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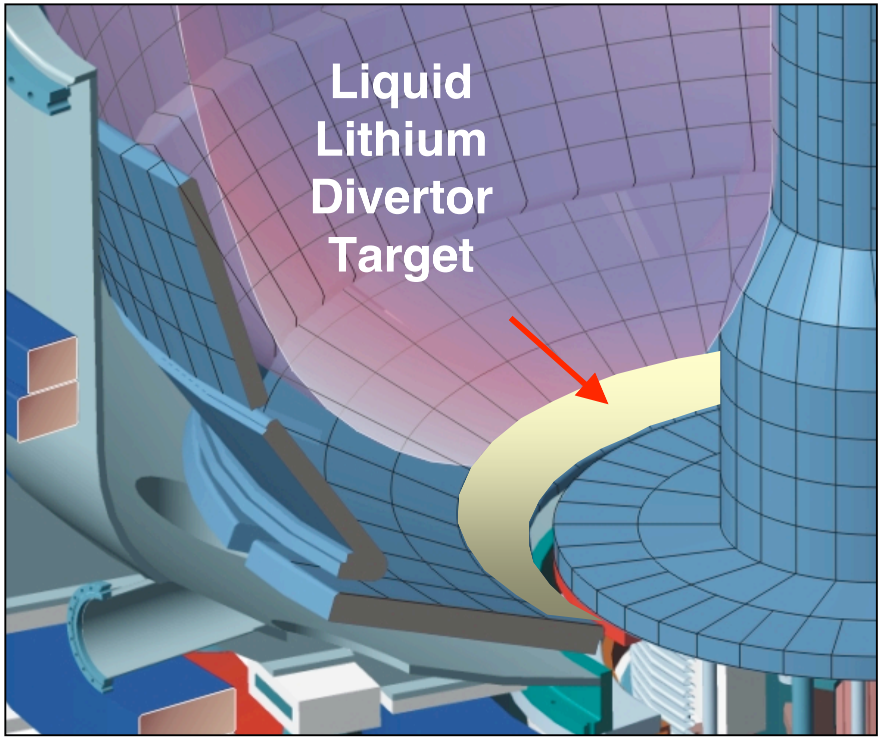
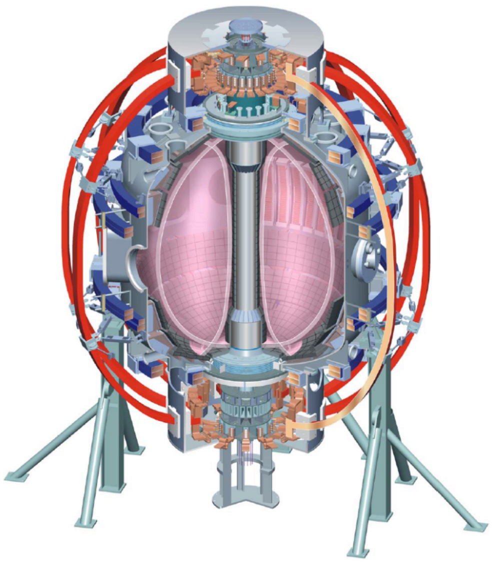
Review of the Results from the NSTX Edge Physics - ETG Meeting on Adoption of the LLD Radius and Width



An LLD Candidate Concept

H. W. Kugel and the LLD Team

May 29, 2007



Outline

- SNL Liquid Lithium Divertor Proposal Structure
- SNL Proposal NSTX Milestone Action Item
- The Adopted LLD Operating Design Goals
- Decision Process / Workshop Design Talks
- Status of Radius and Width Decision Process
- Summary and Conclusion

The SNL, UCSD, NSTX Collaboration Will Develop and Operate a Liquid Lithium Divertor Starting in the Present NSTX 5-Year Lithium Plan

- **Sandia will supply NSTX with**
  - LLD hardware for an outer strike point target (e.g. a boat containing a sintered Mo porus medium).

- **SNL and NSTX collaboration will include**
  - design of the hardware, specification of interfaces and responsibilities, and development of an operational plan.
  - installation and shakedown of the LLD and participation in LLD experiments in NSTX.

- **UCSD will participate through a subcontract with SNL**
  - provide removable lithium feed systems or other hardware for alternate schemes for filling the LLD.

