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

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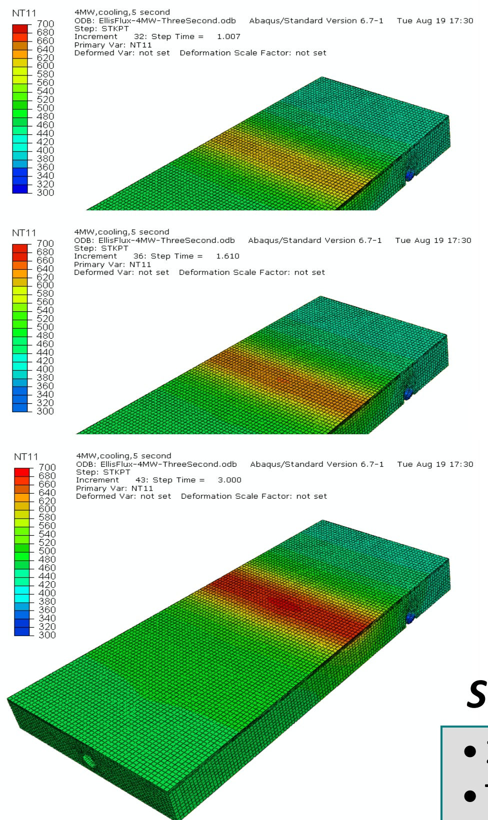
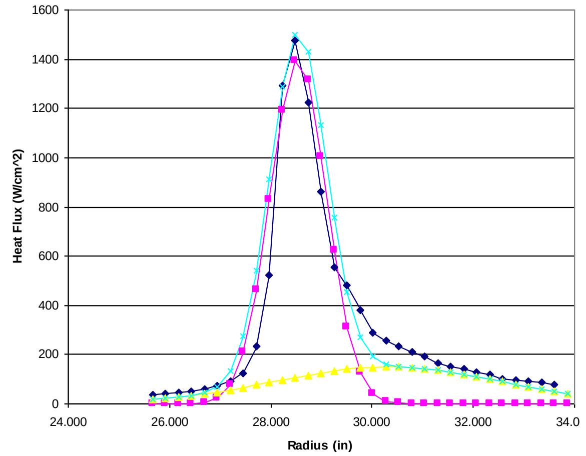
## Early thermal Model and Results

**Stationary strike point heating**



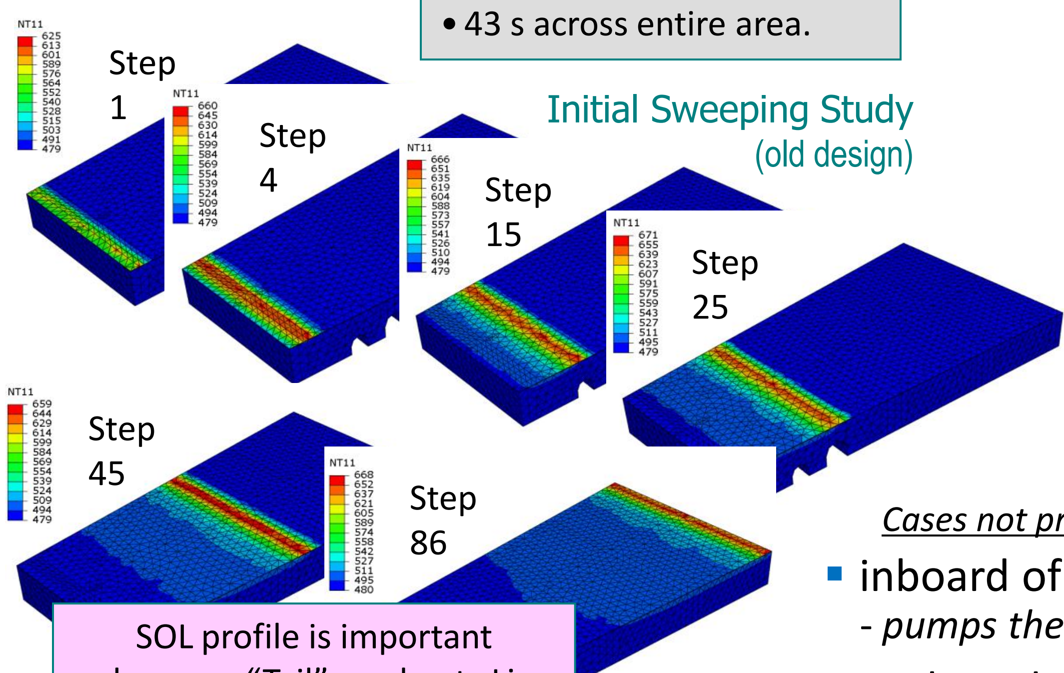



Strike point profile (outer div.).
"Wings" are important in sweeping.

