : n_e reduced by 50%

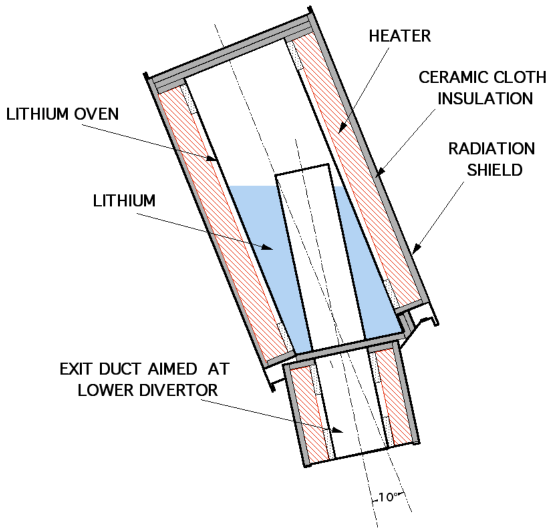


High δ : n_e reduced by 25%



R. Maingi, ORNL
V. Soukhanovskii, LLNL

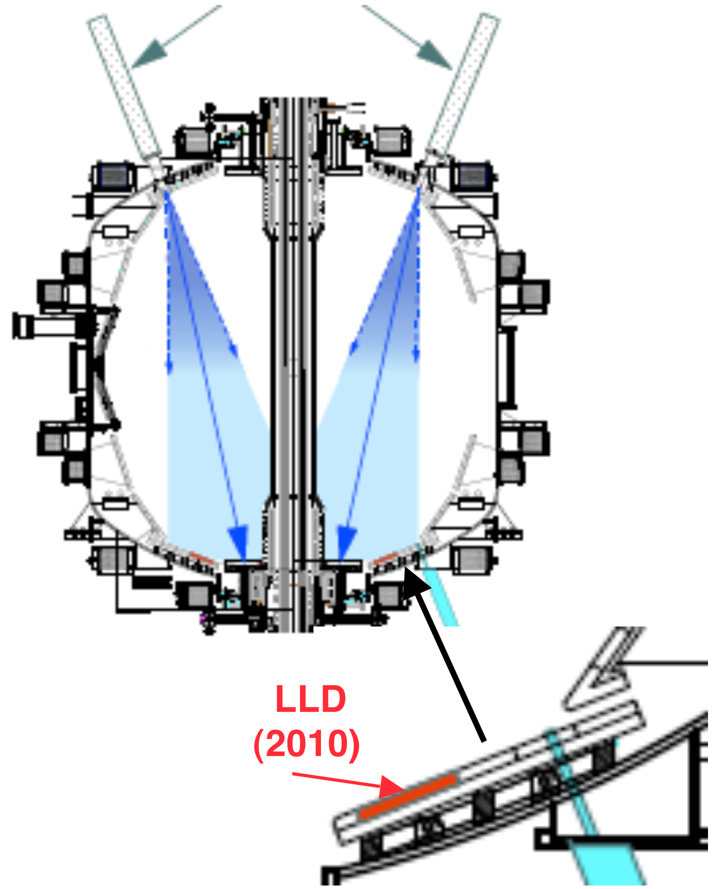
LLD-1 Li Surface Will Be Supplied Using the 2 LITER Units



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

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

Dual Liquid Lithium Evaporator
For Li wall coatings
Now routinely used



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

- In recent experiments, the dual LIThium EvaporatoR (LITER) system evaporated 600g of Li into NSTX
  - 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 closed shutters
  - If HeGGDC was applied, the shutters remained closed
  - The LITER shutters were then reopened after the diagnostic window shutters closed, and the deposition cycle repeated
  - The LITER system has become a routine operational tool used to establish lithium wall conditions
    - LITER used for ~ 80% experiments in 2009