SNL Proposal Milestone Calls for NSTX to Adopt LLD Radius and Width Specifications

- The Requested Geometry Design Parameters
  - Major radius R
  - Width

- Additional Parameters to be determined from SNL and NSTX Engineering Analysis and SNL Experiments
  - Number of segments
  - Gaps between segments
  - Clocking of segments (ϕ_{min}–ϕ_{max})
  - Orientation (horizontal or sloped)
  - Mechanical support and fastening method
  - Heating method & operating temperature
  - Cooling method and duty cycle

The Design Milestones for LLD Operation Adopted from Present 5 Year Plan and ISD Requirements

NSTX

• Design Milestones for LLD Operation

1) Achieve inductionless current drive density control capability in the range:

- Option 1: any scenario

- Option 2: ISD scenario

  $n_e \sim 5 \times 10^{19}$ m^{-3} at Ip = 700 kA (n_e/n_{GW}) ~0.65-0.8

  [from more recent estimates (~15-25% decrease in n_e from recent exps)]

  [FY09]

2) Allow for n_e scan capability in H-mode (e.g.,~ x2)

[FY10]

3) Investigate power handling capability of LLD

[FY10]

NSTX Completed the LLD Design Workshop Process for Arriving at the Radius and Width Decision

- **LLD Radius and Width Design Workshop Talks** **(refer to Drag&Drop LLD Folder)**

1) Basic Scope of Sandia Effort - R. Nygren, 2/27/07
2) NSTX , SNL, UCSD LLD Collaboration - H. Kugel, 2/27/07
3) Progress Toward Design Goals and the Process - H. Kugel, 3/09/07
4) Physics Considerations for the Design of the LLD for NSTX - R. Maingi (ORNL), 3/9/07
5) Liquid Lithium Divertor 0-D Pumping Projections and Sensitivities - R.Maingi (ORNL), 4/03/07
6) Near Term Plans - H. Kugel, 4/24/07
7) Particle Flux and Recycling Analysis in NSTX - V. Soukhanovskii (LLNL), 4/24/07
8) Lithium Chemistry in NSTX - J. R. Timberlake, 4/24/07
9) Fast Ion Loss to NSTX Divertor Region and Implications for the LLD - D. Darrow, 5/02/07
10) Recycling and Particle Fluxes in NBI H-mode Plasmas - V. Soukhanovskii (LLNL), 5/02/07
11) LLD Update - H. Kugel, 5/10/07
12) Liquid Lithium Divertor CHI Implications - R. Raman (U. Washington), 5/10/07
13) A Very Short Summary of CDX-U Lithium Regimes - R. Majeski, 5/10/07
14) Thermal Regime of LLD - L. Zakharov, 5/10/07
15) Edge Physics - ETG review of a candidate radius and width - H. Kugel, 5/22/07

Status of the LLD Radius and Width Decision Process

- The Design Workshop discussions and analysis used to:
  - Identify technical constraints on the candidate geometries.
  - Simulate particle balance and recycling physics.
  - Discuss analysis of available data.
  - Update Decision Matrix.

- The remaining steps are:

  > Edge Physics - ETG review of a candidate radius and width.

  > NSTX Physics Meeting for review of the Edge Physics - ETG discussion.

  - Management Review

Elements of the Decision Matrix
Used for the LLD Radius and Width Analysis

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1. Experimental program impact on high performance low R/a discharges, if LLD component failure occurs.
2. Radial & width variation of the LLD pumping speed.
3. LLD operating temperatue.
4. Installation technical complexity (in- & ex- vessel).
5. Lithium-filling issues.
6. Diagnostic issues.
7. Power handling issues

Summary of Analysis of Experimental Program Impact on High Performance Low R/a Discharges, If LLD Component Failure Occurs

NSTX

- Simplest Gedanken: Assume an LLD whose pumping speed is independent of radius, it functions for a few weeks, and then has a component failure.

RADIUS & WIDTH	PROGRAM RISK LEVEL	COMMENTS
Inner-half, Lower Inner Divertor	Highest	This is the high performance, low R/a region. If LLD malfunctions, stop the run, vent, and fix malfunction
Outer-half, Lower Inner Divertor	Medium	If LLD malfunctions could maybe run inboard if LLD is narrow, but flux expansion would overlap LLD
Inner-half, Lower Outer Divertor	Lowest	If LLD malfunctions could run in high performance, low R/a region almost unchanged

- **Under the above assumptions, the lowest risk location for the LLD to high performance, low R/a discharges is the Outer Divertor.**

Pumping by an LLD 15-20 cm Wide Will Provide ISD option for Density Control for Inductionless Current Drive

