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Lithium Loaded Target Plate for high performance plasma in NSTX

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Contents

Edge plasma temperature has nothing to do with the wall temperature

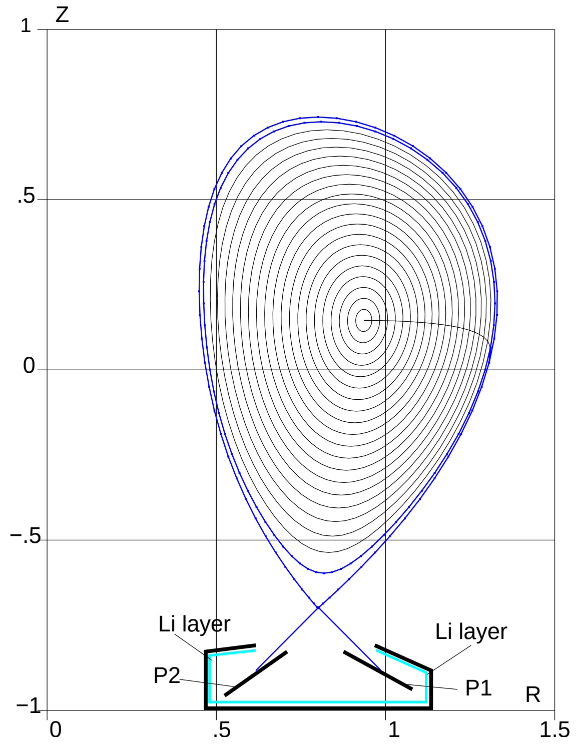
Mean free path of the deuterium ion

$$
\begin{aligned}
\tau &= 3\cdot 10^6 \frac{T_{eV}^{3/2}}{Z^3 n_i(\lambda_C/10)}\sqrt{\frac{\mu}{2}},\\
\lambda_C &= 23 - \ln\sqrt{\frac{2n_{20}\cdot 10^5}{T_{i,keV}^3}} = 16.9 - \frac{1}{2}\ln\frac{n_{20}}{T_{i,keV}^3},\\
\tau_{DD} &= 2\cdot 10^{-2}\frac{T_{keV}^{3/2}}{n_{20}},\\
V_D\left[\frac{m}{sec}\right] &= 219\cdot 10^3\sqrt{T_{keV}},\\
\lambda_D &= V_D\tau_{DD} = 4380\frac{T_{keV}^2}{n_{20}}.
\end{aligned}
\qquad (1.1)
$$

Plasma, impacting the PFC, has no idea about the temperature of the wall.

Any fusion relevant plasma is in a collisionless regime near the wall

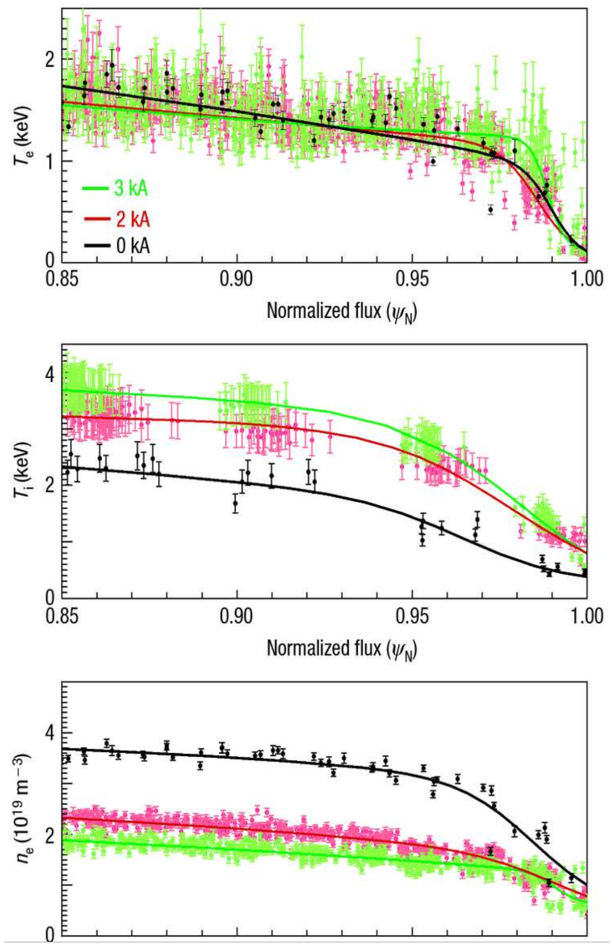
(Pumping lithium plasma facing surface + core fueling) together provide a high edge temperature pedestal, the best possible, diffusion based, confinement, global stability and controlled plasma-wall interaction

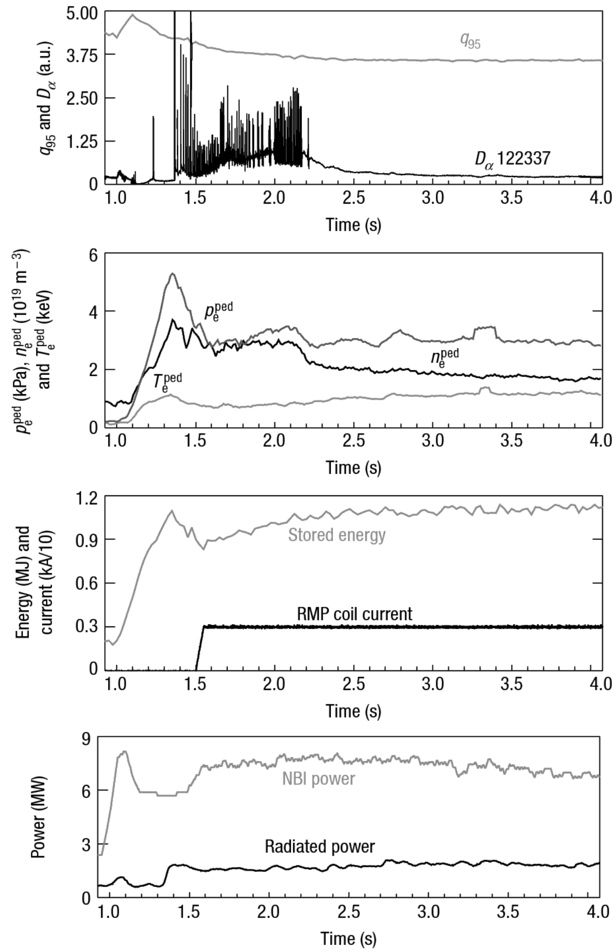


1. *In collisionless SOL the thermo-force* $R_T \propto Z^2$*, driving impurities into the plasma. is absent, leading to* $Z_{eff} \simeq 1$
2. *Blobs and direct plasma-wall interaction are also not expected. There is no indications of blobs in QHM regime on D-IIID.*

LiWall plasma regime, not the plasma with the C- or W-walls, is the only science based concept of the stationary plasma

RMP experiments on D-IIID have confirmed our, LiWF, views





0 kA, 2 kA, 3 kA $I_{RMP-coil}$ *T.Evans at al., Nature physics 2, p.419, (2006)*

Plasma $Tedge$ has nothing to do with the "edge transport barrier"

