NSTX
SAND2011-2956C

Thermal Modeling of the Surface Temperatures on the Liquid Lithium Divertor in NSTX

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Outline

Objectives for Thermal Model

- Predictive model for surface temperature versus heat load and shot time
- Extract information on porous layer of flame-sprayed Mo with infiltrated Li
  1. thermal conductance and
  2. emissivity of surface

Thermal Model and Results

- Initial work on LLD (heaters and gas cooling)
- Attempt to estimate the emissivity of the Li
- Newer work (no pre-heating)

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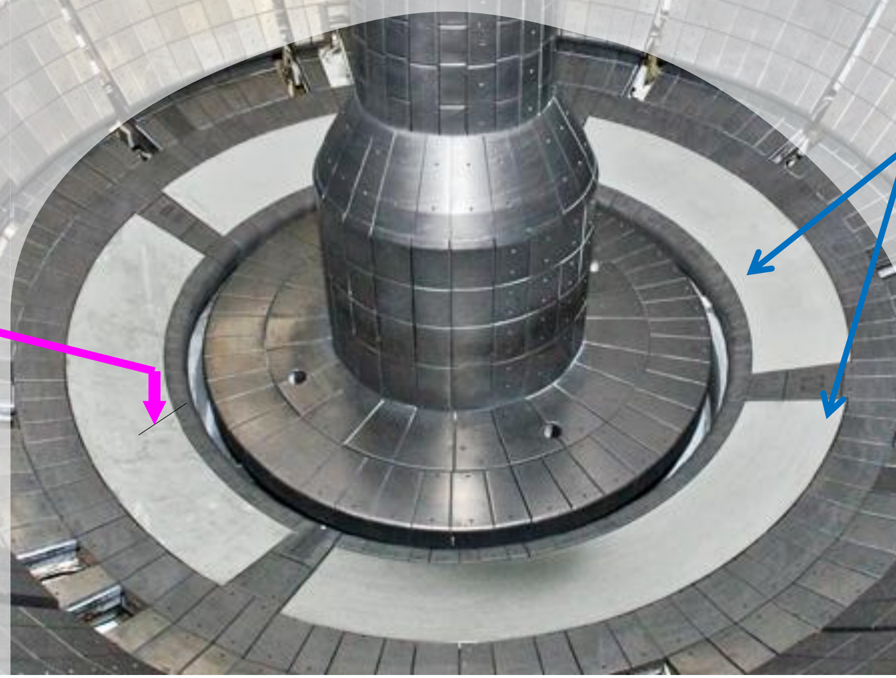
Objectives for Thermal Model

- **Predictive model for $T_{surface}$ vs heat load and shot time**
  (subsequent viewgraphs)
- **Information on porous layer of flame-sprayed Mo with Li**
  1. **thermal conductance and**
  2. **emissivity of surface**

Relate modeling results to IR and TC data during operation

LLD surface cross section: plasma sprayed porous Mo



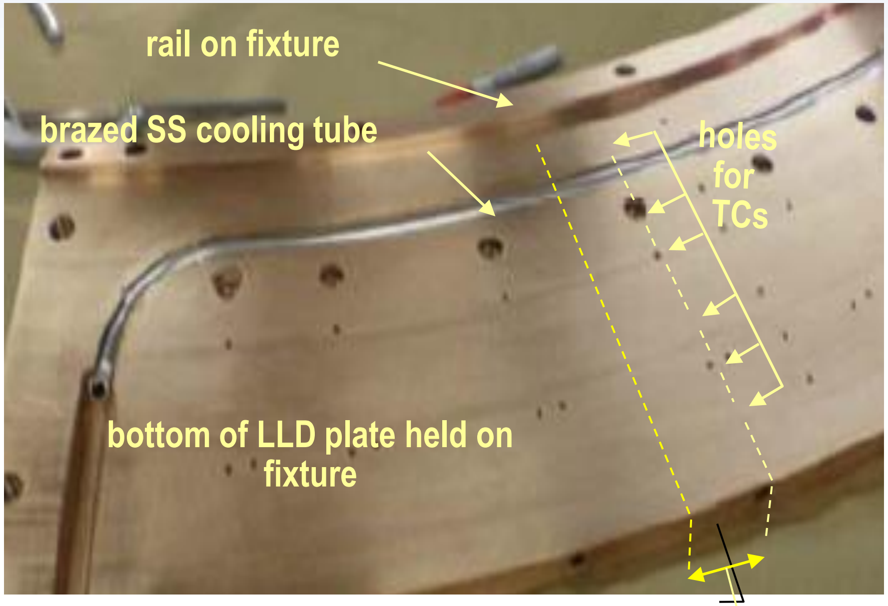
LLD plates (4) after installation

Sandia built these plates as part of an NSTX-lab collaboration funded by a grant by DOE/FES.

ABAQUS thermal model for LLD “half cell”

We use ABAQUS, a general purpose finite element code, for our 3-D model. We analyze a “half cell” of the LLD, and calculate temperatures over time.

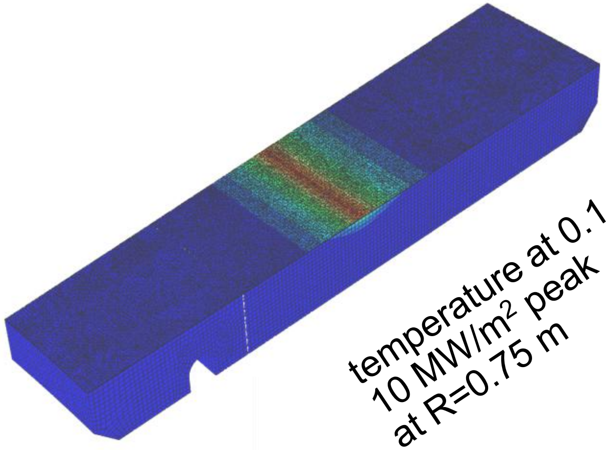
The shape comes directly from the CAD model for fabricating the plates



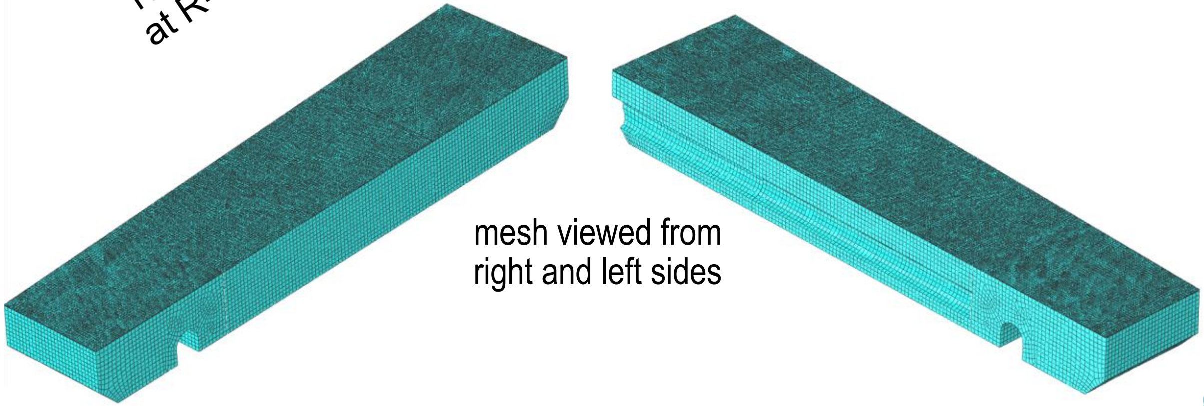
solid angle of the half unit cell

A “unit cell” contains one (of 8) electrical heaters in an LLD plate.

The half cell is divided on a mirror symmetry plane through the heater.