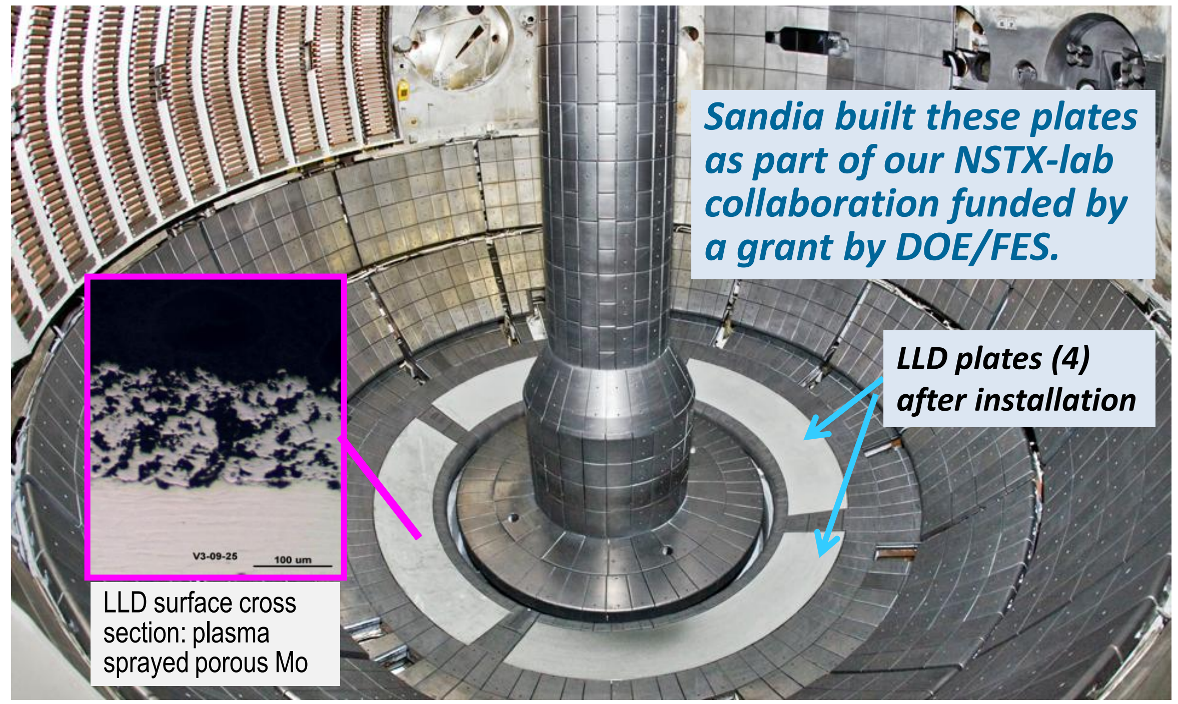
### *Swept strike point on LLD*

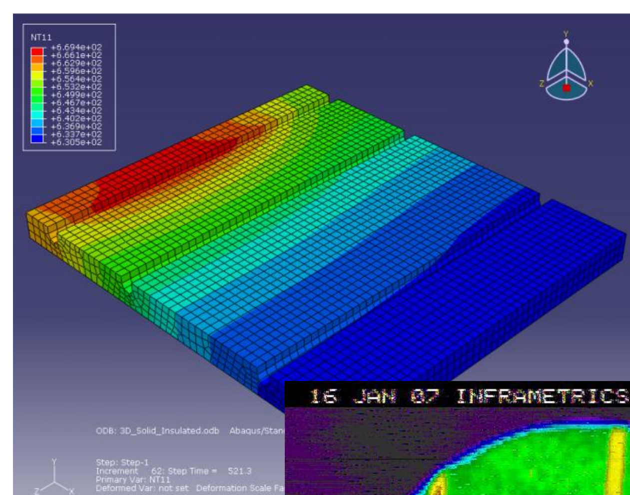
- 200W heater, 25 min.
- T-start 475 K.
- 500 mm/s "sweep"
- 5 ms heat, 2.5mm zones
- 43 s across entire area.

Initial Sweeping Study
(old design)

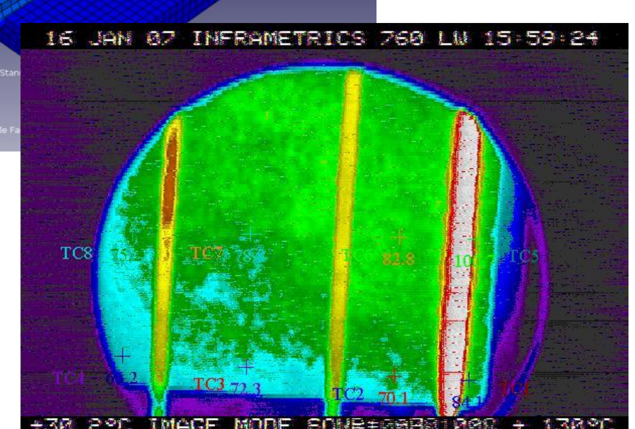



SOL profile is important because "Tail" pre-heats Li ahead of strike point.



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.



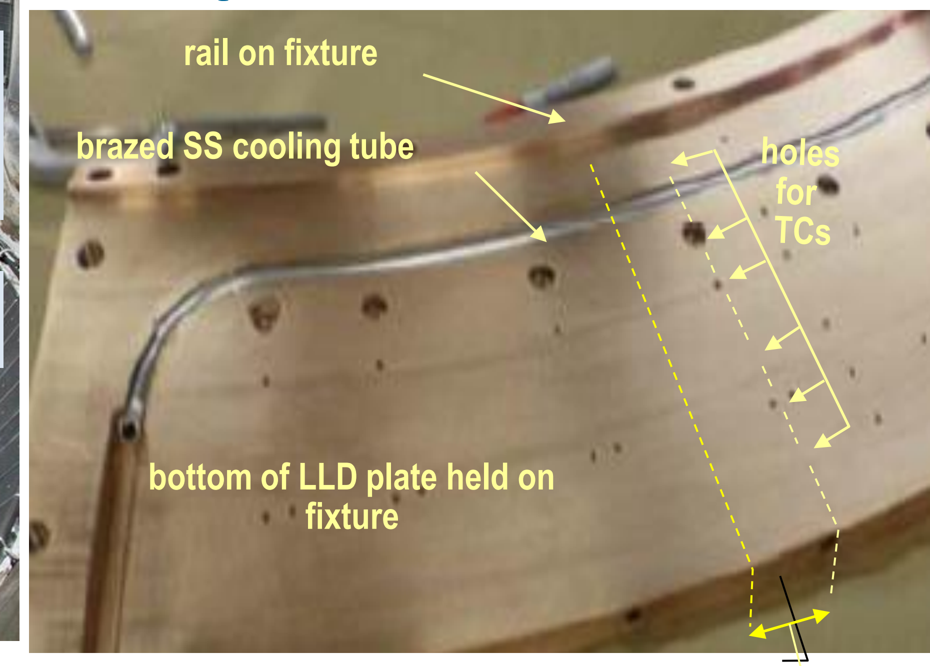

- Initial tests on Mo mesh (above)
- heater failure (below)