Reference Transport Model (RTM) is expected for the LiWall regime

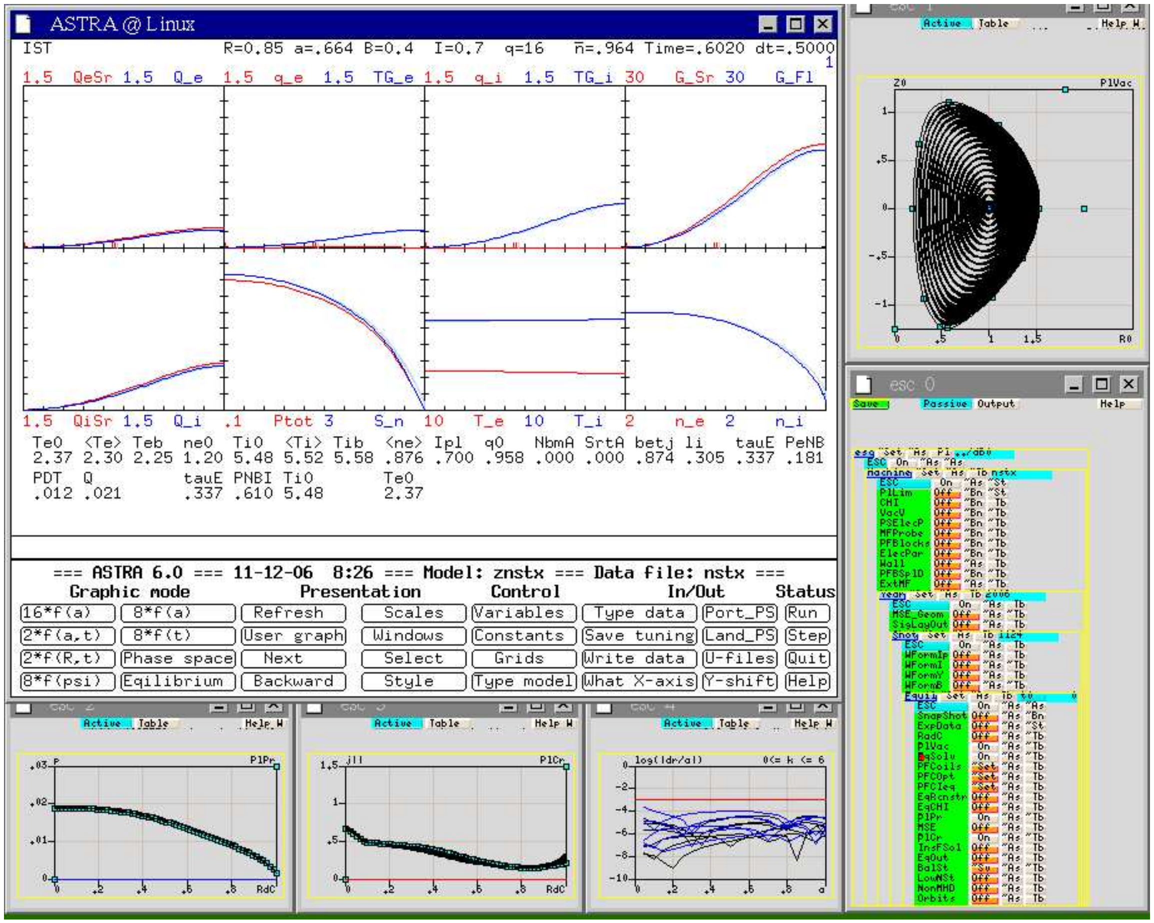
$$
\begin{aligned}
q_i &= \chi_i^{neo-classics} \nabla T_i, && \text{not important,} \\
q_e &= \chi_i^{neo-classics} \nabla T_e, && \text{not important,} \\
\Gamma_{i,e} &= \chi_i^{neo-classics} \nabla n
\end{aligned}
\tag{2.1}
$$

The Table compares the RTM predictions (ASTRA-ESC) with CDX-U data.

Parameter	CDX-U	RTM	RTM-0.8	RTM-0.7	RTM-0.65	glf23
$\dot{N}$, 10^{21}part/sec	1-2	1	0.5	0.35	0.3	0.8-3
β_j	0.150	0.151	0.150	0.150	0.151	0.145
l_i	0.66	0.769	0.702	0.694	0.671	0.877
V, Volt	0.5-0.6	0.77	0.53	0.48	0.40	0.85
τ_E, msec	3.5-4.5	2.7	3.8	4.8	5.3	2.3
$n_e(0)$, $10^{19} part/m^3$		0.9	0.7	0.596	0.590	0.9
$T_e(0)$, keV		0.308	0.366	0.391	0.413	0.329
$T_i(0)$, keV		0.031	0.029	0.028	0.030	0.028

RTM does not contradict CDX-U measurements and equilibrium reconstruction

ASTRA-ESC simulations of NSTX, B=0.4 T, I=0.7 MA, 0.6 MW, 20 keV NBI



Hot-ion mode:

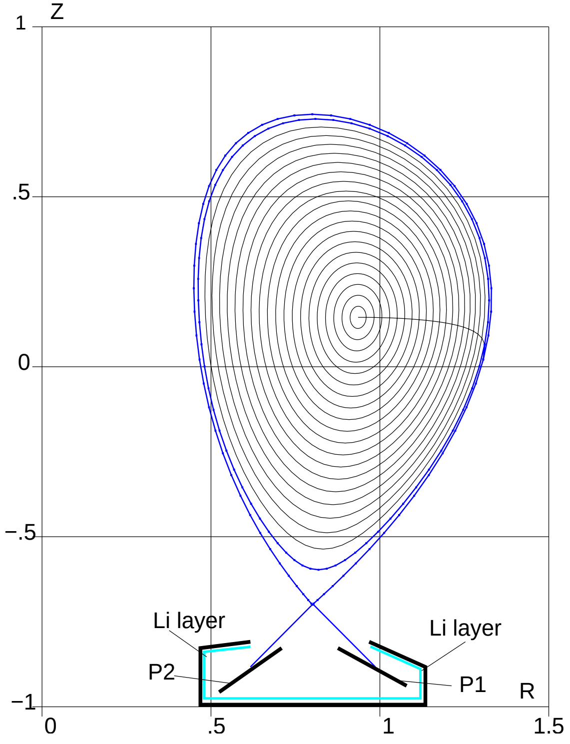
$$T_i = 5.5 \text{ [keV]},$$
$$T_e = 2.5 \text{ [keV]},$$
$$n_e(0) = 0.14 \cdot 10^{20},$$
$$\tau_E = 0.33 \text{ [sec]},$$
$$P_{NBI} = 0.61 \text{ [MW]}$$

NBI energy should be consistent with the plasma temperature:

$$E_{NBI} = 2.5(T_i + T_e)$$

LiWall regime is an extension of QHM or low-collisionality H-mode beyond their plasma density limitations

PLD $\equiv$ actively cooled plates with flowing $h \simeq 0.1$ mm Li layer



Gravity, Marangoni effect, residual $\mathbf{j} \times \mathbf{B}$ *forces,*

$$V_g = \frac{\rho g h^2}{2\nu} \sin\theta = 0.049 \sin\theta \; [m/s], \qquad (3.1)$$
$$V_M = \frac{d\sigma(T)}{dT} \frac{h \nabla T}{\nu} = 0.8 h \nabla T \; [m/s]$$

are sufficient for replenishing Li surface.