Loading LLD-1 Using Lithium Evaporation is the Initial Approach

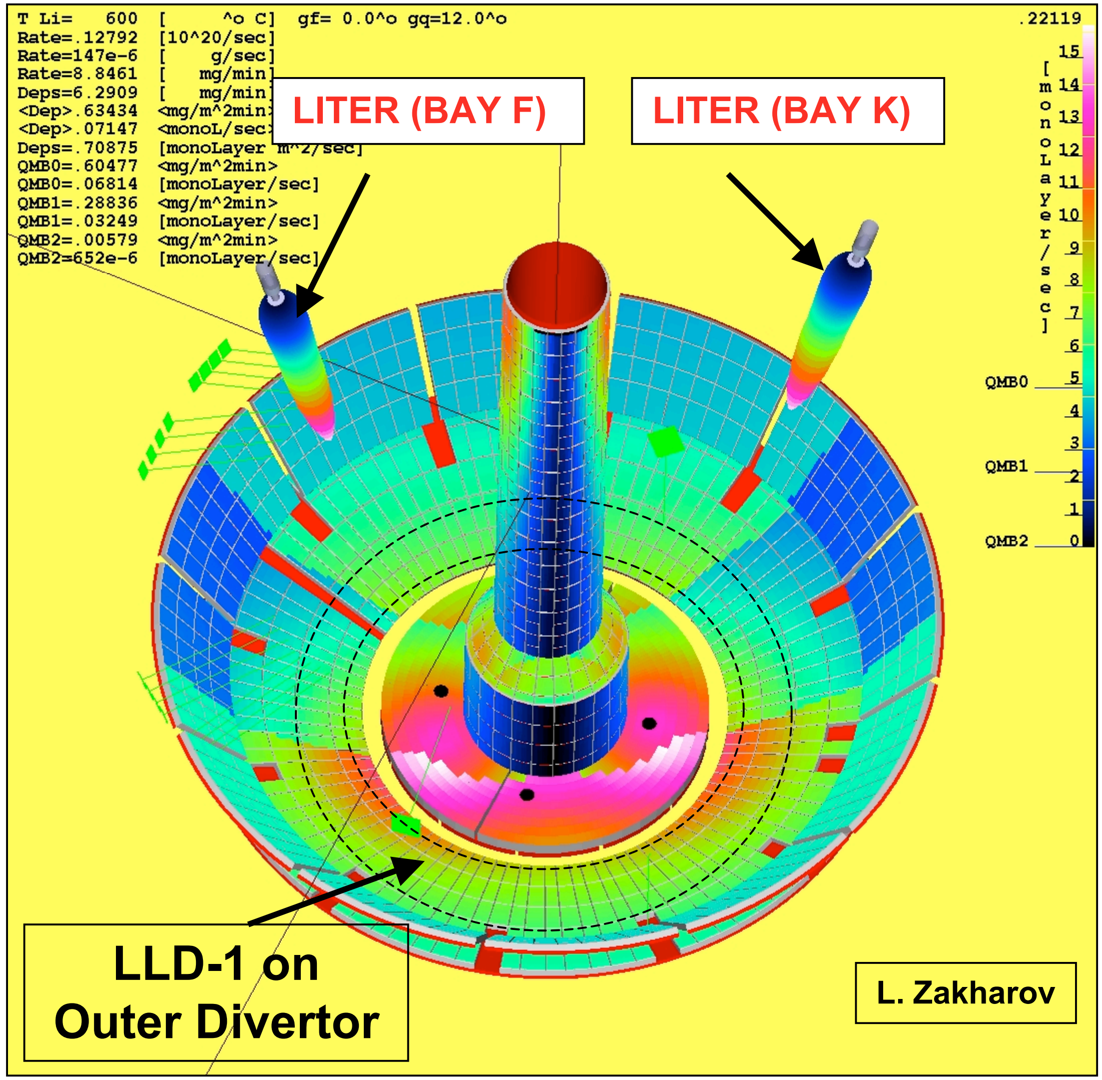
<u>LITER Deposition Capability</u>

- Present LITER deposition efficiency on to LLD is ~ 7% of total output.

- The LLD area is $9.35 \times 10^3 cm^2$. The porous Mo is 0.165 mm thick. The volume envelope of the Mo coating is $1.54 \times 10^2\ cm^3$. This volume has 45% porosity. The volume available for Li filling is $0.45 \times 1.54 \times 10^2\ cm^3 = 69 cm^3$.