*Cases not presented here*

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

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

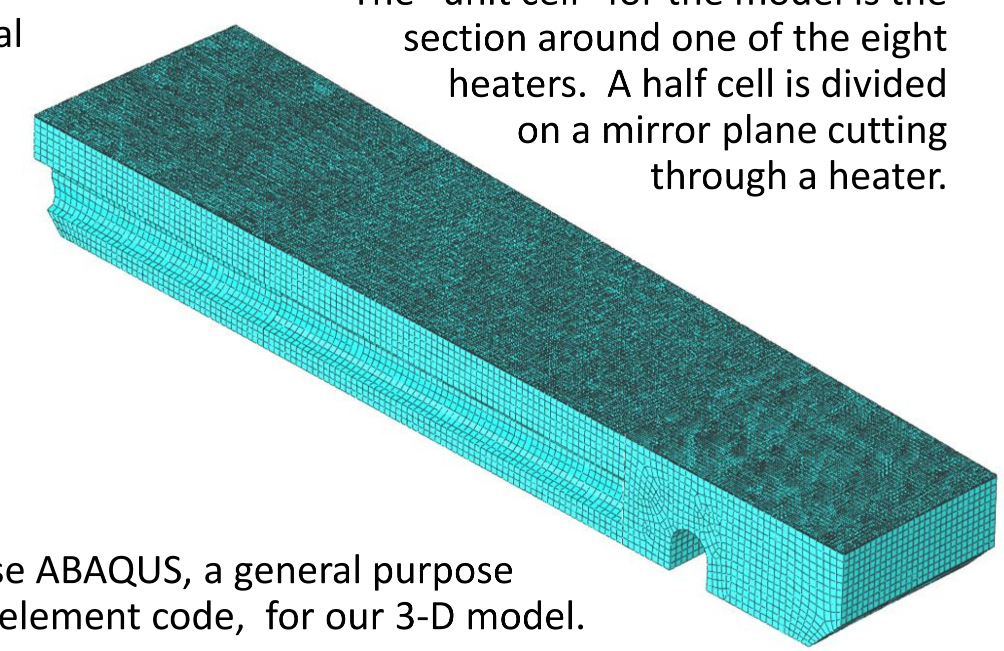
## ABAQUS thermal model for LLD "half cell"




solid angle of the half unit cell

The shape comes directly from the CAD model for fabrication.

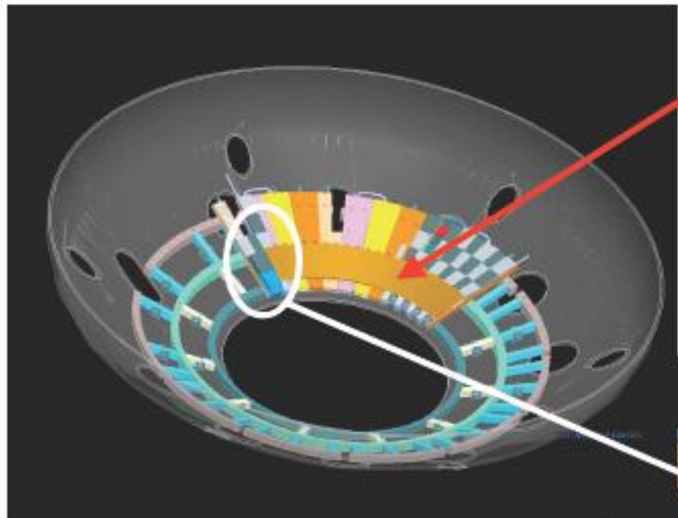
The "unit cell" for the model is the section around one of the eight heaters. A half cell is divided on a mirror plane cutting through a heater.



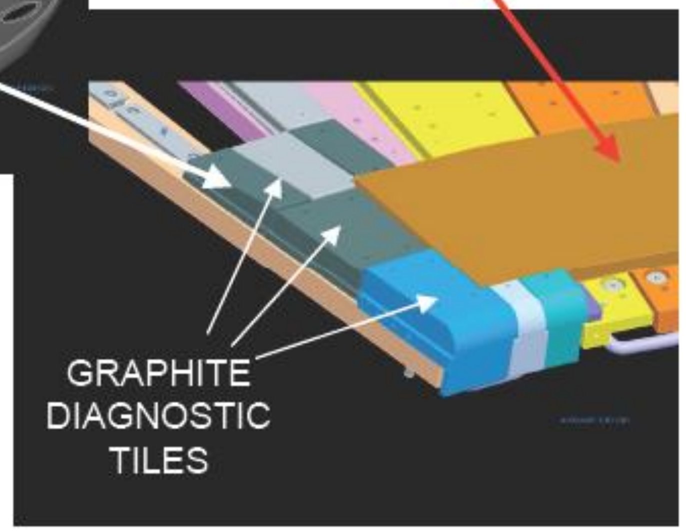
We use ABAQUS, a general purpose finite element code, for our 3-D model.

We analyze a "half cell" of the LLD, and calculate temperatures over time.