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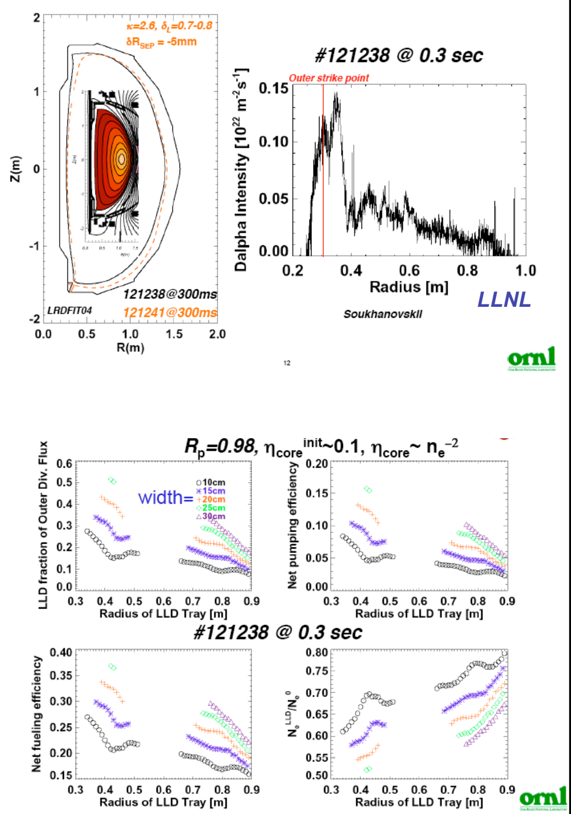
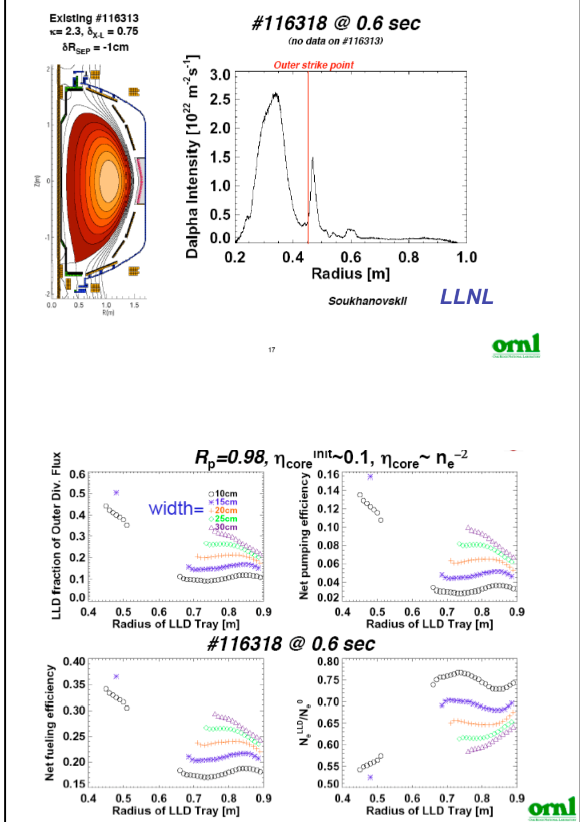
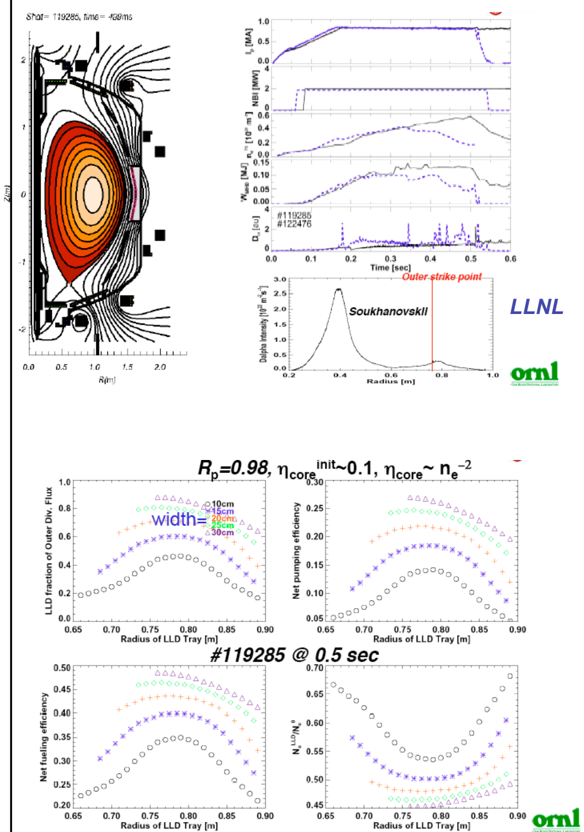
Broad SOL Dα profile in high δ (pf1a) #121238



Narrow SOL Dα profile in medium δ (pf1b) #116318



Narrow SOL Dα profile in low δ (pf2) #119285



- 20 cm wide provides more pumping
- 15 cm wide might allow private-flux region pumping