Lithium can accept 5-10 MW/m^2 *and keep* $T_{Li} < 400^o C$

$$\chi_{Li} = 47.6,$$
$$\Delta T \, [^o C] = 100 \frac{q}{4.7} \cdot h \left[\frac{MW}{m^2} \cdot mm \right]. \qquad (3.2)$$

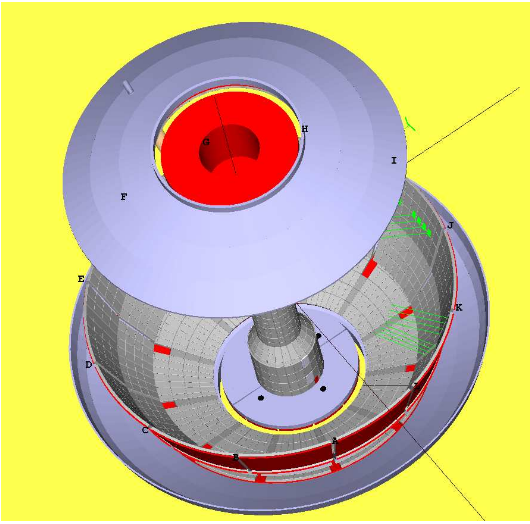
For any PFC (W,C,Li) power extraction are limited

by the coolant temperature,

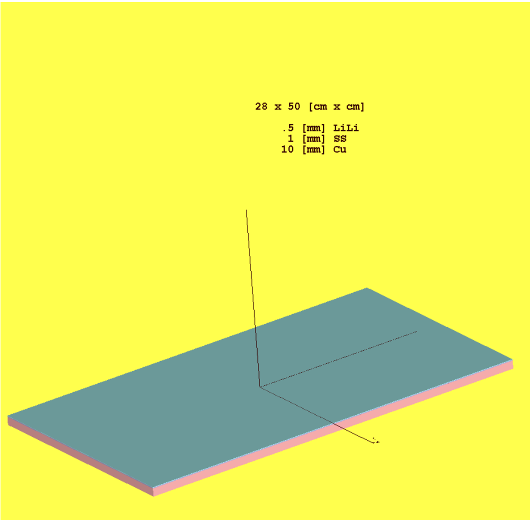
rather than by PFC surface temperature.

There is no contradiction between T limitations for Pumping Li Divertor and high efficiency of power production

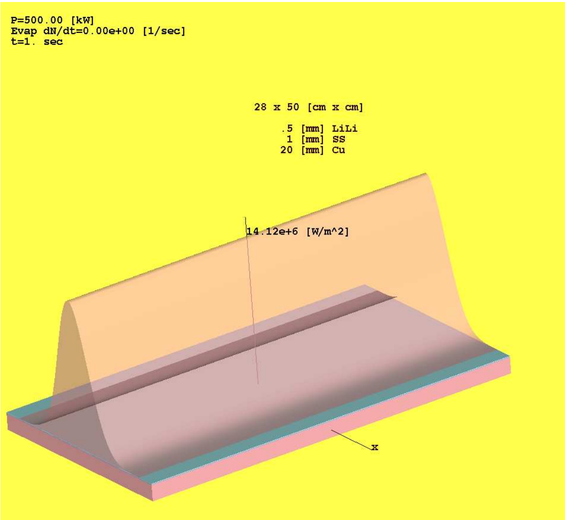
Lithium Loaded Target Plate (LLTP) can provide 10000 active monolayers or $\simeq 3\mu m$ of molten Li necessary for NSTX.



Li coated plate in low inner divertor



Li/SS/Cu (0.5mm/1mm/10mm) sandwich with a trenched surface

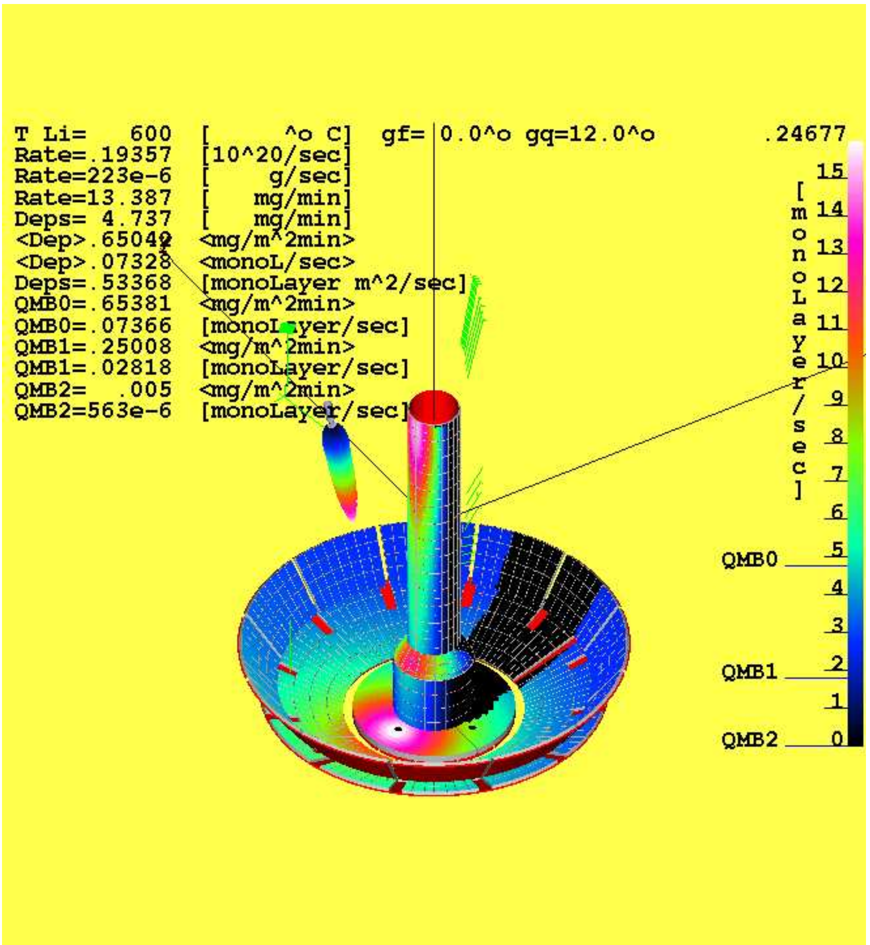


Gaussian (8 cm wide) heat deposition profile

$$\begin{aligned}
&S \simeq 0.75\ [m^2], \quad L_{SOL,m} = 2.5, \quad V_{Li} \simeq 0.35\ [L], \quad M_{Li} \simeq 175\ [g], \\
&\nu_{Pa\cdot sec} = 4.2 \cdot 10^{-4}, \quad I_{ion,MA} = \frac{(0.4-1)\cdot 10^{-3}}{1.6}, \\
&V_{Li,cm/sec} = (2-5)\cdot B_{tor}\frac{h^2_{Li,mm}}{0.01}\frac{0.1}{w_{SOL}}\frac{I_{SoL,MA}}{I_{ion}}
\end{aligned} \tag{3.3}$$

Li/SS/Cu plate could be real first step toward PLD and LiW regime

Solid lithium provides only 150 active monolayers



There is no a meaningful concept of Li on C- based PFC.

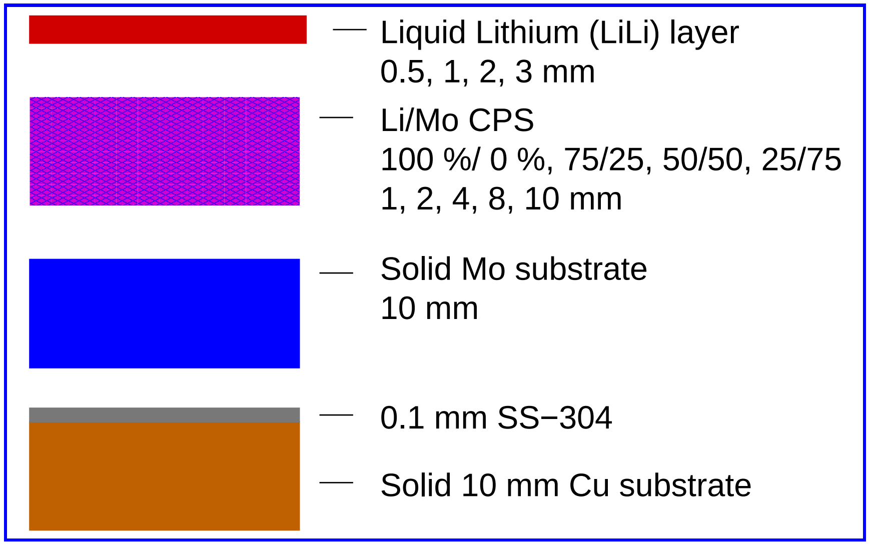
Evaporator at the top of NSTX is extremely inefficient in delivering lithium to the low divertor