## 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.

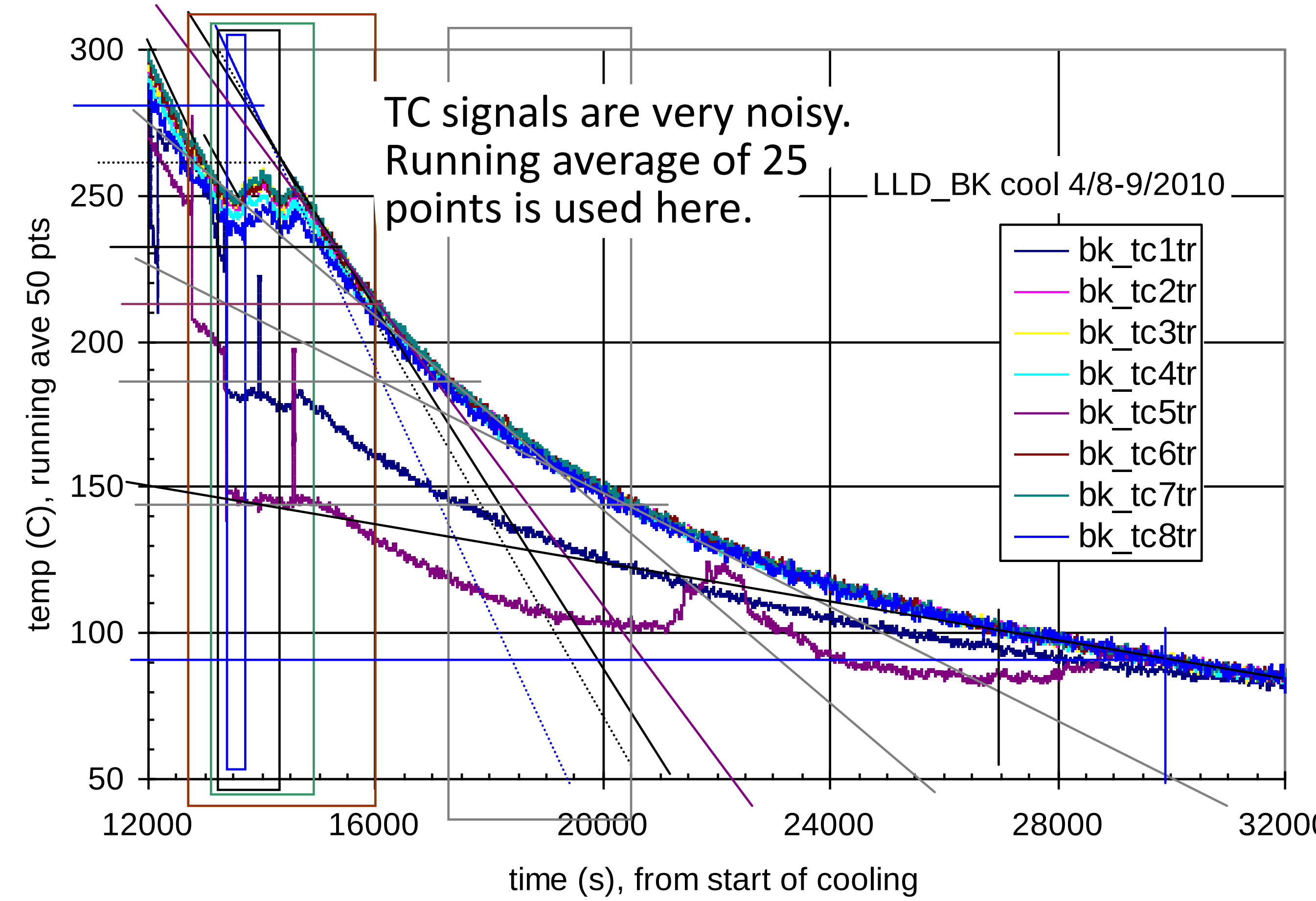
Attempts to fit the cooling curve were not productive.

A good fit required significant losses through conduction and radiation from back of LLD.

This made the fit rather insensitive to the radiation loss from the lithiated surface of the LLD. Thus the approach was not useful for estimating a value of emmisivity.

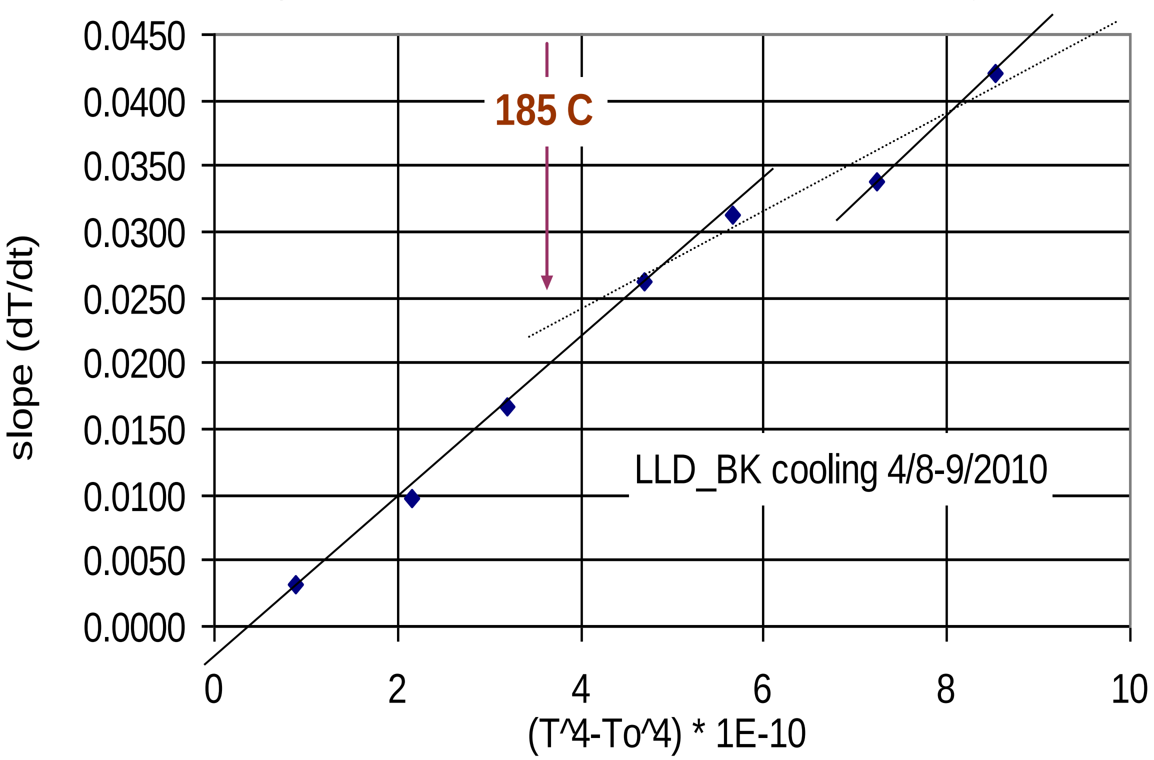
## TCs during long cooling of LLD section BK