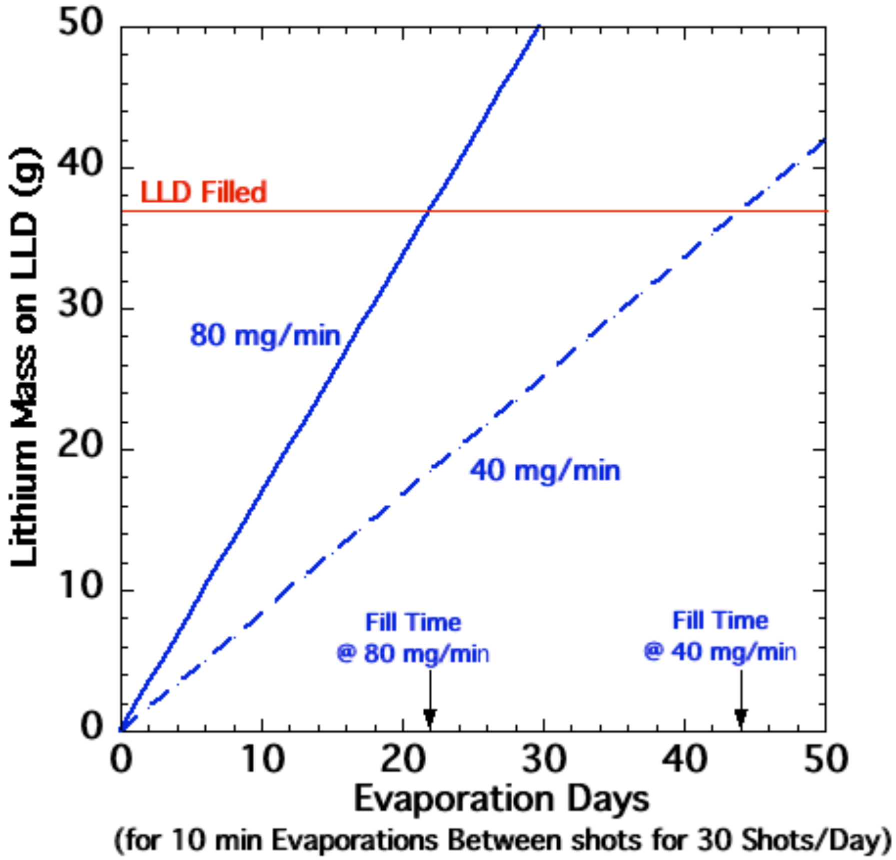
- The required Li fill is $0.53\ g/cm^3 \times 69\ cm^3 = 37$ g.

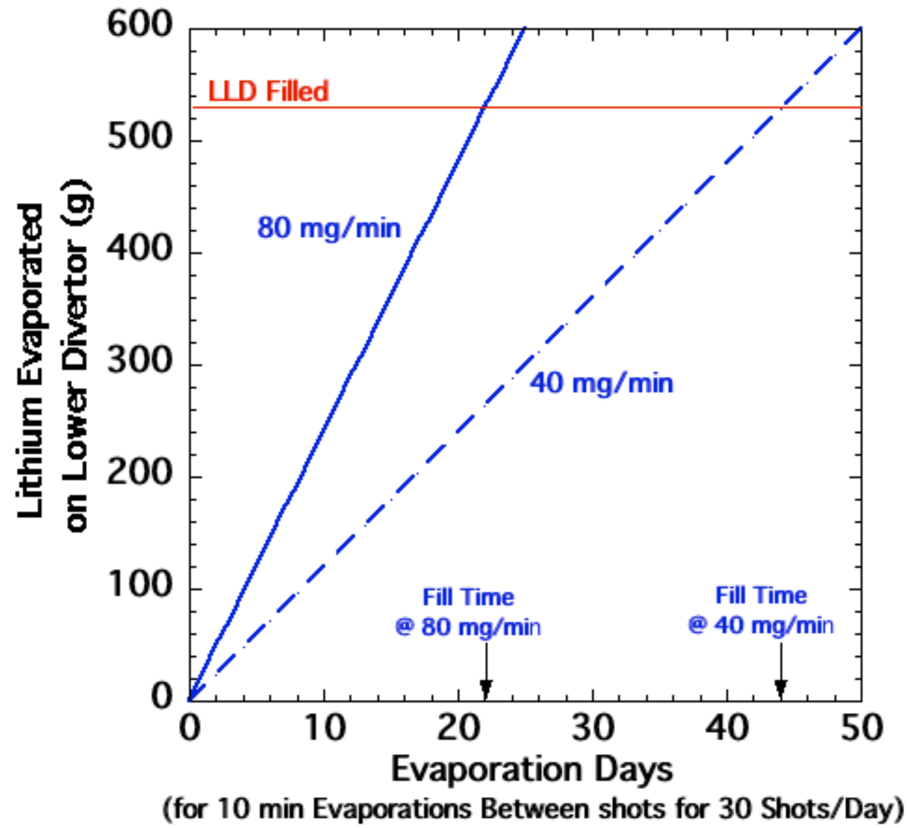
- At a 7% efficiency, this requires 530 g to be evaporated (2 possible scenarios).