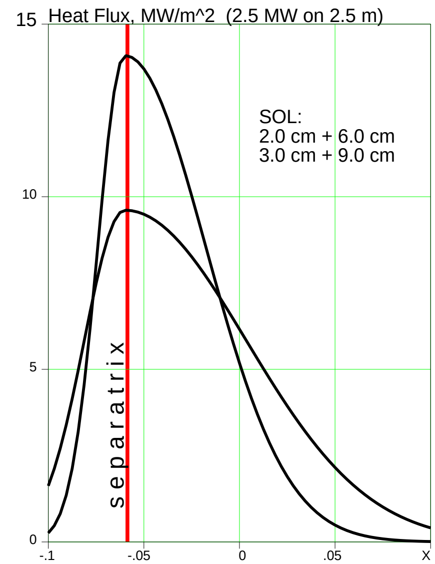
R_n [cm]	θ_{aim}	<IDL-2>	<IDL-1>	< OD-L>
1.03	22.0^o	2.657%	1.512%	12.824%
1.03	12.0^o	3.449%	2.252%	14.170%
1.53	22.0^o	2.675%	1.535%	12.978%
1.53	12.0^o	3.168%	1.962%	14.307%

NSTX evaporator cannot meet the requirements of plasma pumping.

In contrast, Li pellets together with the LLTP may work

Both Liquid Lithium (LiLi) and Li/Mo CPS were considered





Heat flux profile from the SOL

$$Q_{SOL} = Q_0 \exp\left[-\left(\frac{x-x_0}{d(x)}\right)^2\right], \quad \begin{cases} d = d_{out}, & x \geq x_0 \\ d = d_{in}, & x < x_0 \end{cases} \qquad (4.1)$$

Characteristic scale lengths, mm

d_{in}	d_{out}	Δ_{LiLi}	$\Delta_{Li/Mo}$	Δ_{SS}	$\Delta_{Mo,Co}$	Li/Mo CPS
20,30	$3d_{in}$	0.5, 1,2,3	1,2,4,8,10	.1	10	4/0, 3/1, 2/2, 1/3, 0/4

Initial temperature is very important for limits by evaporation

The expected working range of P_{NBI} $\simeq$0.75-1.5 MW. The range of P_{NBI} considered: 0-2.5 MW deposited to LLD.

Initial temperatures:

- 100^{o}C, solid lithium, although

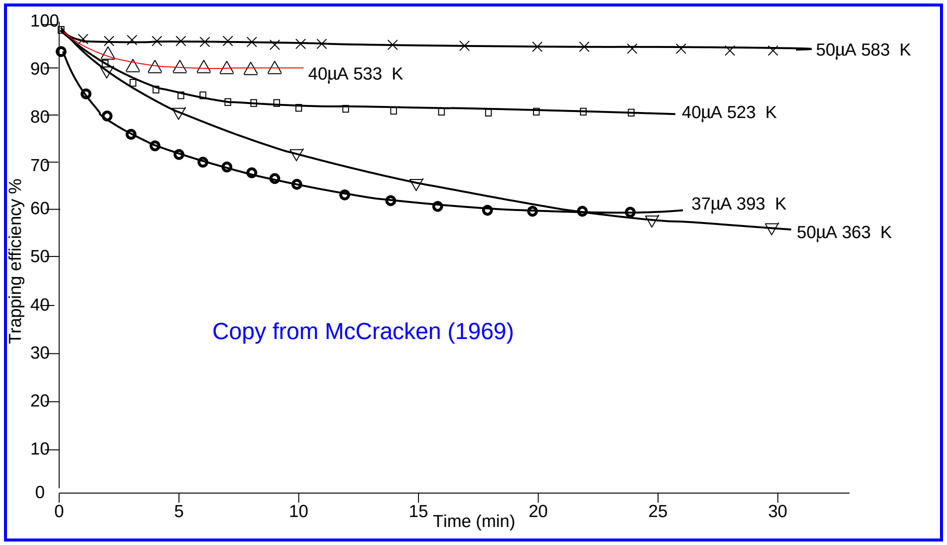
  heat losses for melting of Li have been neglected (!) (additional reserve of ΔT *$\simeq$100^{o}C* for the Li/SS/Cu plate).

- 200^{o}C, liquid lithium.

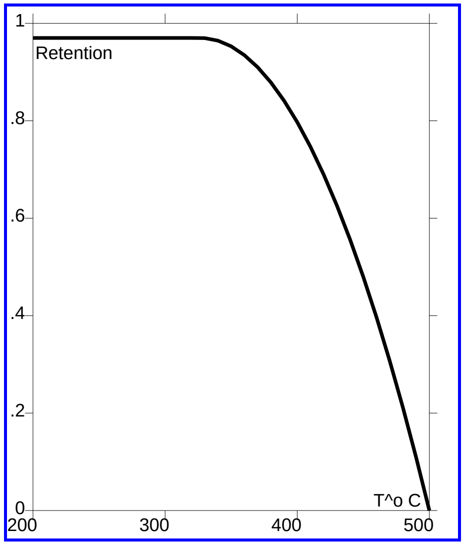
Surface area 0.7 m^2 contains 10^{19} Li particles/monolayer, or $3 \cdot 10^{26}$ Li particles/mm of thickness.

1 working mm of Li is sufficient for pumping 10^4 of $3 \cdot 10^{21}$ D,
more than sufficient for 2 weeks of NSTX operation

Lithium retains Hydrogen in a limited window of temperatures



McCracken retention curves



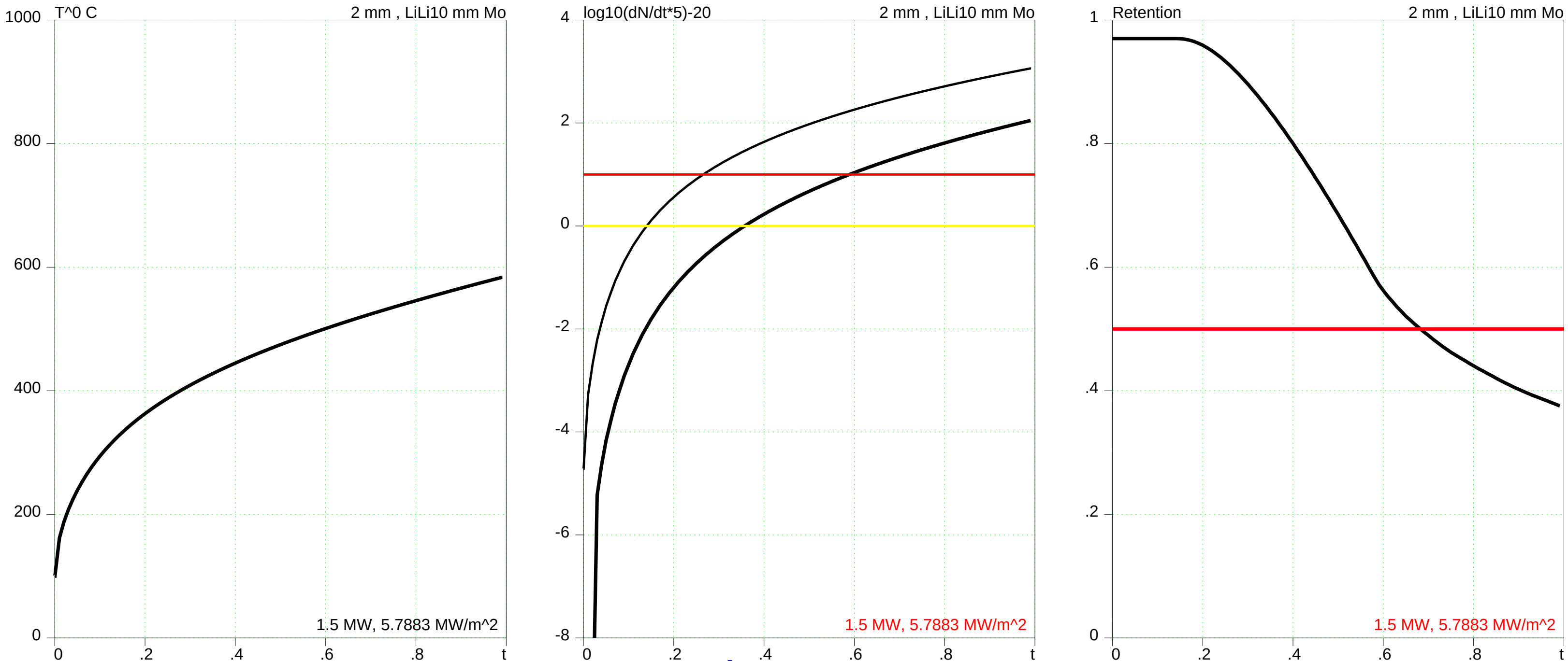
Short term retention curve used in calculations