(1PM on April 8 until after midnight)




## 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.

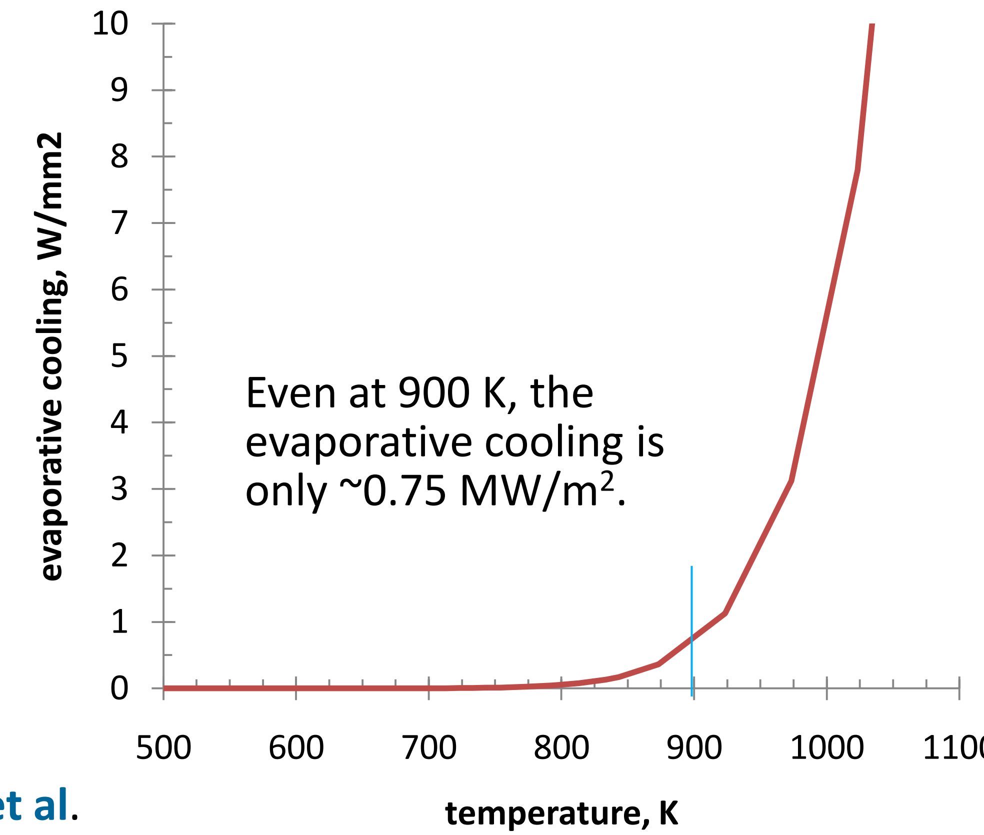



Initial treatment seemed OK - apparent strong dependence on $T^4$.

## How much does evaporation of Li cool the LLD?

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

We also calculate the integrated amount of Li evaporated in our post-processing based on the evolution over time of the distribution of temperature on the face of the LLD.