LLD-1 Lithium Loading Scenario Using Short Evaporations

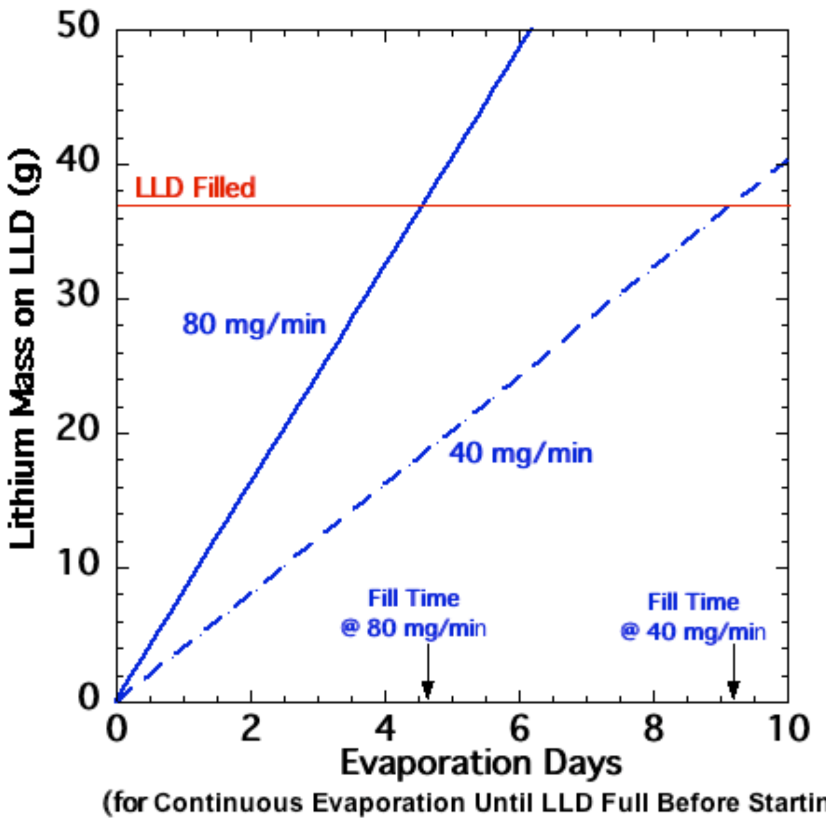
• Evaporate for 10 mins Between Shots until LLD-1 Full

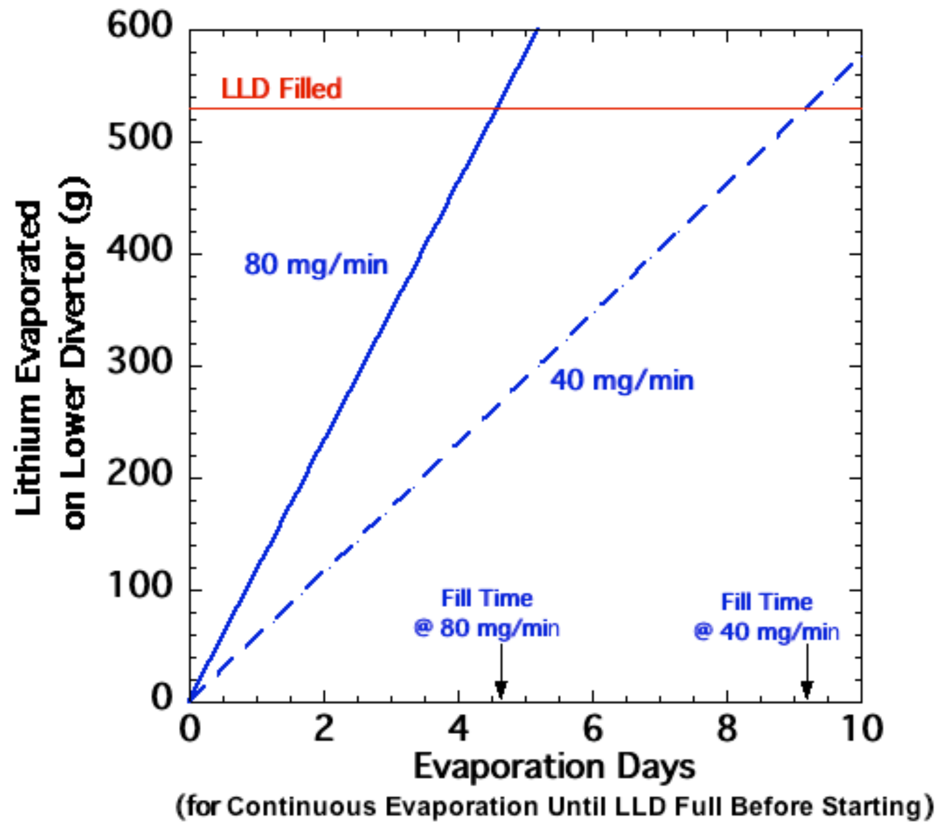




LLD-1 Lithium Loading Scenario Using 24 hr Evaporation

• Continuous Evaporation Until LLD-1 Full





Summary and Conclusions

- NSTX Will Test the Potential Benefits of Liquid Lithium Divertor for Integrating High Plasma and PSI Performance.
- LLD-1 on Outer Divertor will test flexible broad area pumping to reduce density for increased neutral beam current drive capability.
- Installation of LLD-1 in progress for pumpdown December 2009.
- Plasma operations begin in March 2010.