Probably short lasting retention allows temperatures above 350^{o}C (R.Majeski)

Short term retention curve was taken arbitrarily

Requires special technology studies

3-D Cbebm code (written for Marangoni effect) is used to simulate heating of Li surface



Waveform of surface temperature T_{Li}

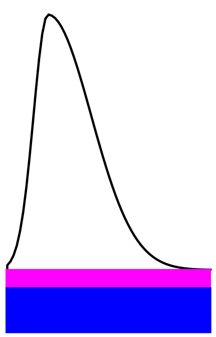
Evaporation $\log_{10}(dN/dt) - 20$

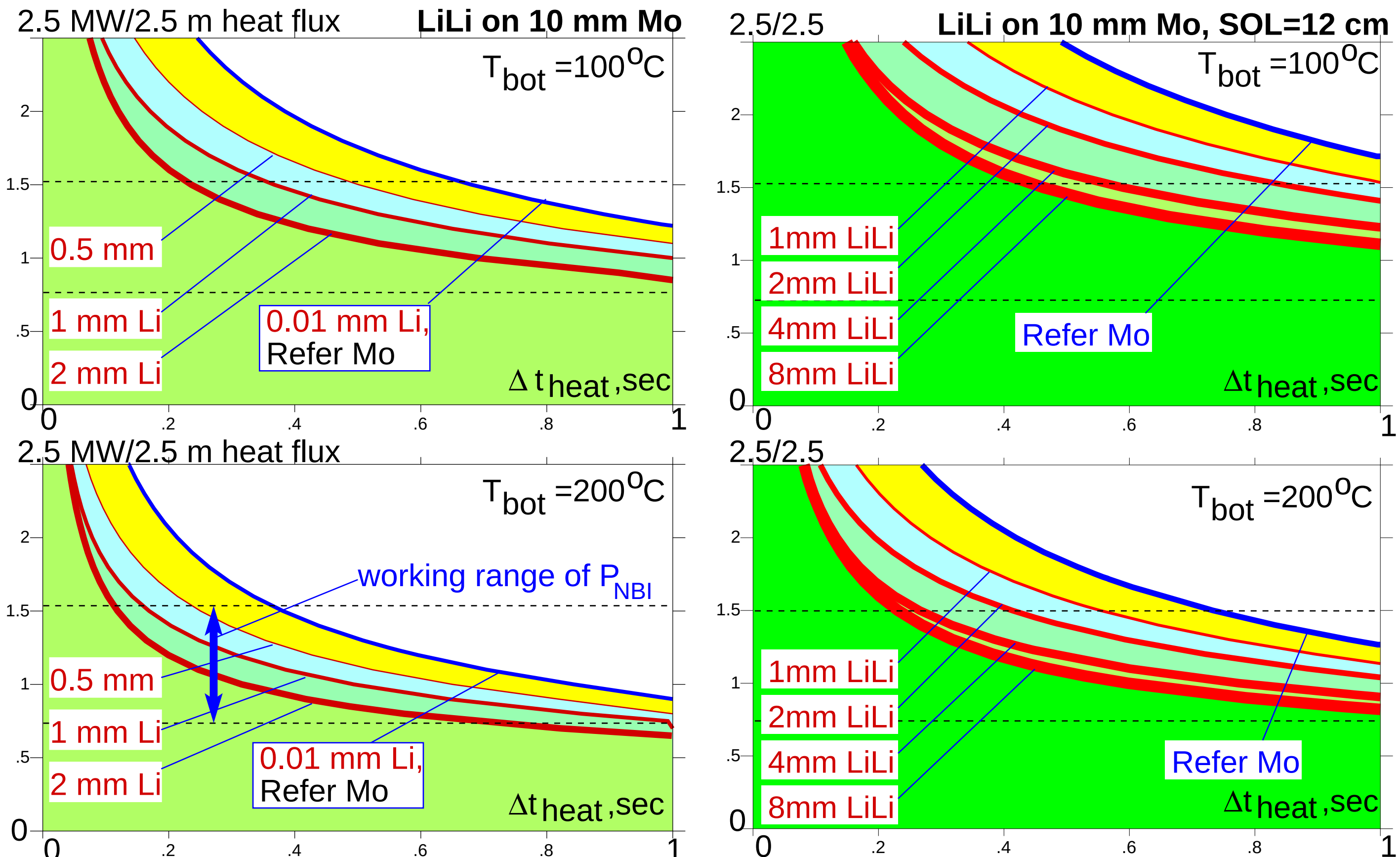
Overall retention

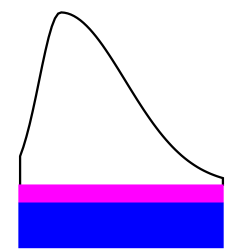
Evaporation limit was set to $10^{21}\ 1/sec$