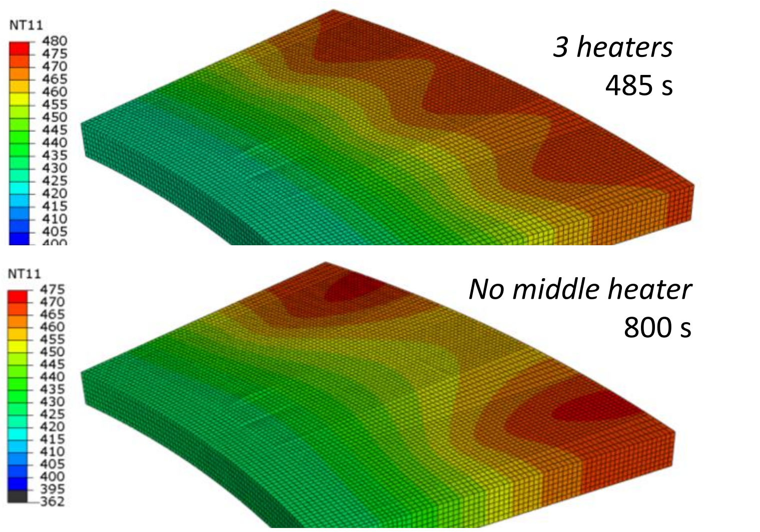



### Our expression for evaporative cooling

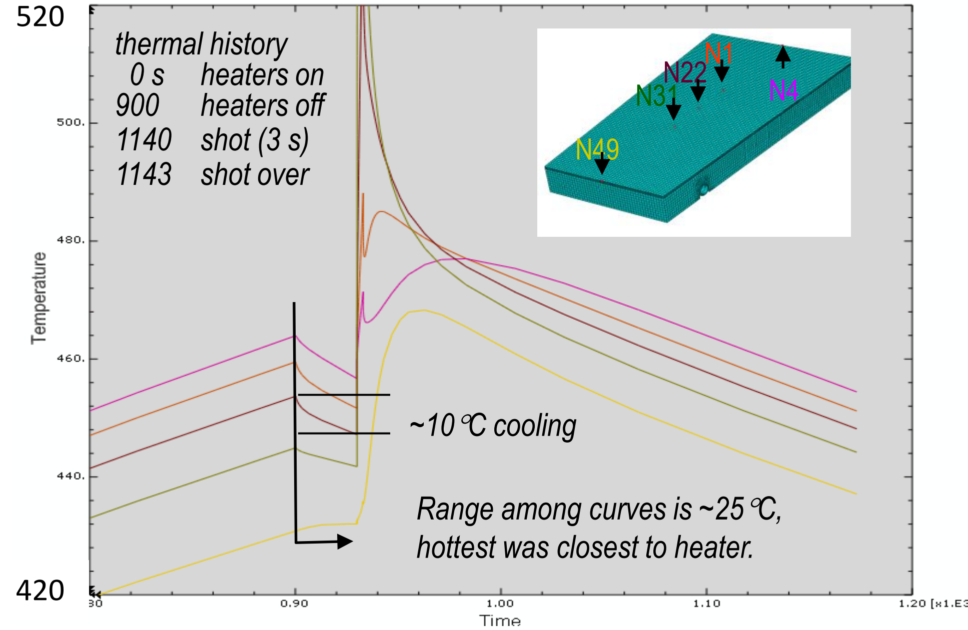
Cooling ($W/mm^2$)
= 595.7 * [10^(8-8143/T] /SQRT(6.941*T)

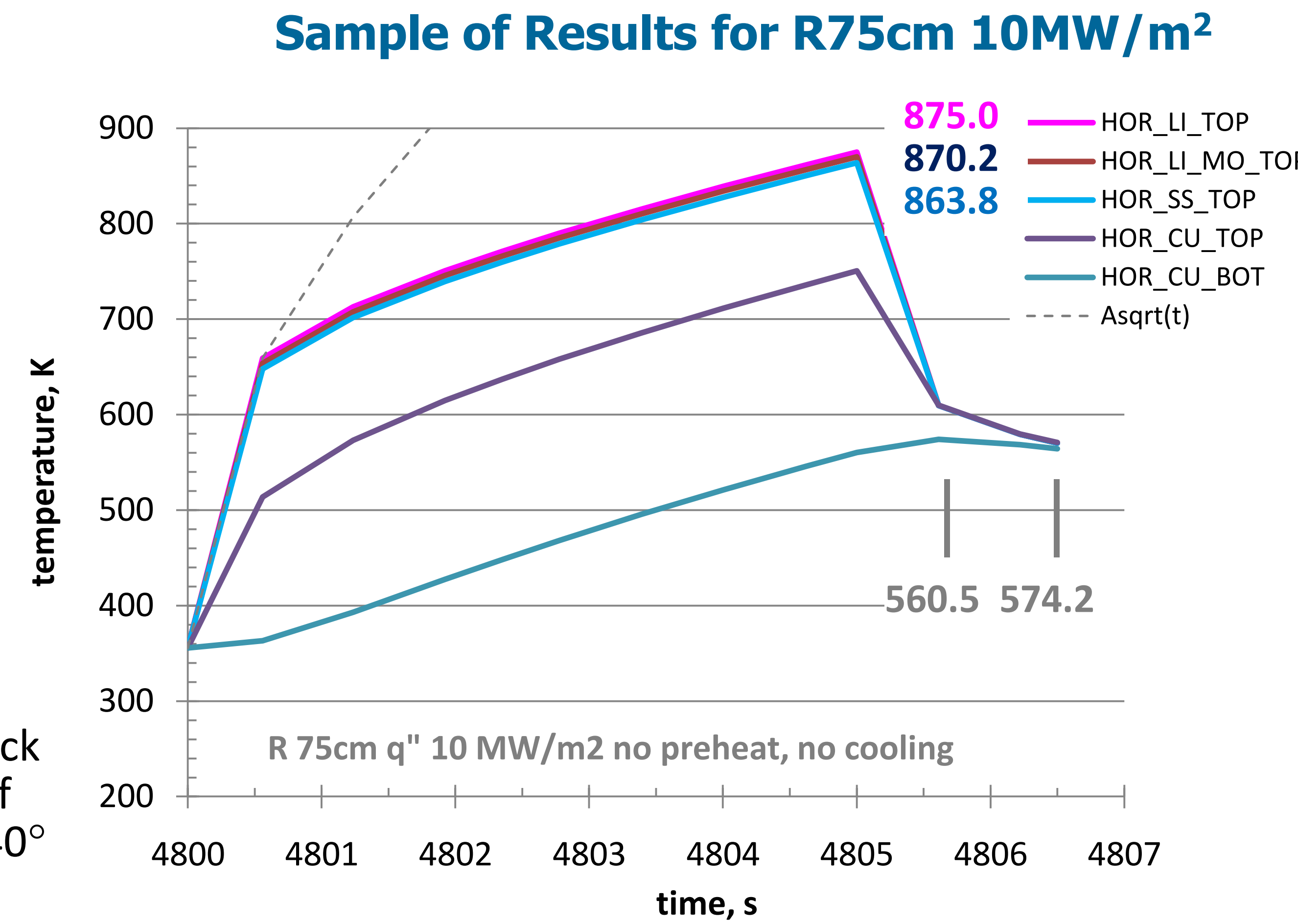
$P_{vapor}$ (Torr)
= 3.5E22 * [10^(8-8143/T] from **Jensson et al**.