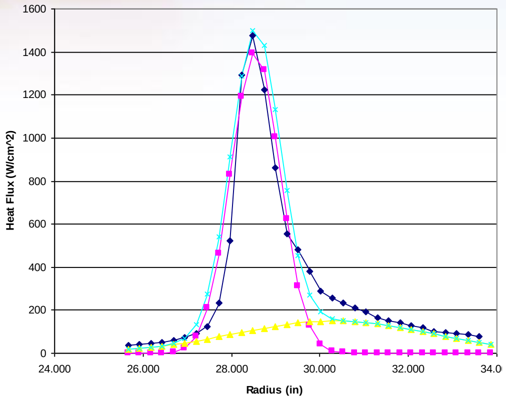


temperature at 0.1 s
10 MW/m^2 peak
at R=0.75 m



mesh viewed from right and left sides

EARLY THERMAL MODEL & RESULTS

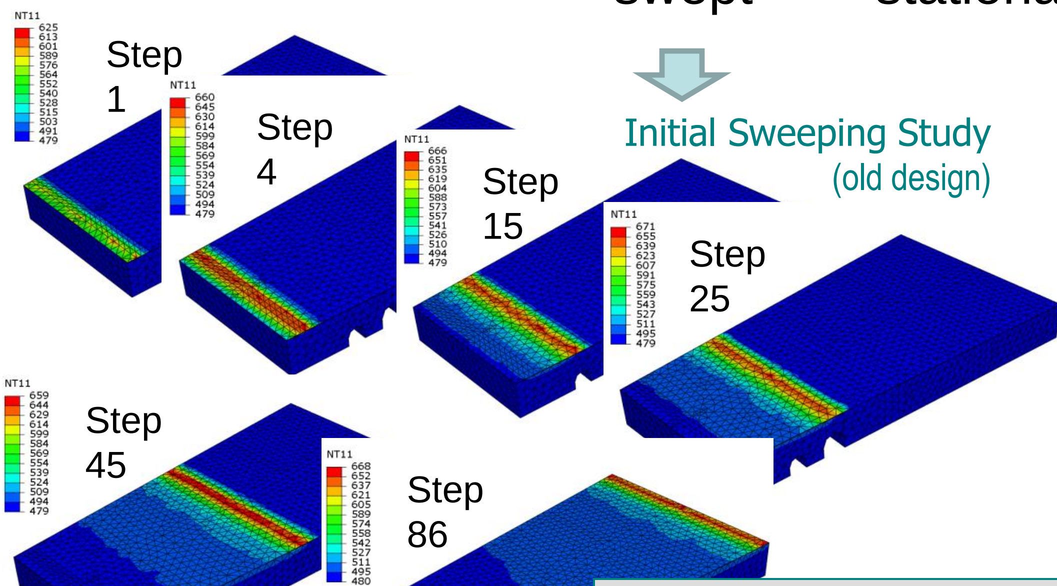


Strike point profile (outer div.).

"Wings" are important in sweeping.

Strike point on LLD

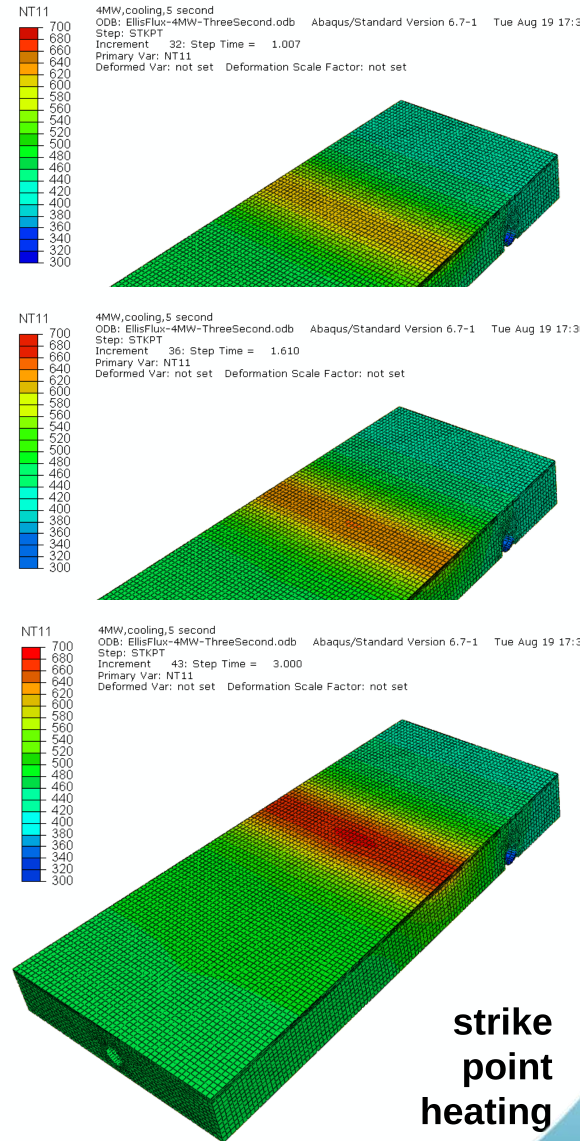
swept stationary



Initial Sweeping Study (old design)

SOL profile is important because "Tail" pre-heats Li ahead of strike point.

- 200W heater, 25 min.
- T-start 475 K.
- 500 mm/s "sweep"
- 5 ms heat, 2.5mm zones
- 43 s across entire area.



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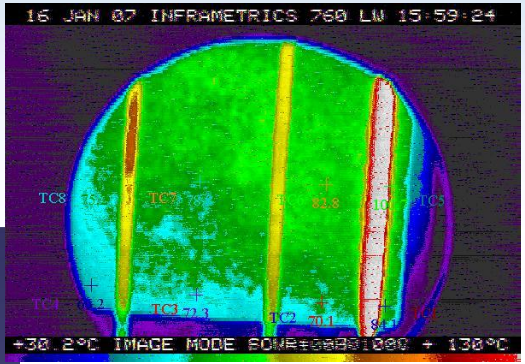
EARLY THERMAL MODEL & RESULTS

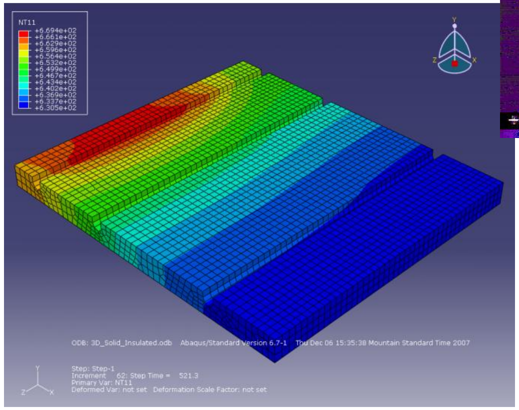
- Initial tests on Mo mesh
- heater failure

<u>*Cases not presented here*</u>

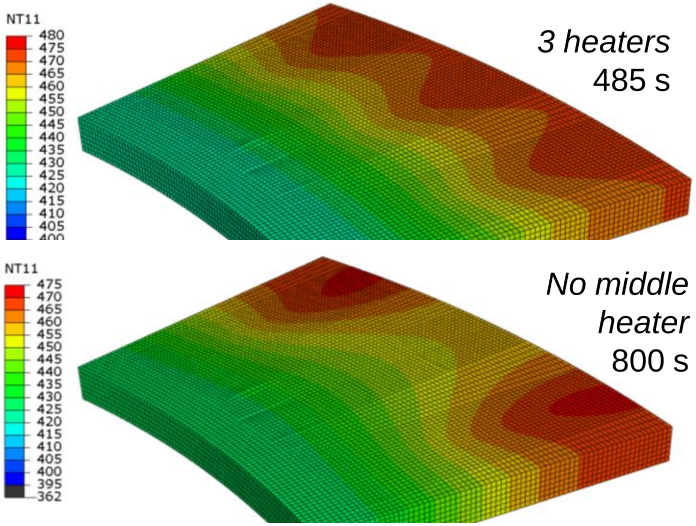
- inboard of LLD
  - *pumps the outer SOL**
- outboard of LLD
  - *pumps private flux region**

* *longer shot times with strike point off the LLD*

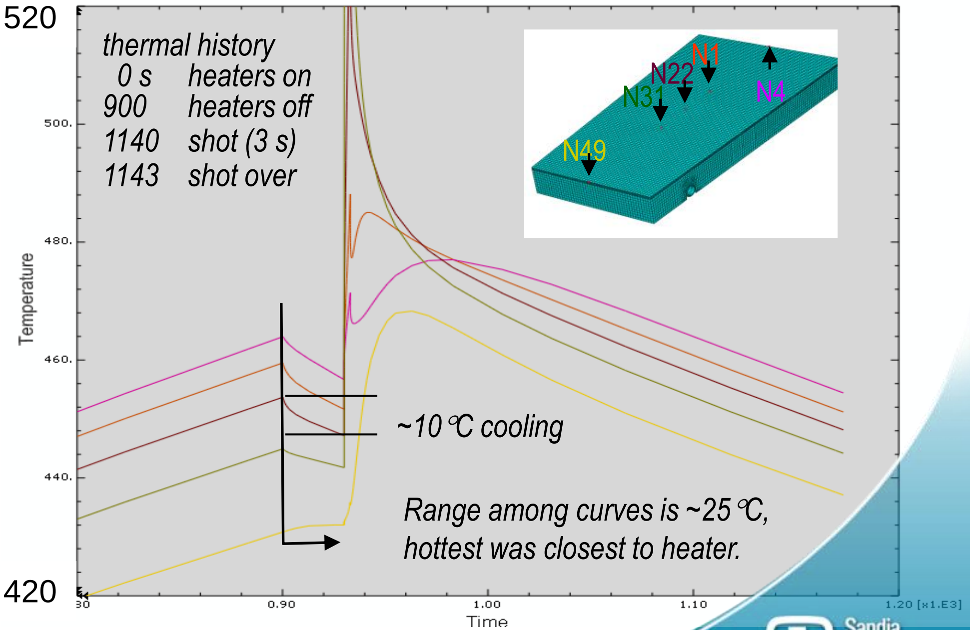




Sandia initially studied a CVD Mo-coated pyrolyzed C mesh as a Li reservoir for the LLD. The thermal conductivity of the mesh was unknown.