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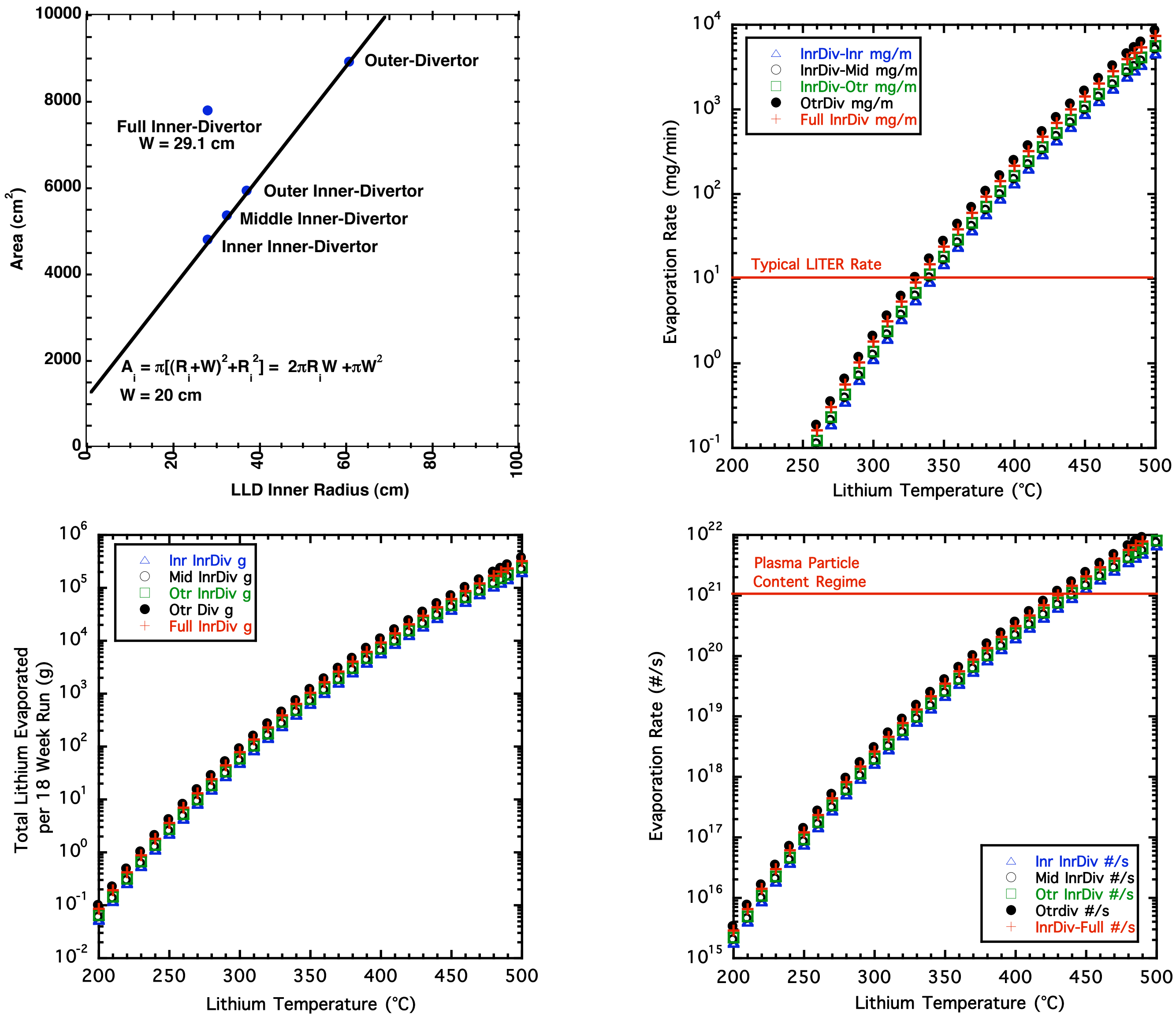
LLD Operating Temperature Should Not Exceed About 300°C for All Candidate Locations



Summary of Analysis of LLD Radius Location and In- & Ex-vessel Technical Complexity