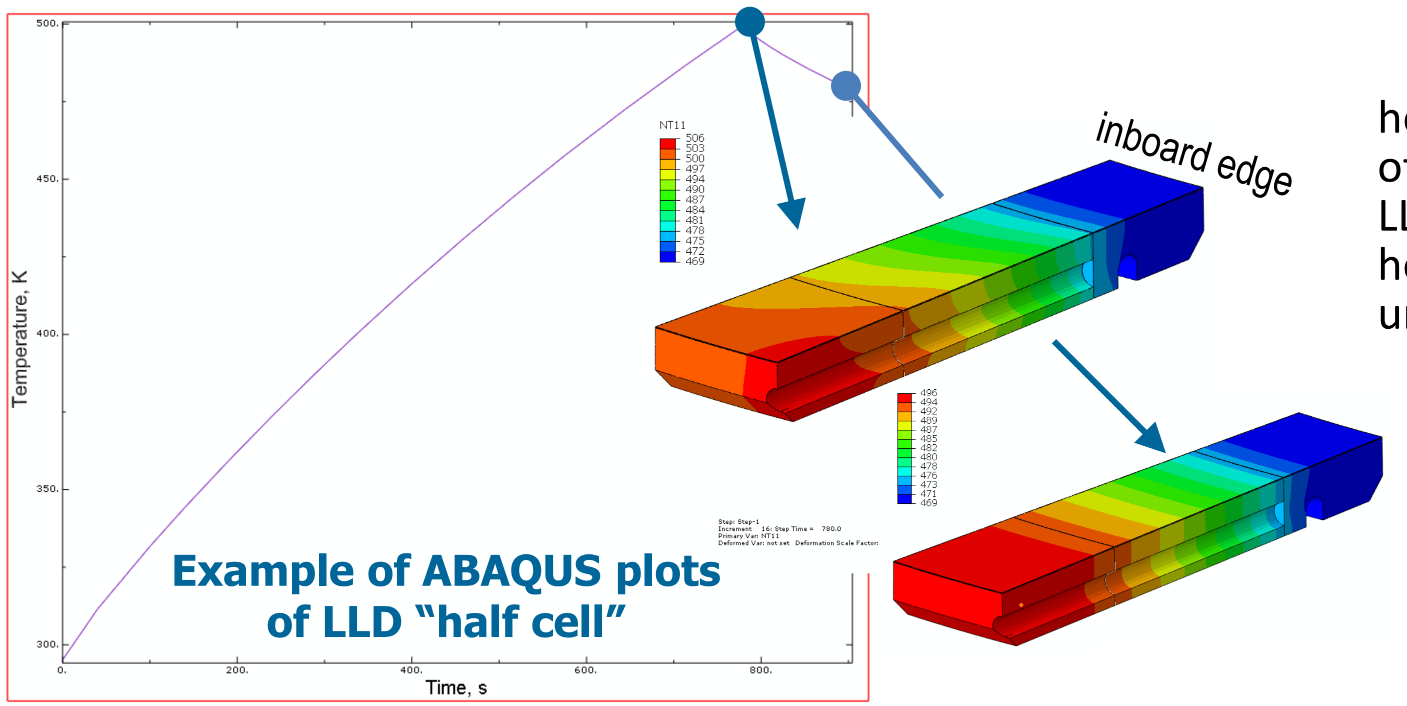
$$\text{Evaporation } \Gamma_{evap} \text{ (atoms/cm}^2\text{-s)} = 3.5\text{x}10^{22} \frac{P(Torr)}{\sqrt{mass(a.u.)T}}$$




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




**0.5s:**

heat penetrates to back of Cu plate (bottom of LLD). Li surface is 140° hotter than the underlying Cu.

**5.0s:**

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.

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

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)

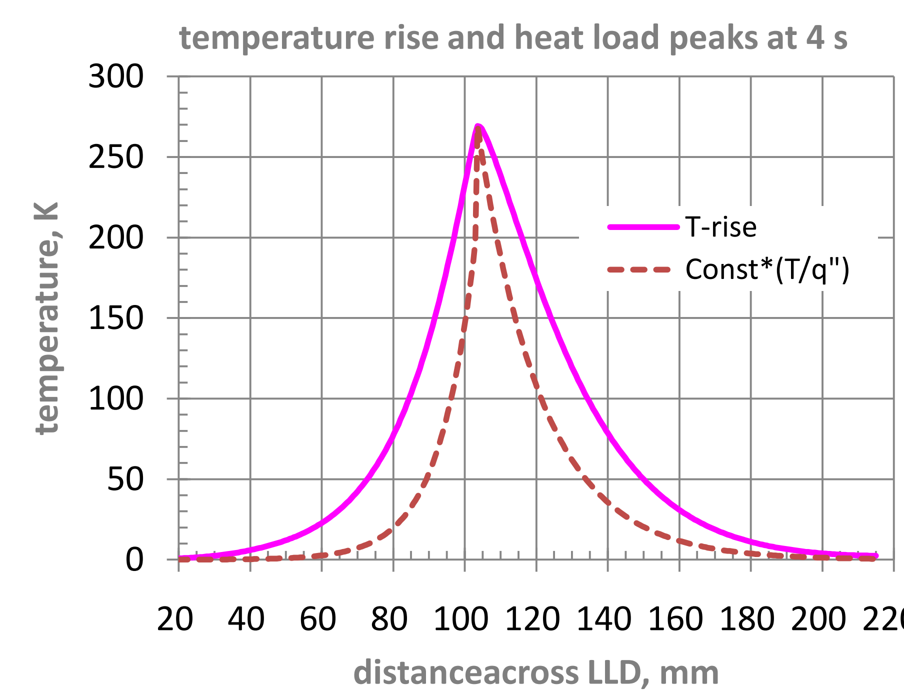
Case: Heating of plate, N2 cooling
- Mo properties for Li/Moly layer
- Initial temperature 22°C
- 400W applied to heater surface
- 0.029W/cm$^2$K film coefficient and 22°C sink temperature for cooling tube.

The rise in temperature of the Li is in proportion to the heat load.

After 4 s at 10 MW/m$^2$, the rise in temperature is 465° and at 5.4 MW/m$^2$ it is 262°.

For each, the peak rise in temperature divided by peak heat load is 46.6 degrees per MW/m$^2$.

Evaporative cooling is not a big factor here.