The role of reduction in retention after 350^o is unknown

Operational space is limited by evaporation limit





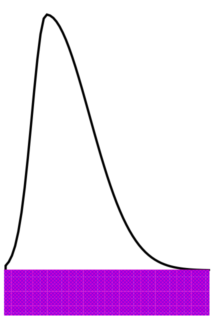


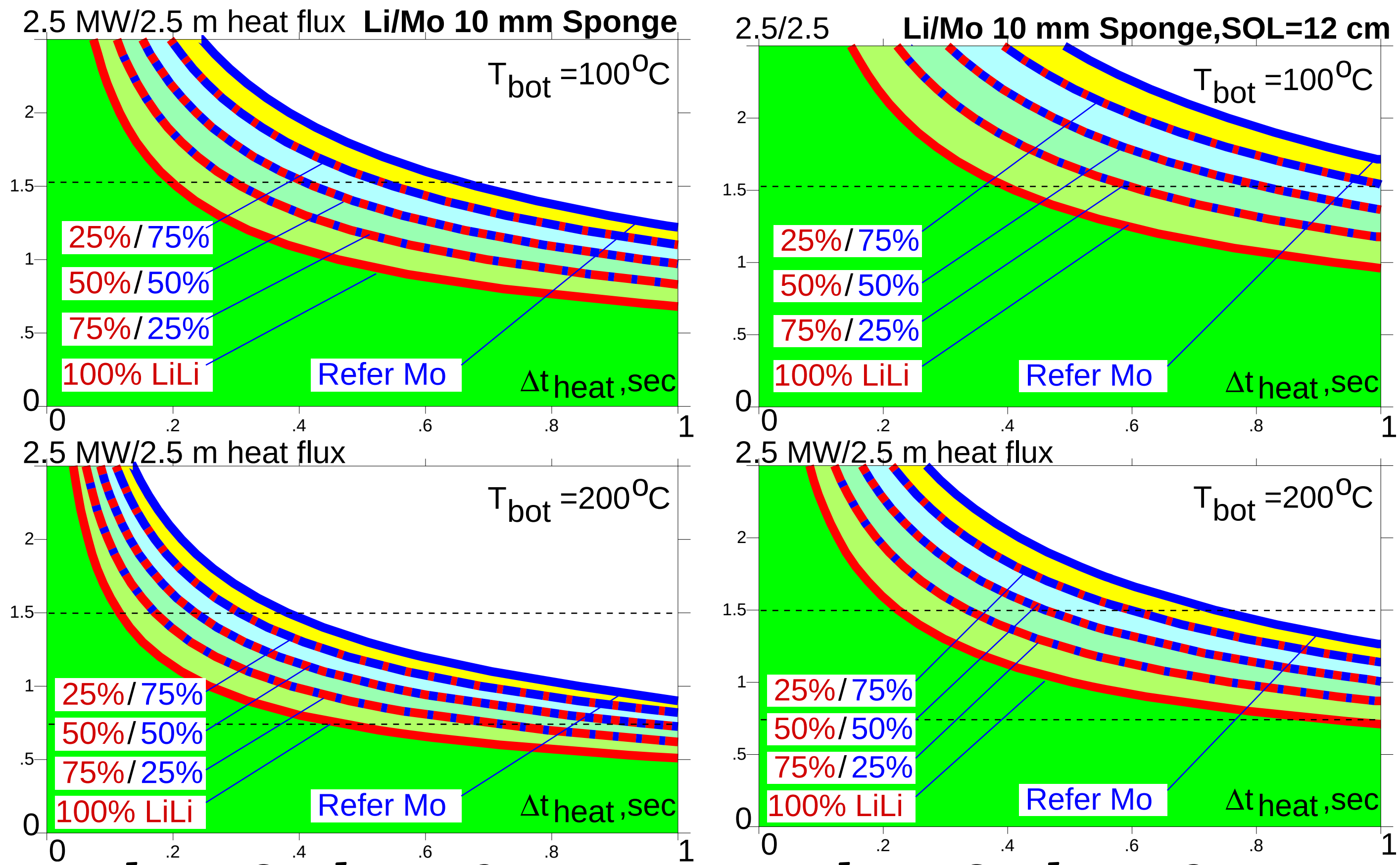
$d_i = 2, d_e = 6$ cm $\quad\quad$ $d_i = 3, d_e = 9$ cm

Operational space is situated between the axis and the curve for each case.

100^o of initial ΔT is equivalent to 3 cm of d_{SOL}

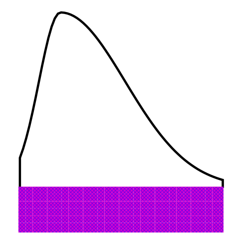
Regarding the thermal regime, CPS has advantage over LiLi





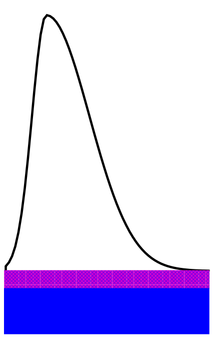
$$d_i = 2, d_e = 6 \text{ cm}$$

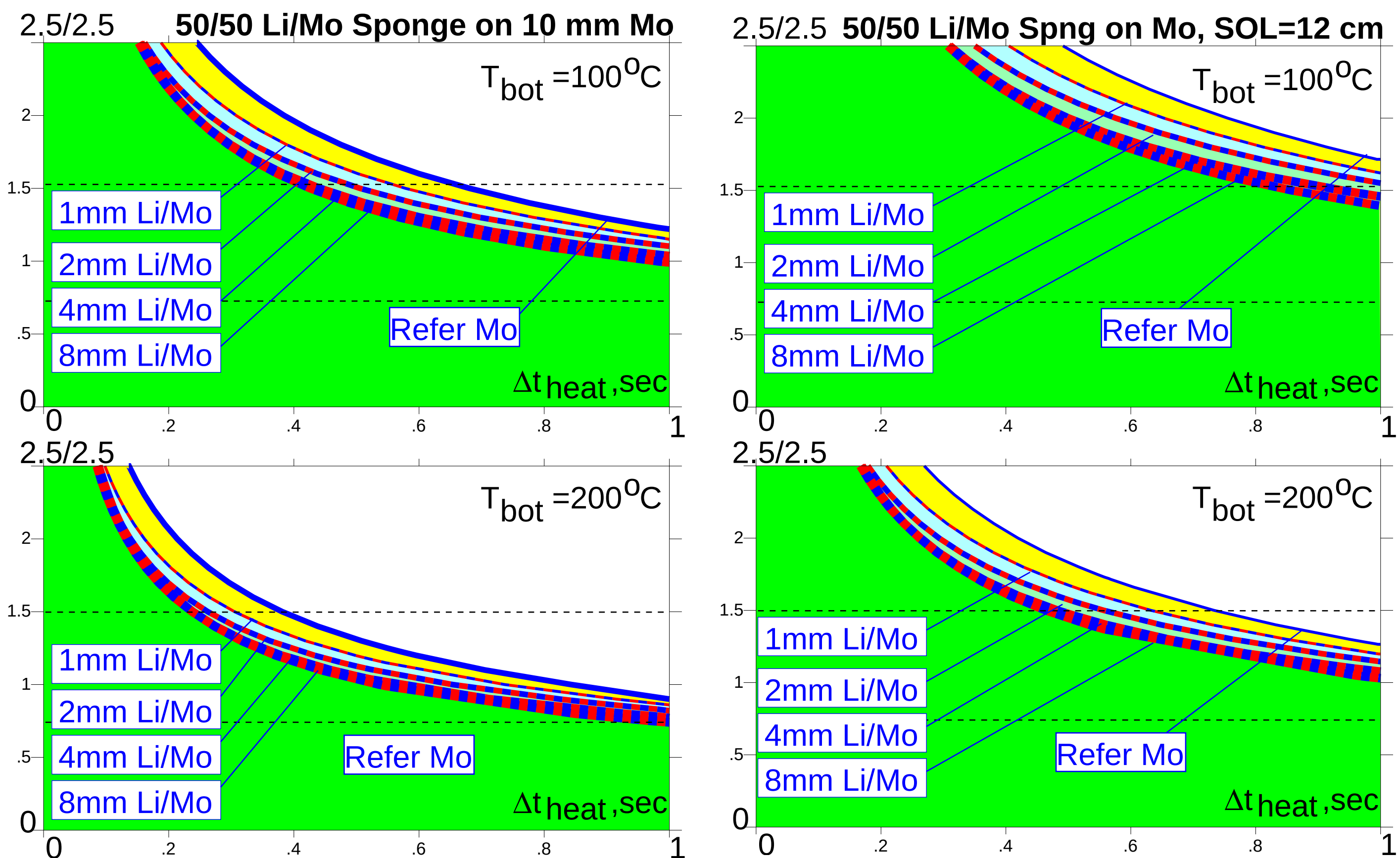
$$d_i = 3, d_e = 9 \text{ cm}$$

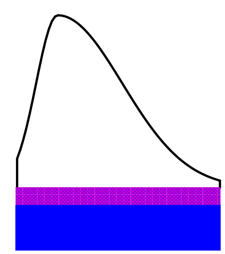


$\chi_{Li/Mo} = C_{Li}\chi_{Li} + (1 - C_{Li})\chi_{Mo}$ **requires technology test**