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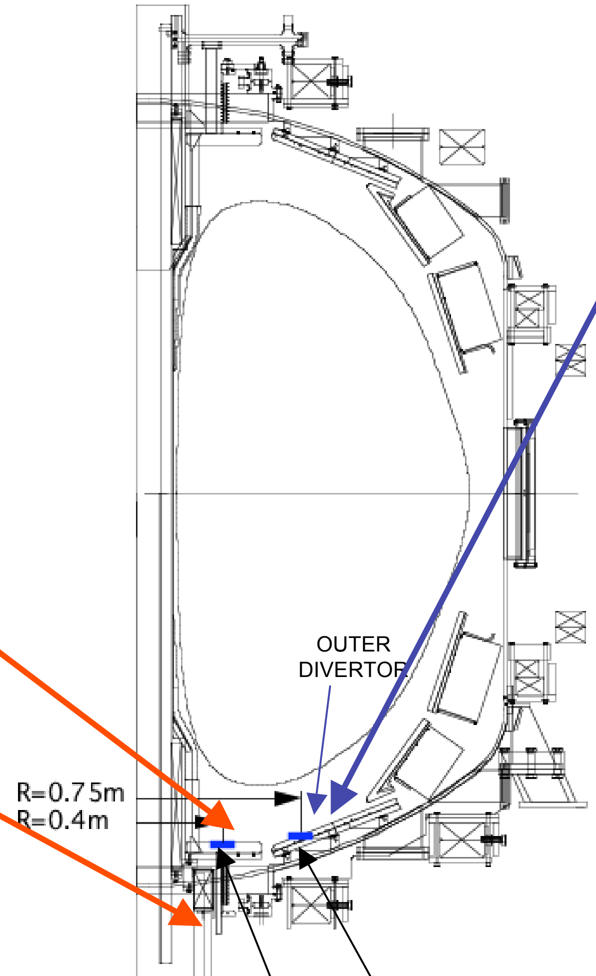
INNER DIVERTOR

- Interference with Lower Inner Divertor gas ports.

- Difficult to reach Inner Vessel feedthrus. Cannot be reached during operations.



- **Candidate locations for toroidal, LLD at Inner or Outer Divertor**

OUTER DIVERTOR

- **Either**
  - **Flat installation on conical section**
- **Or**
  - **Sloping installation on conical section more difficult**
- **Possible P-CHERS shielding issue**
- ***Convenient access to feedthrus and easiest modification of instrumentation***

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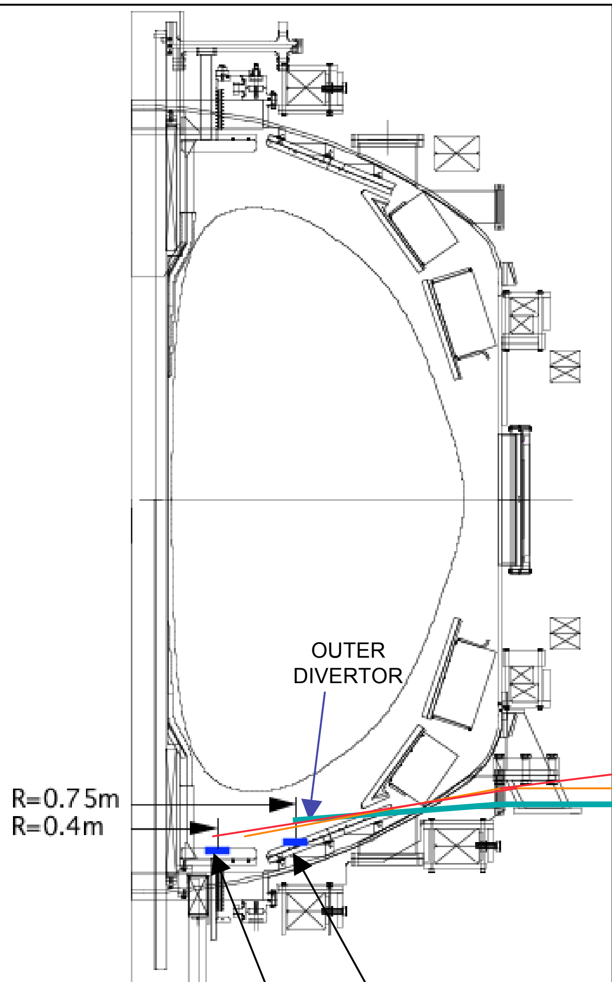
LLD Lithium-filling is Most Accessible from Horizontal Outer Divertor Ports



- **Candidate locations for toroidal, LLD at Inner or Outer Divertor**

INNER-HALF INNER DIVERTOR

- Li feed stroke ~137 cm from Horizontal Divertor Port

OUTER-HALF INNER DIVERTOR

- Li feed stroke ~117 cm from Horizontal Div Port

OUTER DIVERTOR

- Li feed stroke ~102 cm from Horizontal Divertor Port.