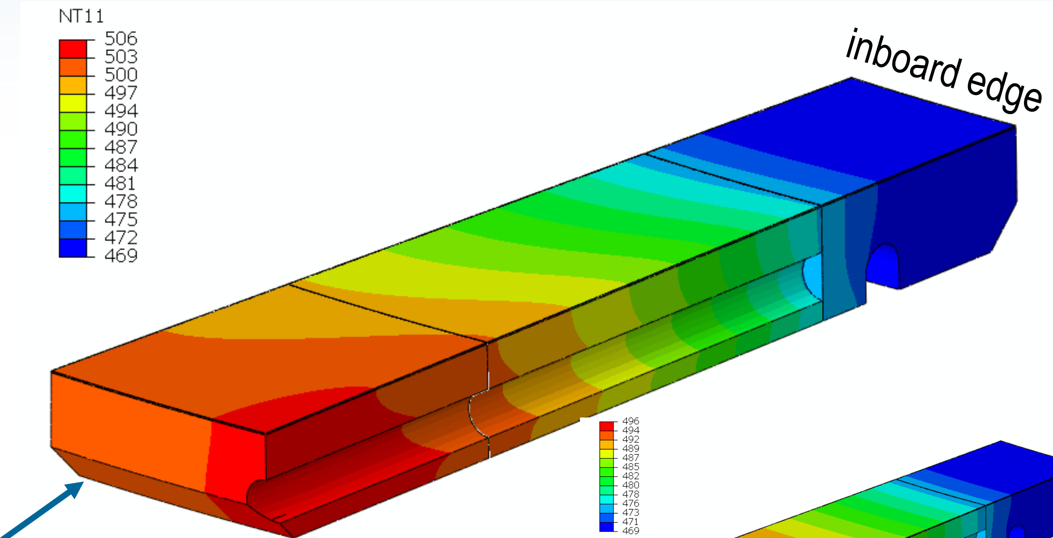
Heat to ~480K, electrical heaters operated at 400 W each

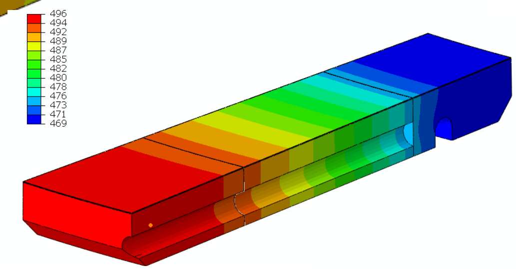


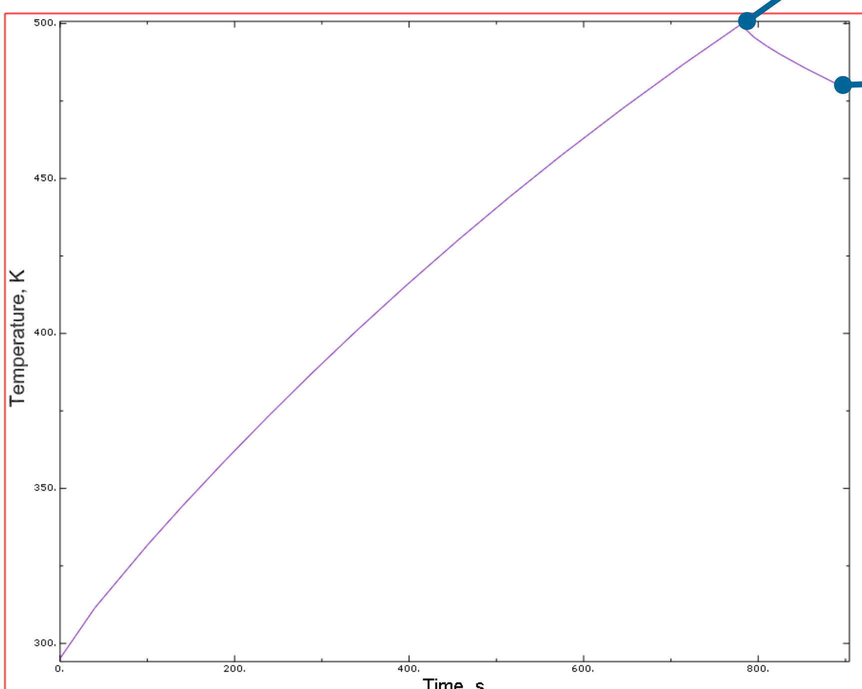
Example of ABAQUS plots of LLD "half cell"

Possible conditions in model:

- heating from the plasma
- heating
  - electrical heaters or hot gas
- continuous cooling
  - nitrogen flow in the tube
  (before, during and after shots)







<u>Case: Heating of plate, N2 cooling</u>

- Mo properties for Li/Moly layer
- Initial temperature 22°C
- 400W applied to heater surface
- 0.029W/cm^{2}K film coefficient and 22°C sink temperature for cooling tube.

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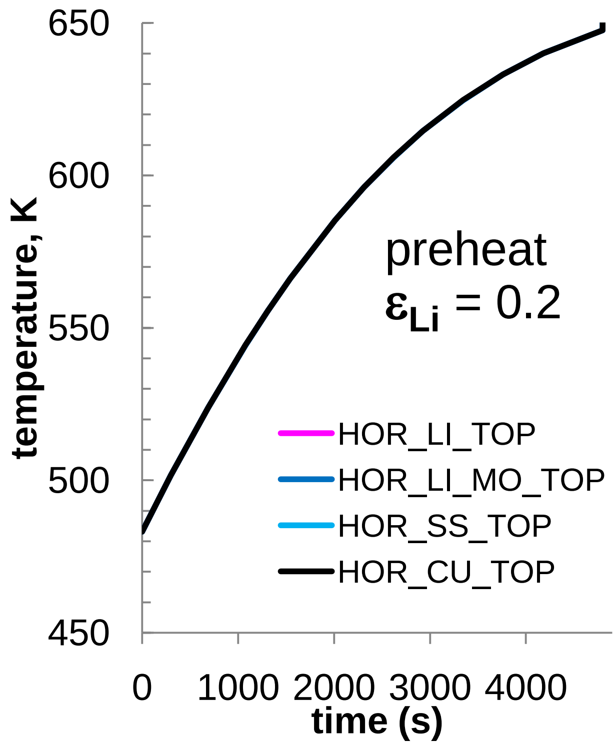
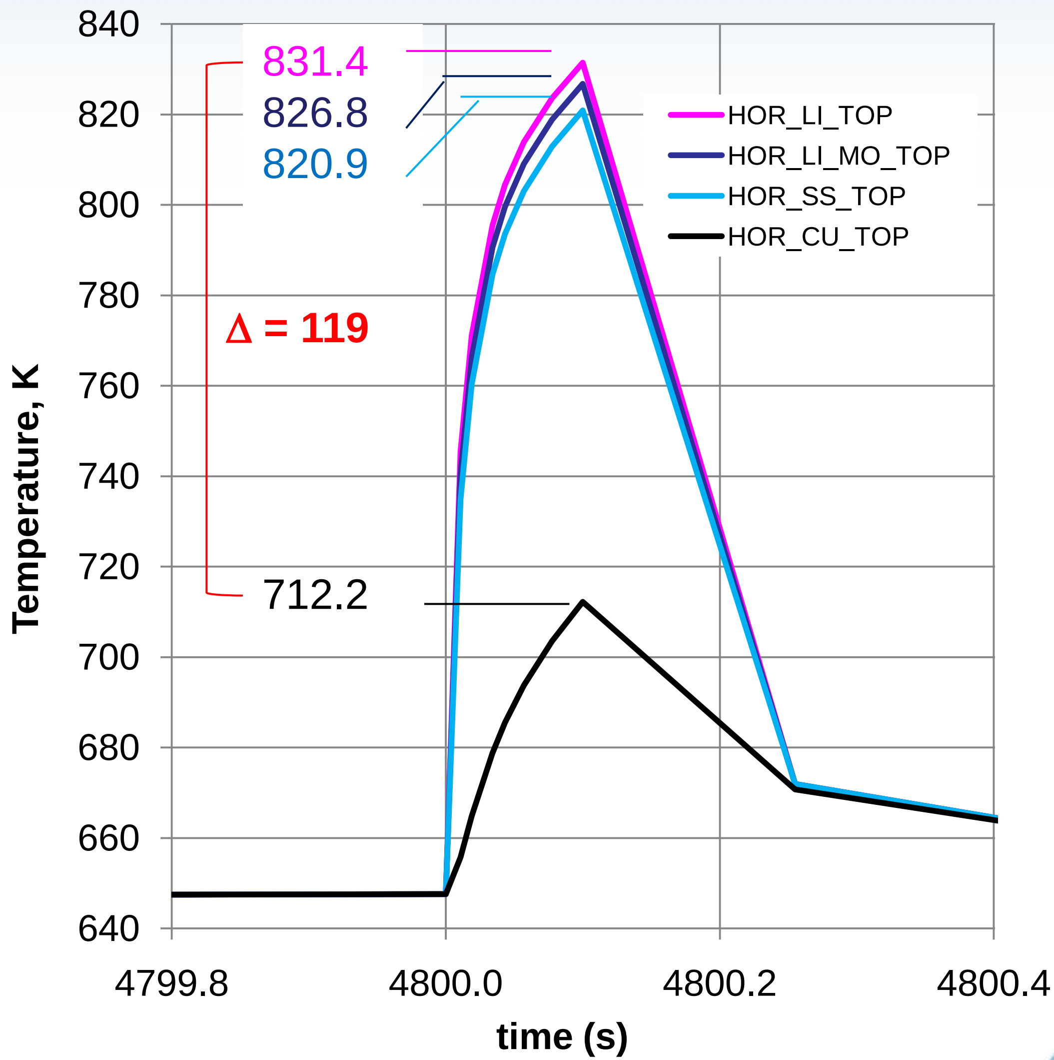
Sample of Results for R75cm 20MW/m²