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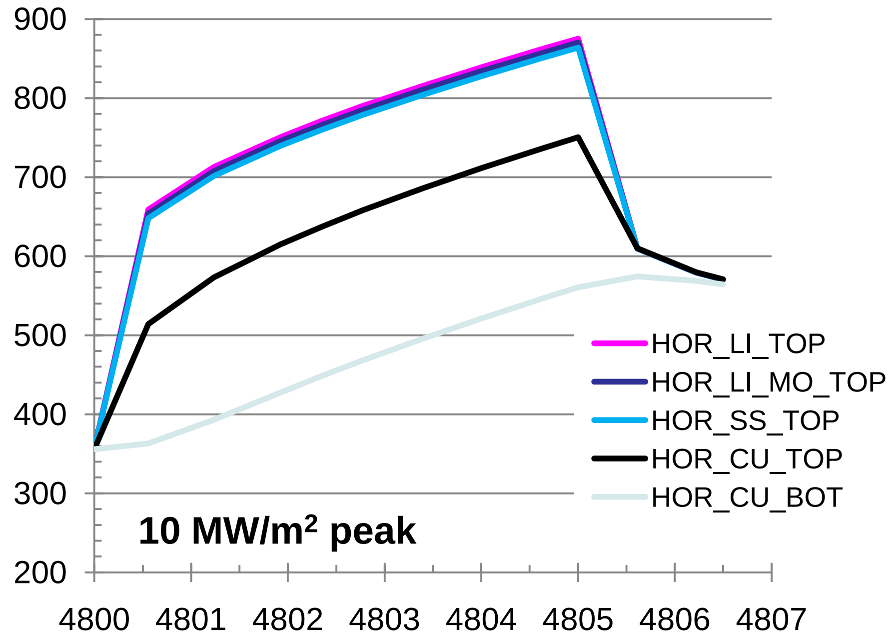
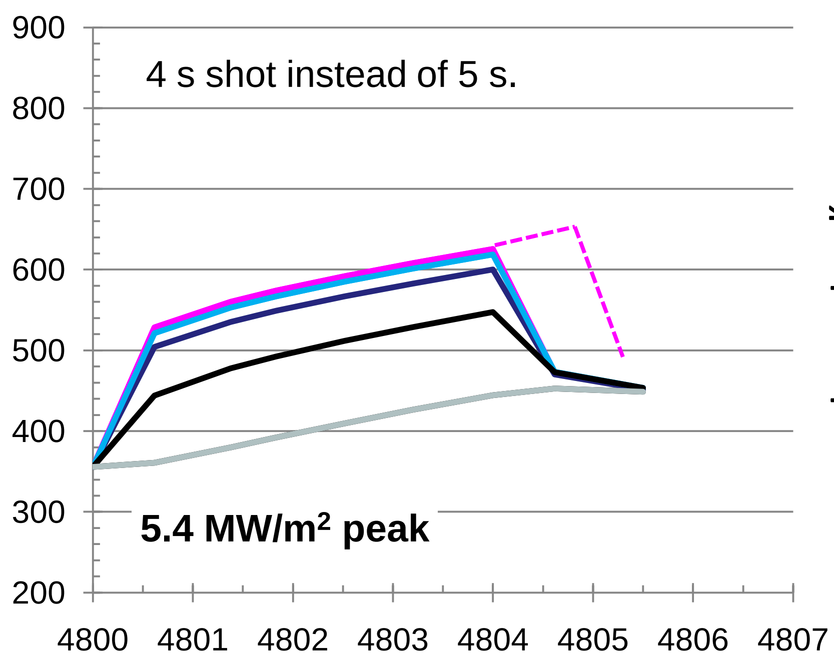
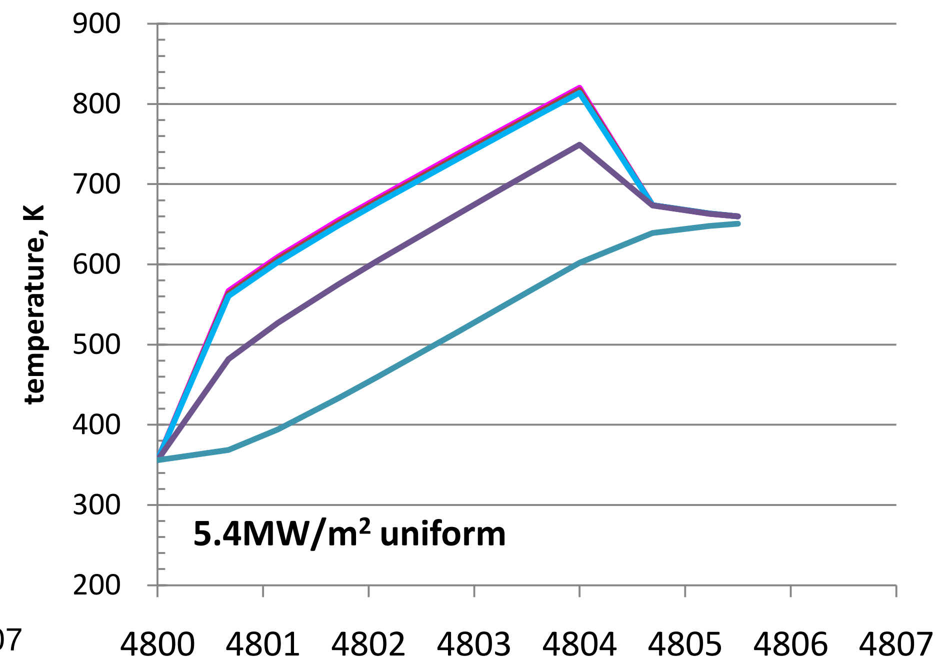
## Comparison of Results (R 75cm)




We can confirm that lateral heat conduction accounts for the broadening by comparing the peaked case (above left) to a case with a uniform heat load of 5.4 MW/m$^2$ over the entire LLD. ( above right).

If lateral heat conduction were insignificant, heat would diffuse only downward into the plate (1-D equivalent) and, for the uniform load, the temperature everywhere would be the same as that for a peaked loading.

But this is not the case. A uniform loading gives a much higher maximum temperature.

# 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, 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.

*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.
- Knowing emissivity is important for IR measurements and in 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 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.