50/50 Li/Mo CPS may have the best characteristics



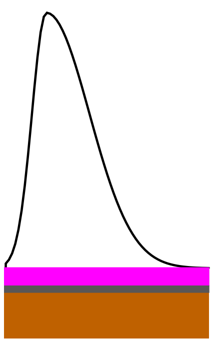


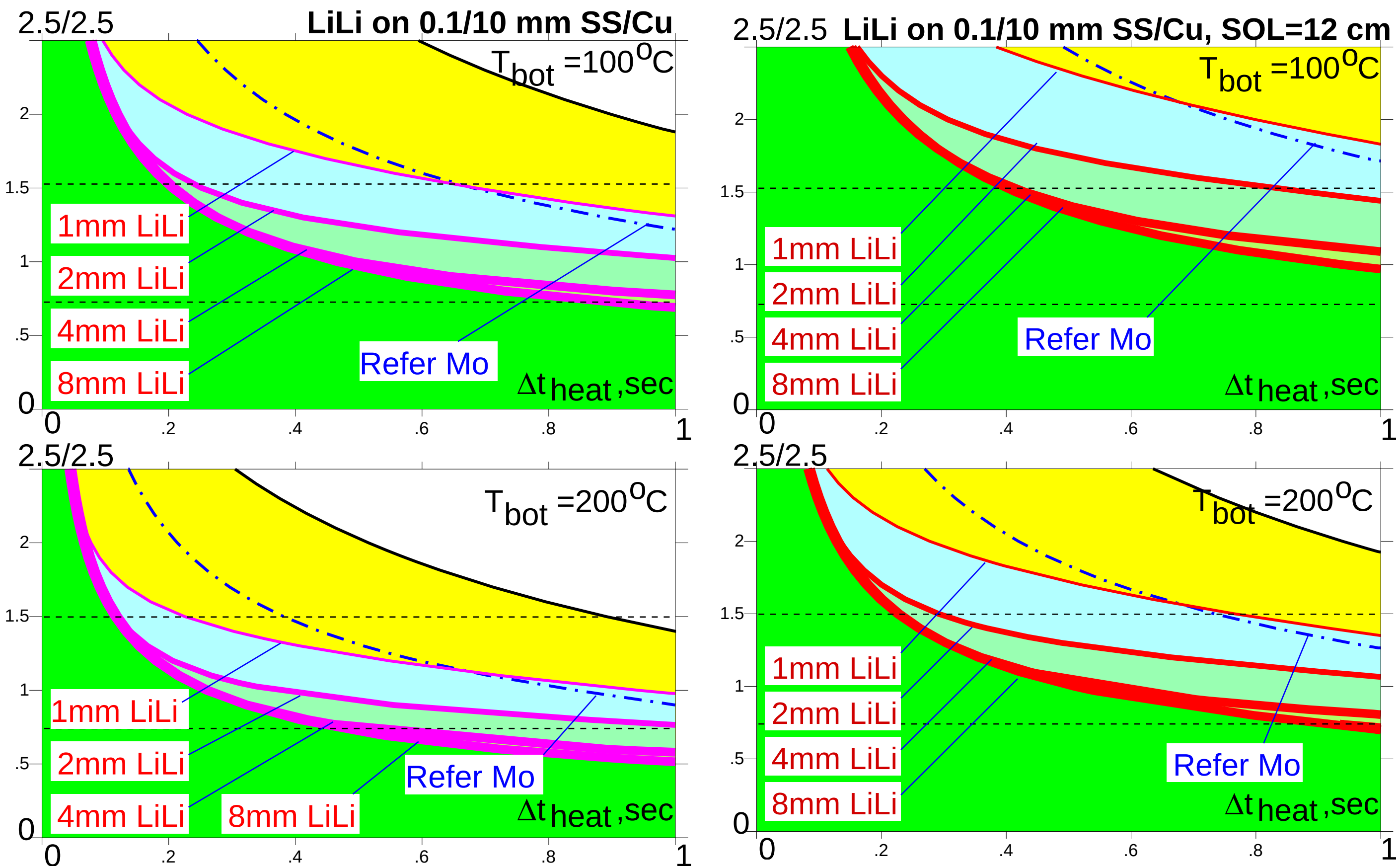


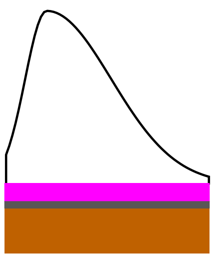
$d_i = 2, d_e = 6$ cm $d_i = 3, d_e = 9$ cm

Potential clogging by LiOH, LiD, etc requires technology studies

The plate 0.1-1 mm of Li on 0.1/10 SS/Cu provides the operational space for LiWall regime in NSTX