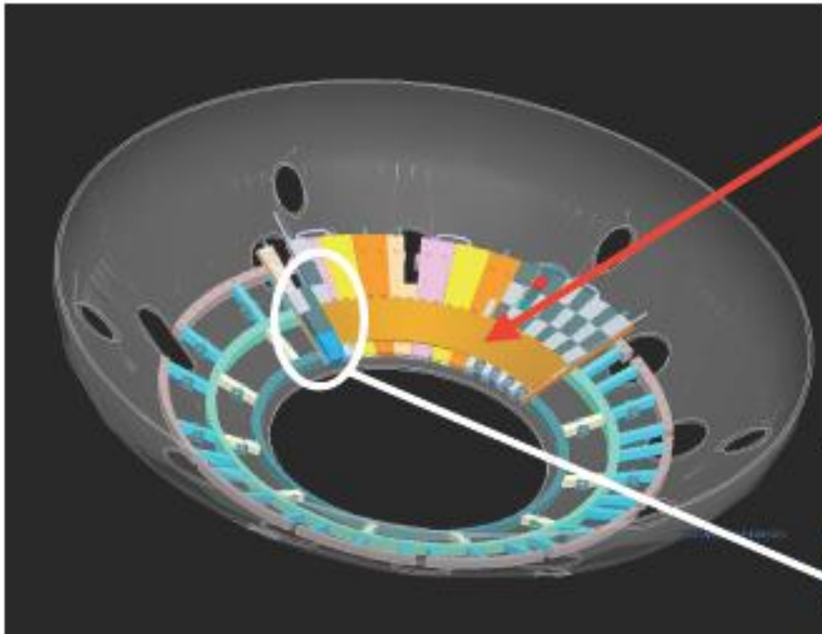
- strike point at 75 cm (near middle of LLD)
- preheating with electrical heaters
- gas cooling
- plasma shot of 0.1s (4800 to 4800.1 s)



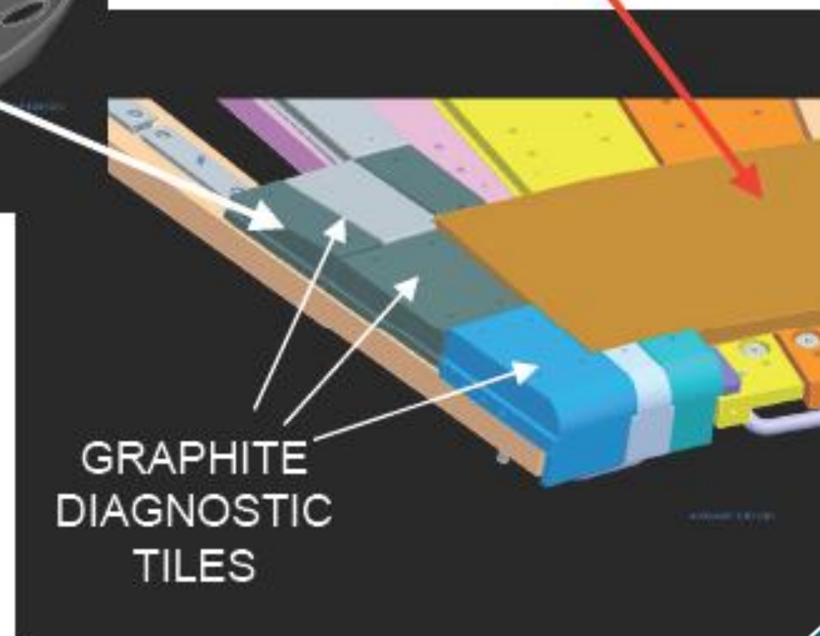


In 0.1s at 10MW/m² copper heats slightly, but Li surface is almost 120 higher.

Can the cooling cycle provide information?



- 4 Toroidal 90° segments separated by graphite Diagnostic Tiles
- Each copper substrate segment is clad with a thin stainless steel barrier with a front face of porus flame sprayed Mo



Behind the LLD are rails that support the passive pates and the vessel wall.

The LLD radiates from the back and top and conducts heat through its support stem and the walls of the gas cooling tubes.

Radiation Exchange between two infinite plates where $T_1 > T_2$

Radiation, two infinite plates, solve as follows:

$q_1/A_1 = -q_2/A_2$ where q's are net radiant energy leaving, also received irradiation G_1 equals the radiosity J_2 of the other and vice versa.

Also, for a surface $J = E + \rho G$ and $\rho = 1-\alpha$ for an opaque surface, and for a gray diffuse surface $\alpha = \varepsilon$, and on gets for each surface:

$J_1 = \varepsilon_1 E_{b1} + (1-\varepsilon_1)G_1$ and $J_2 = \varepsilon_2 E_{b2} + (1-\varepsilon_2)G_2$; since $G_1 = J_2$, these may be solved for J_1 and G_1

$J_1 = [\varepsilon_1 E_{b1} + (1-\varepsilon_1)\varepsilon_2 E_{b2}]/[1-(1-\varepsilon_1)(1-\varepsilon_2)]$

$G_1 = [\varepsilon_2 E_{b2} + (1-\varepsilon_2)\varepsilon_1 E_{b1}]/[1-(1-\varepsilon_1)(1-\varepsilon_2)]$; then from the 1st equation, $q_1/A_1 = -q_2/A_2$, we get

$q/A = [E_{b1} - E_{b2}]/[1/\varepsilon_1 + 1/\varepsilon_2 -1] = \sigma (T_1^4 - T_2^4)/[1/\varepsilon_1 + 1/\varepsilon_2 -1]$

So, if we apply this separately to the front and back surfaces, but also assume that the tiles and the mounting structure behind the LLD are the same, then we have two the loss channels for both faces

$\text{r-loss}_{top} = A_{top}\, \sigma (T_{LLD}^4 - T_V^4)/[1/\varepsilon_{Li} + 1/\varepsilon_{Tiles} -1]$

$\text{r-loss}_{bott} = A_{bott}\, \sigma (T_{LLD}^4 - T_V^4)/[1/\varepsilon_{Cu} + 1/\varepsilon_{SS} -1]$

$\text{r-total} = \sigma (T_{LLD}^4 - T_V^4) \{A_{top}/[1/\varepsilon_{Li} + 1/\varepsilon_{Tiles} -1] + A_{bott}/[1/\varepsilon_{Cu} + 1/\varepsilon_{SS} -1]\}$

RE Nygren 26apr2010 note from Heat Transfer, Alan Chapman 4th Ed.