- *minimum feed stroke for outer divertor location*

Summary of Analysis of LLD Diagnostic Issues

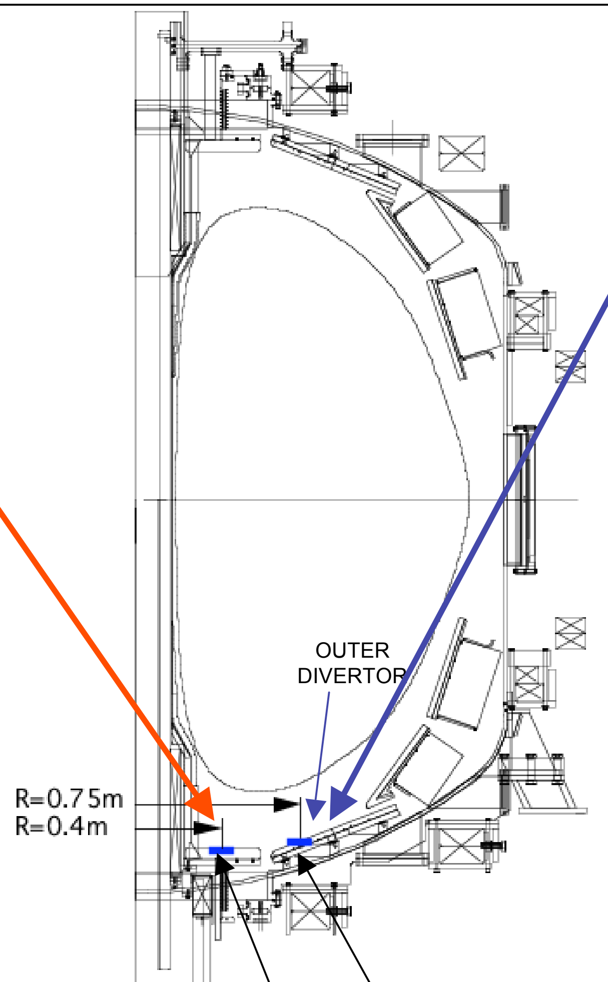
• *In-vessel Instrumentation Easier to Modify on Outer Divertor*

• INNER-HALF INNER DIVERTOR

- Loss of 1 or 2 Bz coils
- Loss of 2 TC
- Loss of 2 LP

• OUTER-HALF INNER DIVERTOR

- Loss of 1 or 2 Bz coils
- Loss of 2 TC
- Loss of 2 LP spaces



• Candidate locations for toroidal, LLD at Inner or Outer Divertor

• OUTER DIVERTOR

- Loss of 2 Bz coils
- Loss of 2 TC
- Loss of 1 LP spaces
- FL response changes
- Possible PCHERS shielding issue

• In-vessel Instrumentation easier to modify on outer divertor

Summary of Analysis of Lithium Inventory

LLD Liquid Lithium Inventory Requirement

Fuel per Shot
The adopted specification for LLD design calculations for deuterium fueling per shot is 50 T-liters.

D_2 moles/shot
50T-liters D_2/shot = 50 T-liters x (1mole/18250 T-liter) = 2.740×10^{-3} D_2 moles/shot

D moles/shot
D moles/shot = 2 x D_2 moles/shot = 5.479×10^{-3} moles/shot

Li mass consumed /Shot
The amount of Li needed to convert the total D fuel inventory into LiD per shot is M_{Li}= (5.479×10^{-3} moles-Li/shot) x 6.94 g/mole-Li = 3.80×10^{-2} g = 38.0 mg

Total Number of Shots per 18 Week Run
Assume best case of 30 shots /day Total shots = (30 shots/day) x (5 days/wk) x (18 weeks) = 2.700×10^{3}

Total Minimum Li Mass Consumed per 18 Week Run
m_{total} = (3.80×10^{-2} g/shot) x (2.700×10^{3} shots) = 103 g

- 100 g of Li will be consumed by pumping during 18 Wk Run
- 200-300 g of Li consumed by pumping + evaporation during an 18 week Run

Boronization Appears To Be Incompatible With Long Term LLD Operation

NSTX

- NSTX Bornization via Trimethylboron,$B(CD_3)_3$ into HeGDC deposits B/C films with a stoichiometric ratio of about 1/3 (W.R. Wampler, et al, SNL)
- Hot liquid lithium on BC_3 films will react strongly to form Li_2C_2 (lithium carbide)
- Liquid lithium will not wet granular B and Li_2C_2
  - Lithium fill methods that depend on lithium wetting will not flow & fill
- Evaporation of lithium directly on to BC_3 films will cause:
  - Li_2C_2 will form as power deposition heats the surface and cause reduced D pumping
  - B and Li_2C_2 will result in ceramic thermal insulating layer between lithium film and substrate, thereby raise Li temperature and accelerate the lithium evaporation rate above 300°C
- Much He ohmic discharge conditioning might remove this ceramic skin if substrate will not be damaged