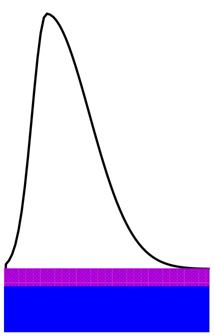


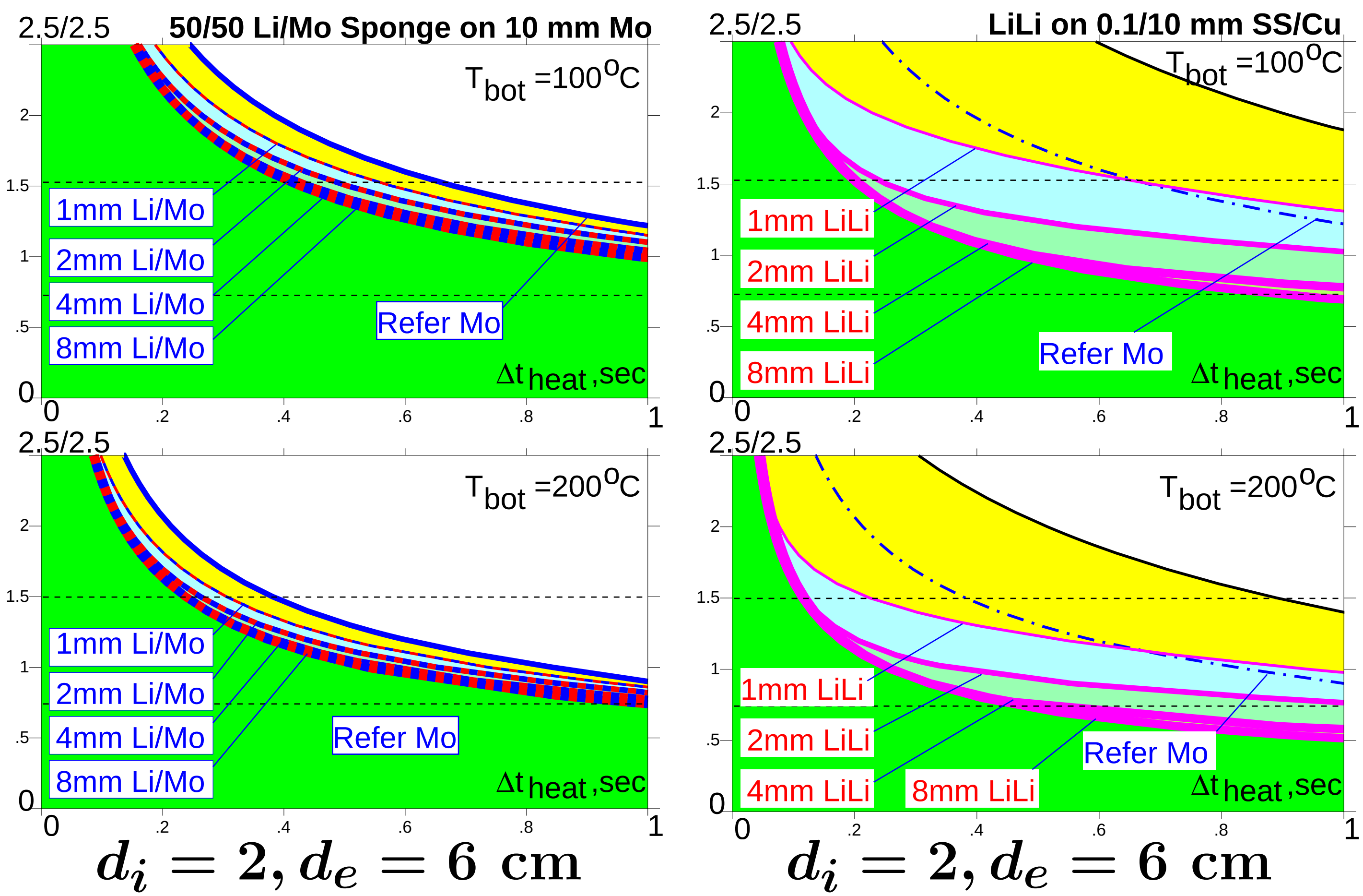


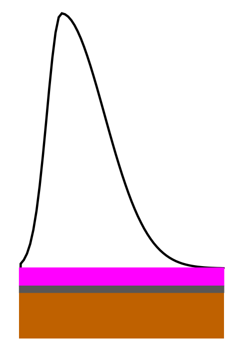
$$d_i = 2, d_e = 6 \text{ cm} \qquad d_i = 3, d_e = 9 \text{ cm}$$

The heat flux profile in the SOL is a crucial unknown

1/0.1/10 mm Li/SS/Cu plate outperforms 10 mm Li/Mo CPS

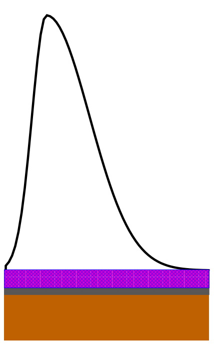


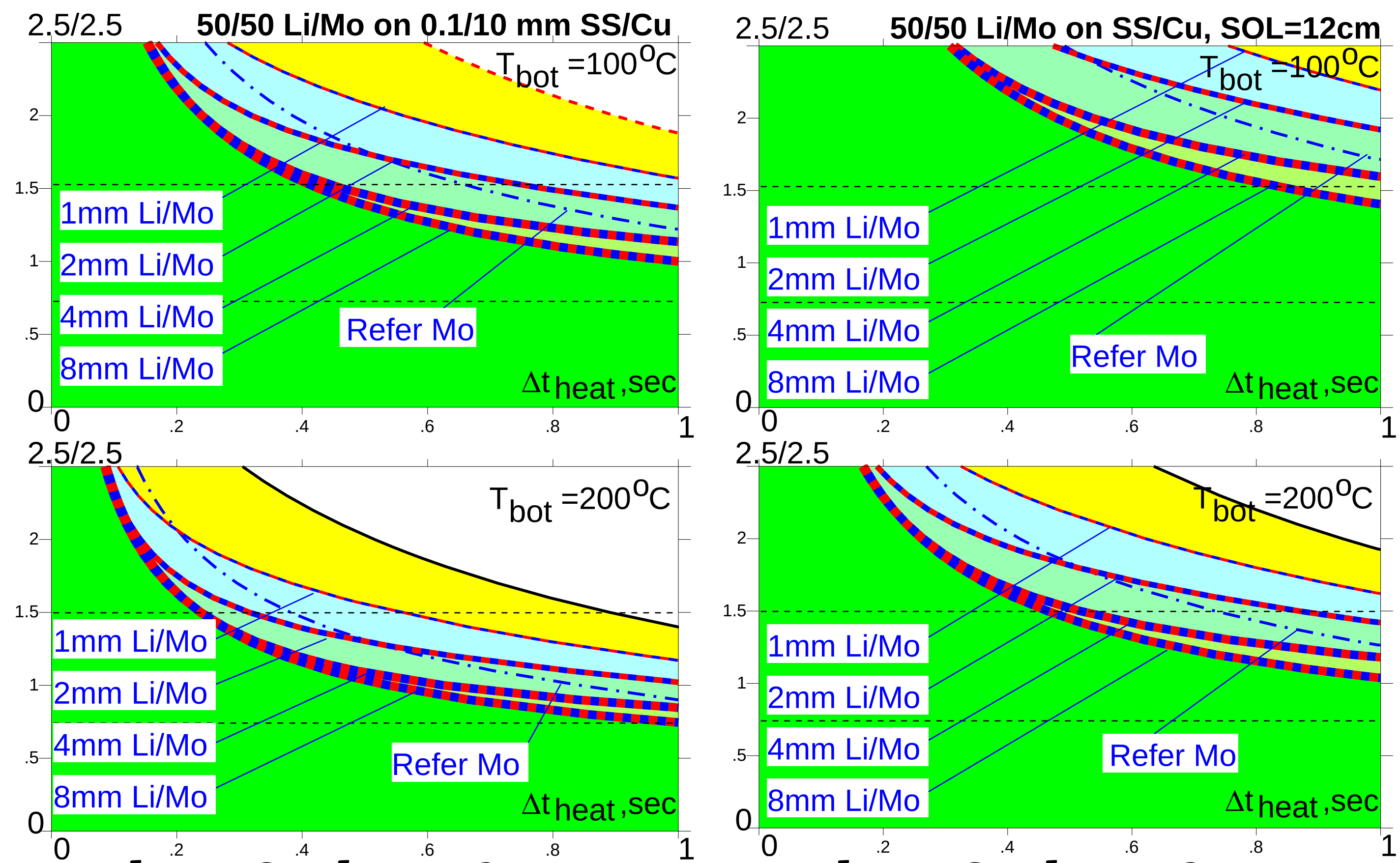




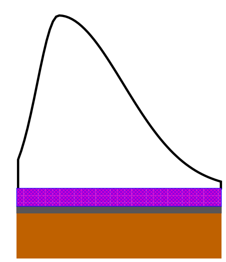
The plate also has fewer technology unknowns

1 mm Li/Mo CPS on 0.1/10 mm SS/Cu plate is the best





$d_i = 2, d_e = 6$ cm $d_i = 3, d_e = 9$ cm



1 mm Li/Mo CPS on 0.1/10 mm SS/Cu is similar to T-11M,FTU

LLTP is a prototype of the Pumping Lithium Divertor, adjusted for NSTX and consistent with the strategy for ST

Neither evaporator, nor Mo sponge based “LLD”, promoted by PPPL/NSTX (May-2007 version) management, are consistent with PLD requirements

Installation of Li/SS/Cu plate will be the turning point for PPPL toward relevance to the energy R&D, lost at present

Proposed as an interim solution for NSTX, LLTP has a chance to be a longer term solution if replenishment by the Li pellets will be successful.

The role of theory is to reveal the obstacles to the progress

LLTP was suggested a year ago to PPPL/NSTX management. The answer was "NO". It is "NO" also this year.

There is no scientific, technical of budgetary issues with LLPD. In all aspects it is superior to both "evaporator" and to so-called "LLD".

In its countless "NO"s during the last 10 years, the current PPPL administration is self-consistent in blocking fusion development in PPPL.

Fusion energy R&D needs Pumping LD. It is a new obsession, now

with fusion metallurgy (NHTX), which intend to drag

PPPL into fusion irrelevant research