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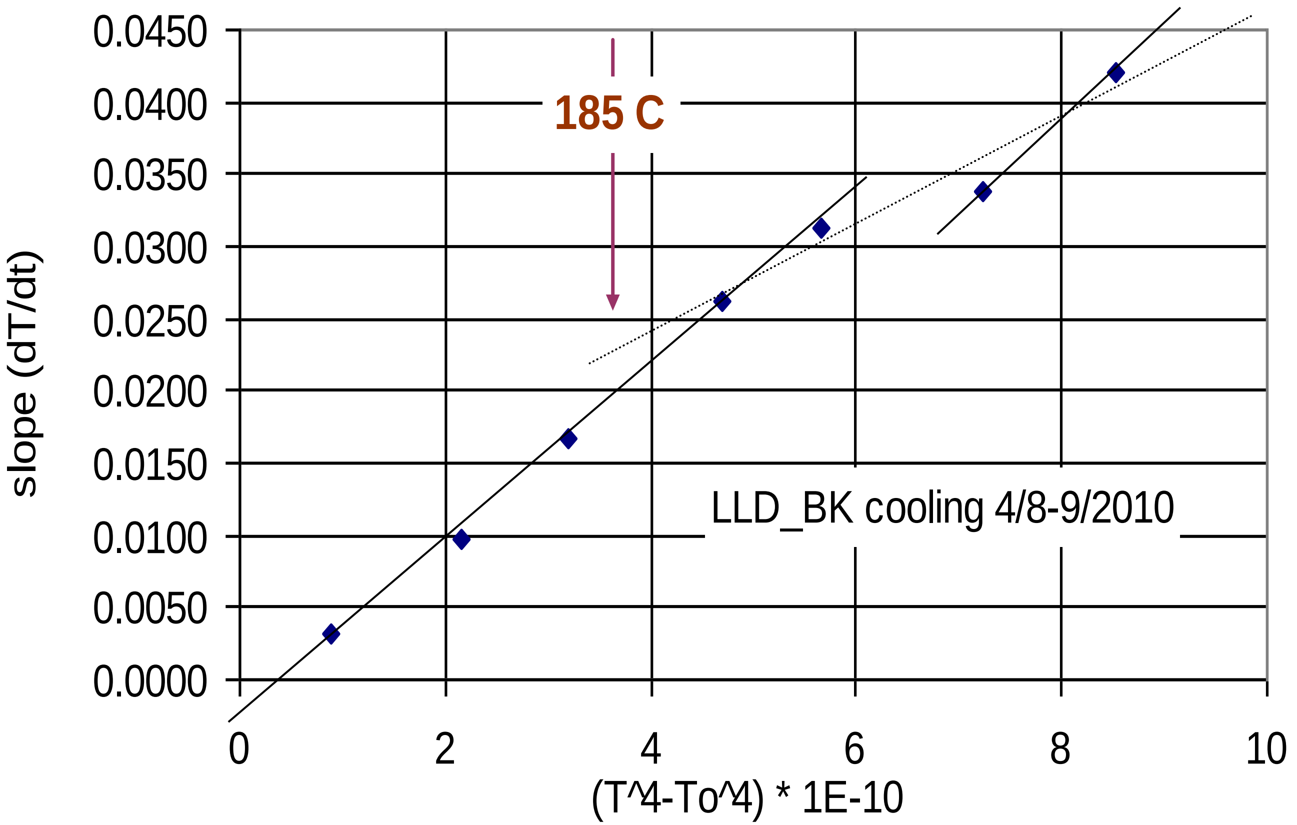
TCs during long cooling of LLD section BK

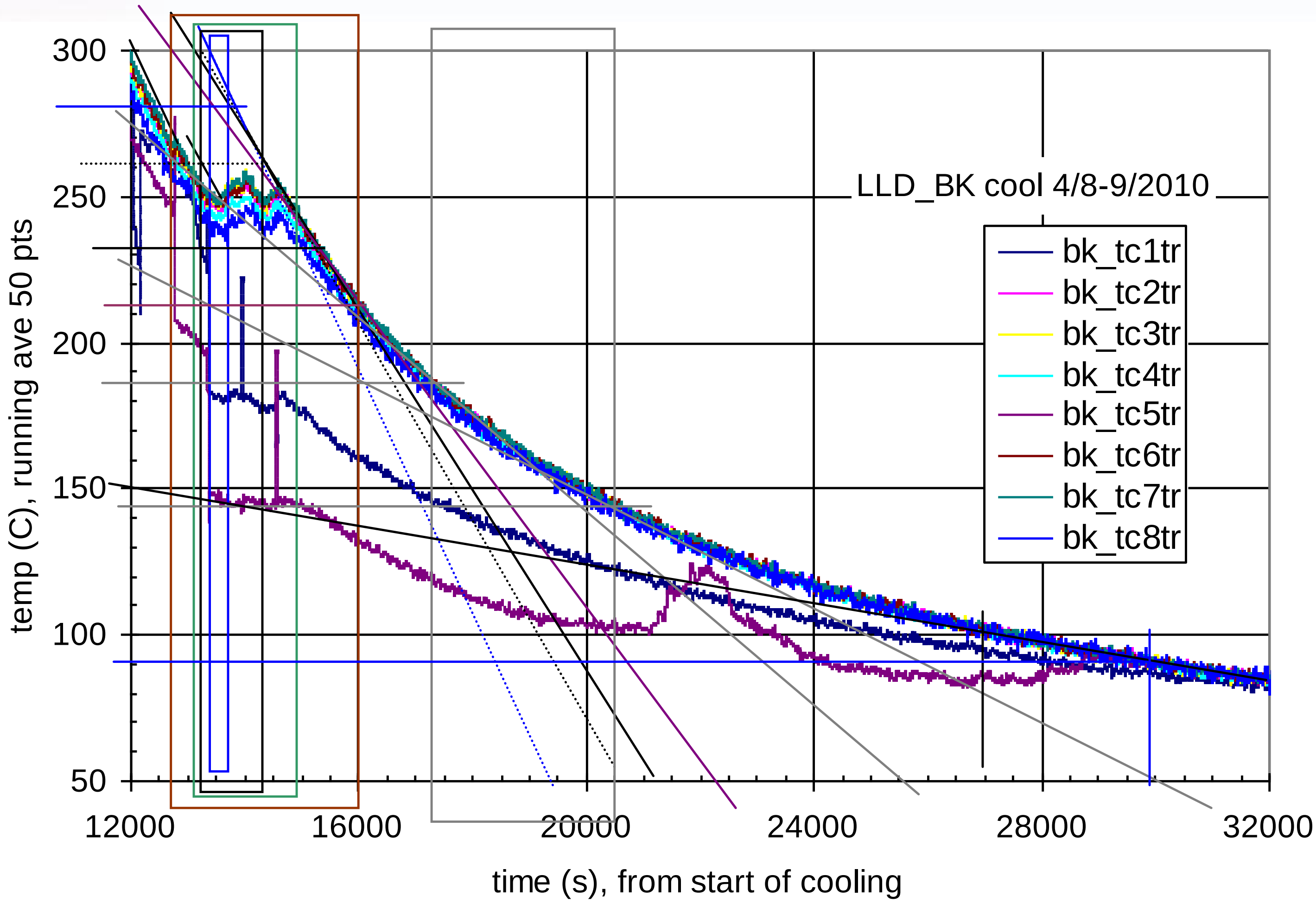
Idea: If radiation dominates cooling (overnight) then we can estimate the emissivity of the Li surface from the cooling overnight .
Plot has initial treatment of slopes.



Initial treatment was encouraging with apparent strong dependence on T^4.

TCs during long cooling of LLD section BK

(1PM on April 8 until after midnight)



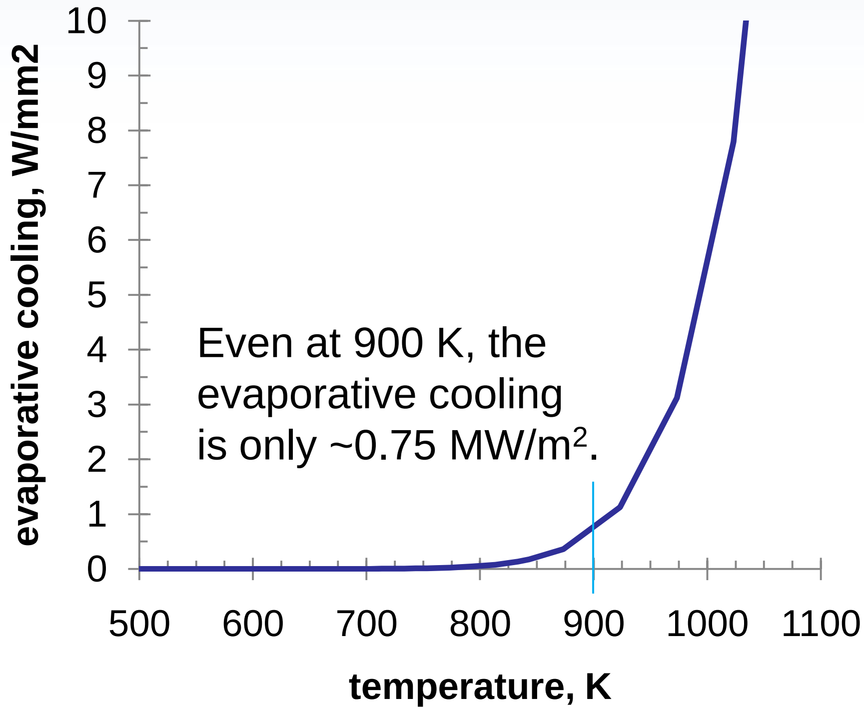
TC signals are very noisy. Running average of 25 points is used here.