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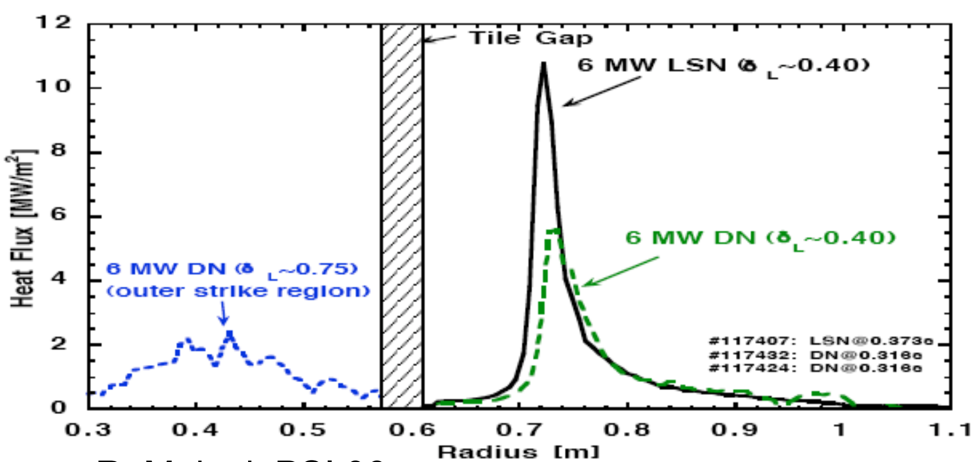
LLD Power Density Simulation Studies Are in Progress at SNL and PPPL Benchmarked by NSTX Measurements

NSTX

LLD Typical Design Parameters

Typical Measured Lower Divertor Incident Power Densities

- Low Triangularity Plasmas: 10 MW/m2
- Medium Triangularity Plasmas: 6 MW/m2
- High Triangularity Plasmas: 5 MW/m2



R. Maingi, PSI 06

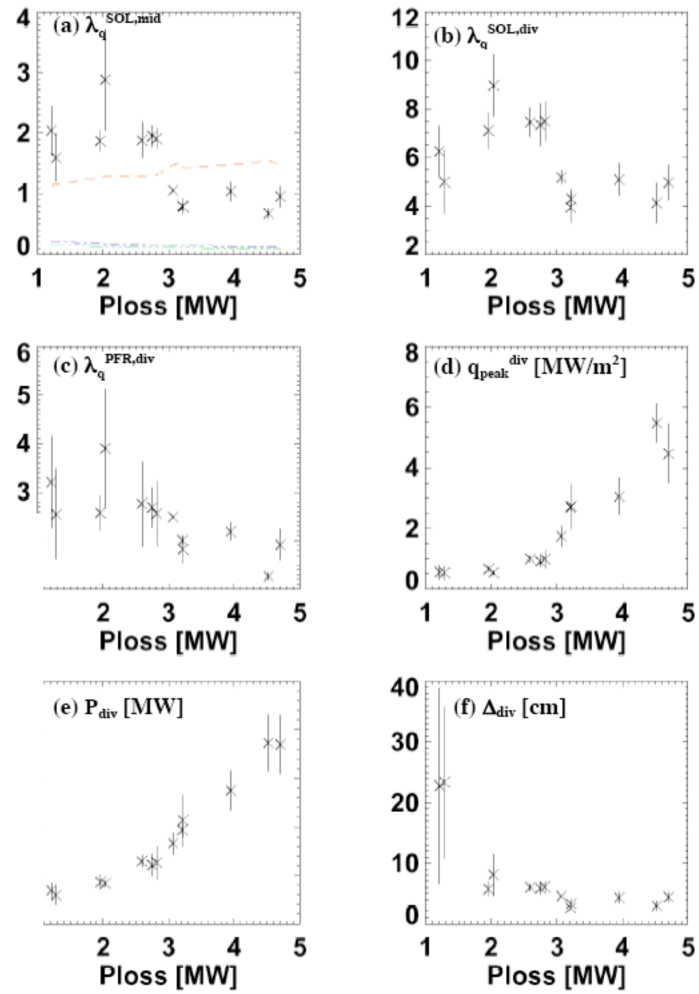


Fig. 1 – characteristics of outer divertor heat flux profile vs. loss power.