But analysis to get a good fit showed little sensitivity for value of emissivity due to competing losses for conduction and radiation from back of LLD.

How much does evaporation of Li cool the LLD?

Evaporation of Li is a quantity of interest. We include the cooling effect of evaporation in the model.

We calculate the integrated amount of lithium evaporated separately in post-processing based on the evolution over time of the temperature across the face of the LLD.



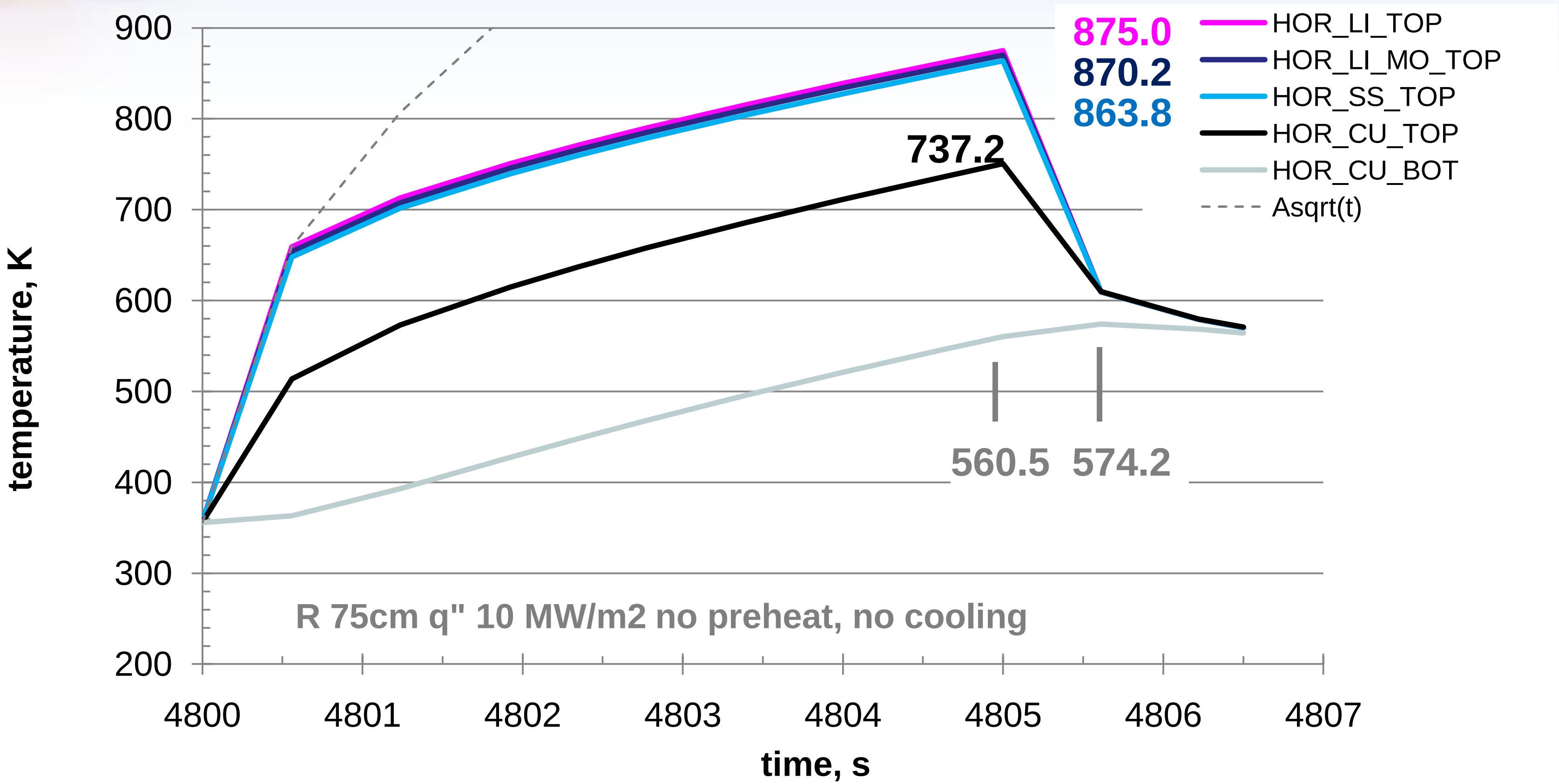
Our expression for evaporative cooling

Cooling (W/mm^2) = 595.7 * [10^(8-8143/T] /SQRT(6.941*T)

Based on the expression for vapor pressure of 3.5E22 * [10^(8-8143/T]
from **Jensson et al**. (old HEDL Report) and the equation below.

$$\text{Evaporation } \Gamma_{evap}\,(\text{atoms/cm}^2\text{-s}) = 3.5\text{x}10^{22}\,\frac{P(Torr)}{\sqrt{mass(a.u.)T}}$$

Sample of Results for R75cm 10MW/m^2



<u>0.5s</u>: heat has penetrated to back of Cu plate (bottom of LLD) and Li surface is over 140° higher than the underlying Cu (top surface).

<u>5.0s</u>: Li has risen from ~650K (0.5s) to 875K. As heat load stops, temperatures near the top surface drop as LLD goes toward its average temperature.

<u>Li temperature</u> does not follow SQRT(time) but is like the linear pattern for heating of a solid plate after the heat reaches the back.

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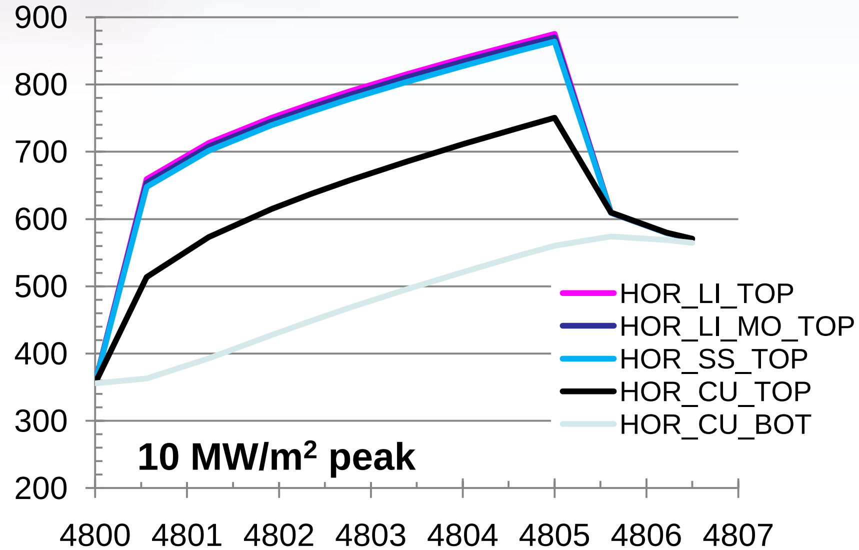
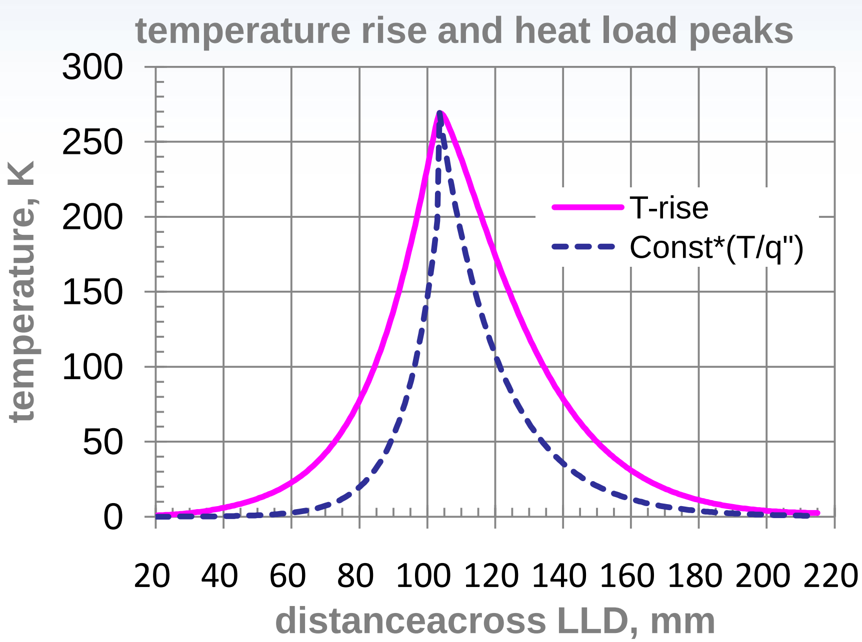
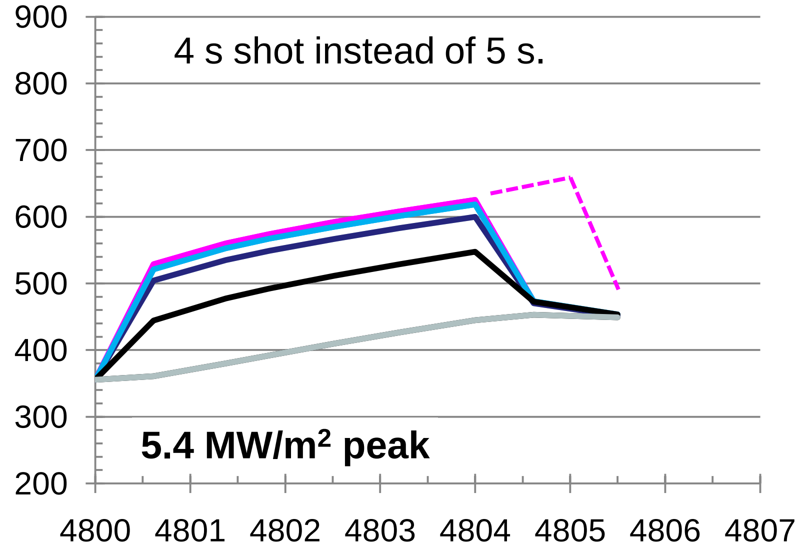
Comparison of Results (R 75cm)







<u>The rise in temperature of the Li is in proportion to the heat load</u>.

After 4 s at10 MW/m^2, the rise is 465° and at 5.4 MW/m^2 it is 262°.

In each case the value of rise in temperature divided by heat load is 46.6 degrees per MW/m^2.

Evaporative cooling is not a big factor here.

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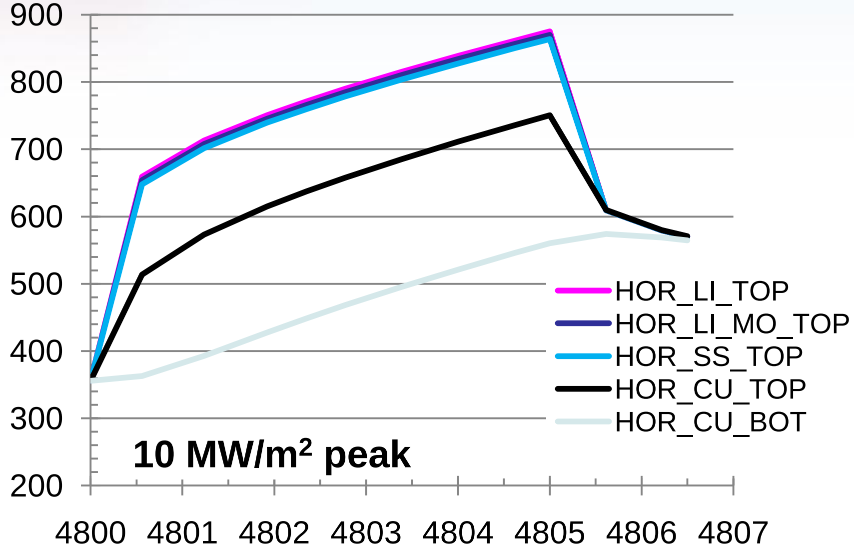
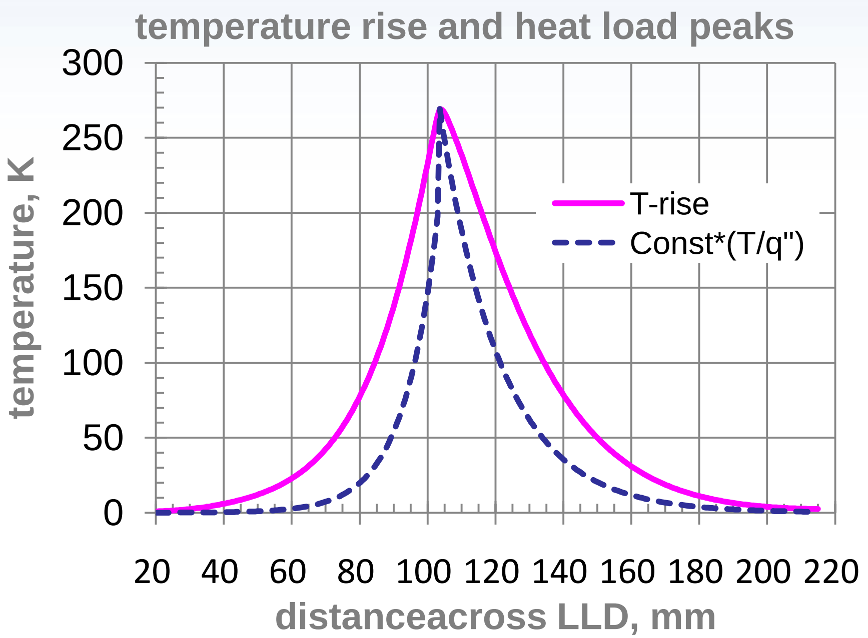
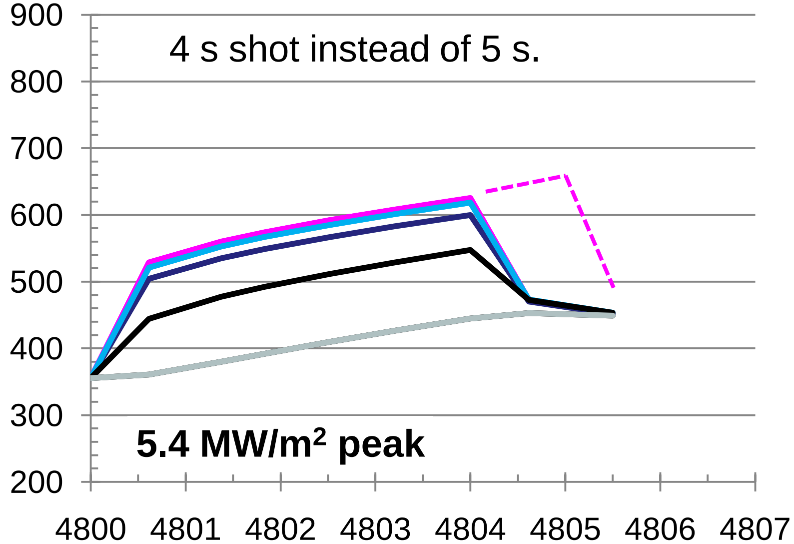
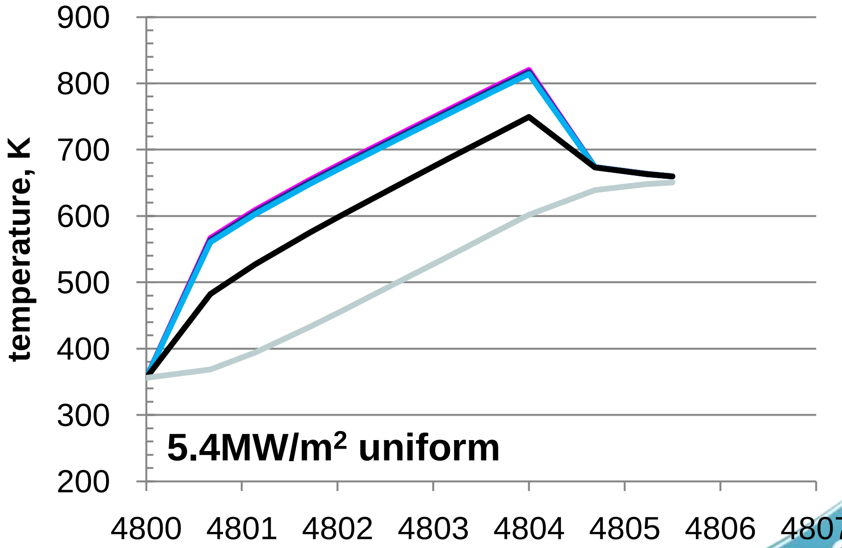
Comparison of Results (R 75cm)









Final Comments

The objectives in our thermal modeling changed as time progressed and results from the first campaign with the LLD became available.