R. Maingi, ORNL

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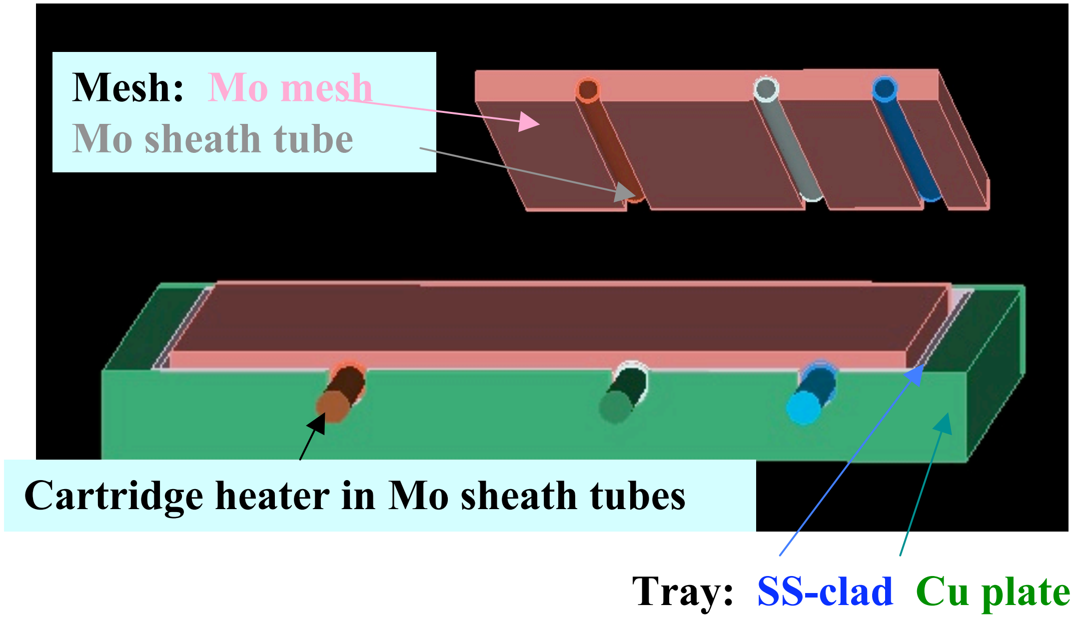
SNL Wetting Test of Candidate Power Handling Concept

NSTX

Our concept uses cartridge heaters to heat a Mo mesh to a temperature where the Li wets the mesh while the container remains cooler and perhaps below the melting point of Li. The advantage of this scheme is that any penetrations on the container plug automatically and there is no driving force for Li to migrate onto or outside of the container.

In our initial concept for the LLD or in sizing experiment for the wetting test, we did not try to minimize the amount of Li inventory for NSTX. The concept we have now provides enough thermal mass for some diffusion of heat from the heat Li surface and, in this regard, the high conductivity mesh is more effective that Li or Li on a stainless steel plate. The inventory for this scheme in NSTX would be about 1 liter or ½ kg of Li per tray and a total of 2 kg. The uneven spacing of the heater in the sketch below is simply to test two spacings.



- Mesh has ~50% volumetric porosity.
- Mesh is formed with CVD over C skeleton that entirely covers C.
- Initial C skeleton has pyrolytic grpahite added before final closeout when CVD Mo skin is added. Resulting structure has high thermal conductivity, approaching that of pyrolytic graphite rather than Mo.
- Mesh has channels troughs for Mo sheath tubes.
- Mesh rises above edge of tray.
- Thickness of mesh is governed by diameter of cartridge heaters. Sketch shows a 150 x 250 mm mesh with thickness of 9mm to accept cartridge heaters of ¼" OD.

Summary and Conclusion

- For comparable pumping speeds, the lowest risk location for the LLD to high performance, low R/a discharges is the Outer Divertor

- LLD 15-20 cm wide pumping on Outer Divertor provides reduction in density for high performance ISD Inductionless Current Drive milestone
    - 15 cm wide might allow private-flux region pumping
    - 20 cm wide provides more pumping

- LLD operation must be restricted to below about 300°C

- LLD on Outer Divertor
    - allows easiest access to feedthrus and
    - allows easiest modification of instrumentation
    - allows minimum Li-filling feed stroke (via Horizontal Divertor Port)

- LLD power density simulation studies benchmarked with NSTX measurements are in progress at SNL and PPPL

- An LLD 15-20 cm wide on the Outer Divertor, about 2.5 cm Outboard of the CHI-gap meets NSTX requirements

PPPL LLD Power Density Simulations Are in Progress

NSTX

Google: [Leonid Zakharov] → http://w3.pppl.gov/~zakharov

Operational and design space of LLD,
Li/Mo Capillary Porous System (CPS) and
Li/SS/Cu plate

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NSTX Meeting,

May 29, 2007, PPPL, Princeton NJ