- Initially we looked at operation with electrical heaters and how we might estimate the thermal conductance of the real Li/Mo layer.
- Our attempts to estimate this thermal conductance and also the emissivity of the surface of the LLD were unsuccessful.

Many interpretations of data depend on the temperature of a Li surface in the device being operated (NSTX, T-II, HT-7, EAST, FT, TJ-II) but this is often a poorly know value.

- Detailed thermal modeling and better understanding of the surface chemistry and its effect on emissivity would be useful.

Final Comments

Now we are modeling "cold start" cases (no preheat of LLD) and looking more closely at the melting and evaporation of Li. Our preliminary results suggest the following conclusions.

- The rise in temperature of the Li is less than one would find with a simple 1-D analysis. The temperature peak is broader than that of the heat load due to lateral heat conduction away from the peak.
- Evaporative cooling is not a big factor in the cases we have modeled so far.
- Emissivity is important for IR measurements and in our thermal modeling.

Emissivity from which lithiated surface?

Evaporation of Li is of interest. The work function depends on surface chemistry and impurities.

Sandia will collaborate with Purdue University and add an IR camera and software to PRIHSM to monitor a heated lithium target while JP Allain and co-workers modify and monitor surface chemistry.

E N D

T H A N K Y O U

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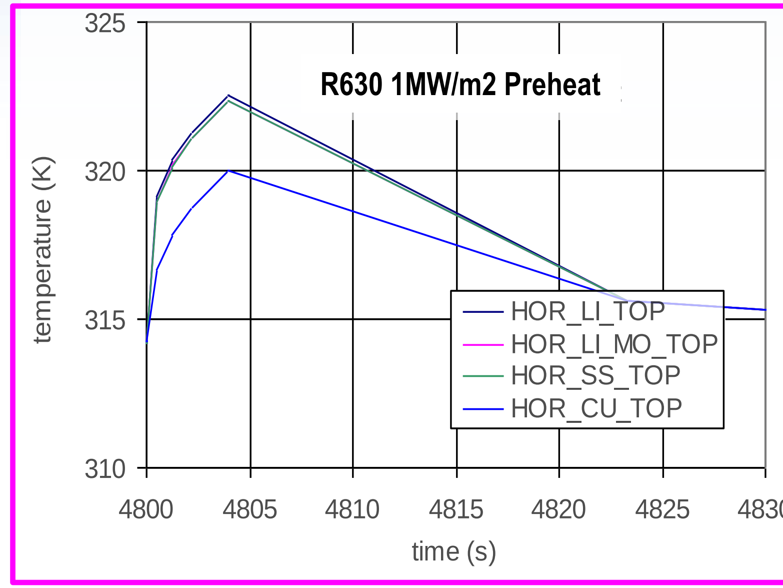
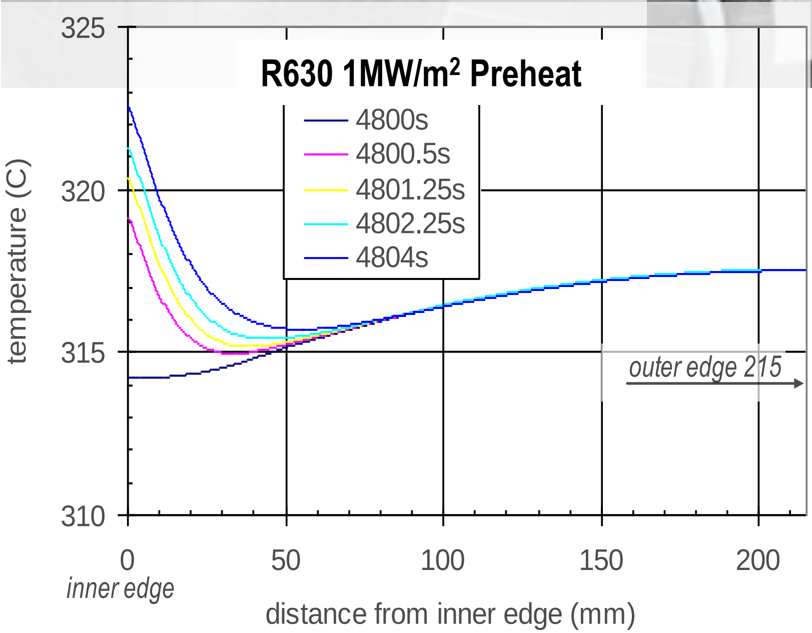
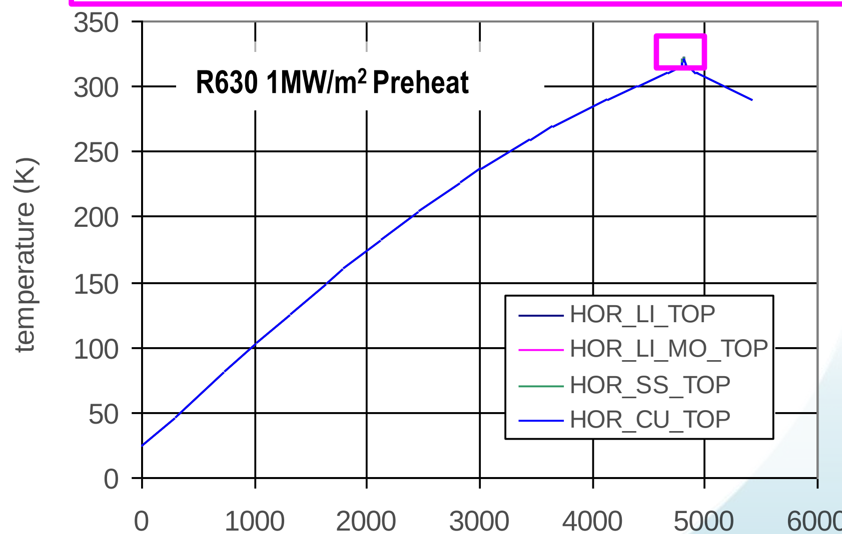
Sample of Results for R63cm 1MW/m^2

- strike point at 63 cm (near LLD's inner edge)
- preheating with electrical heaters
- no gas cooling (included in other analyses)
- heating from heater(s) set by trial and error based on TC measurements
- plasma heating from 4800 to 4804 s







Poloidal distribution of temperature on the surface of the LLD model at several times during the 4-s shot.

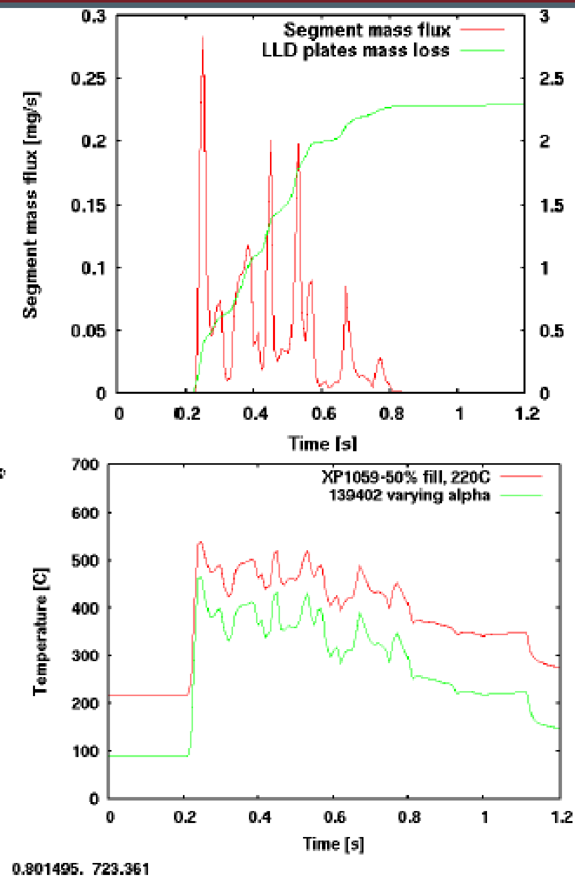
NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

LLD plate heating during XP1041-A

M.A. Jaworski (PPPL), et al.

XP1059 prediction for 220C starting temperature

- Same parameters utilized for this simulation, except starting temperature
- Evaporative cooling significant
  - Prevents straight linear adjustment of previous temperature solution
  - Total mass loss from all four LLD plates is about 2.3mg
- May be pessimistic if a liquid lithium layer is present (alpha → 1)



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