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Plasma heating and thermal response modeling of the LLD

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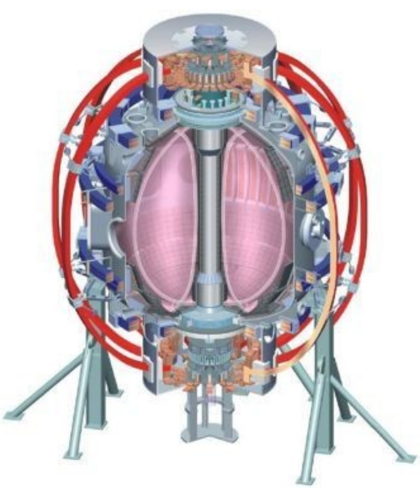

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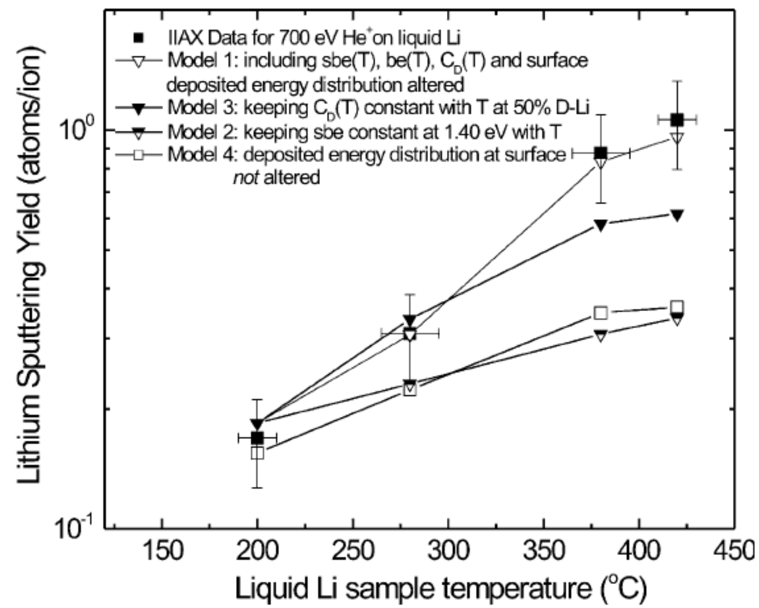
A tool for physics analysis

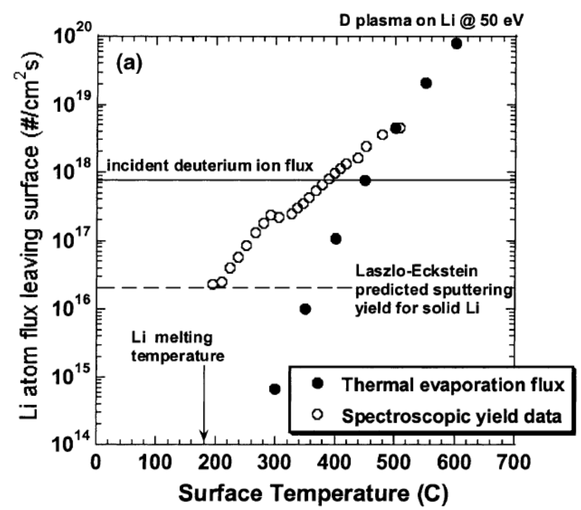
- Heat transport in solids is the state-of-the-art of the 19th century (Fourier's been dead since 1830)
  - Thermal model of the LLD is not an end unto itself
  - Novelty involved in the present implementation is the inclusion of a porous material model for the Mo-Li system
  - Thermal models are pretty "standard-fare" (provided you have someone to run it)
- Purpose of the model is twofold: physics and operations
  - Physics analysis tool for pulling apart temperature dependent processes in the PFC (e.g. sputtering, evaporation, desorption, chemical erosion, impurity gettering, retention, recycling), and building relationships with target plasma conditions (e.g. probe measurements of N_e, T_e, V_f, as well as other diagnostics)
  - Operations support and future planning: provide information to those planning shots and determining maximum allowable machine powers while having a validated tool for future scoping studies (e.g. all metal inboard div.)

Linking small experiments and tokamaks

- Small experiments have the advantage of control
  - Study phenomena at leisure
  - “Operations knob” is the “physics knob”
  - E.g. temperature dependent sputtering
- NSTX “operations knob” not necessarily the same as the “physics knob”
  - LLD temperature at the beginning of the shot is operating knob
  - Plasma heating controls LLD temperature during the pulse
  - A thermal model of the LLD can provide the link between plasma heat fluxes and the lithium temperature



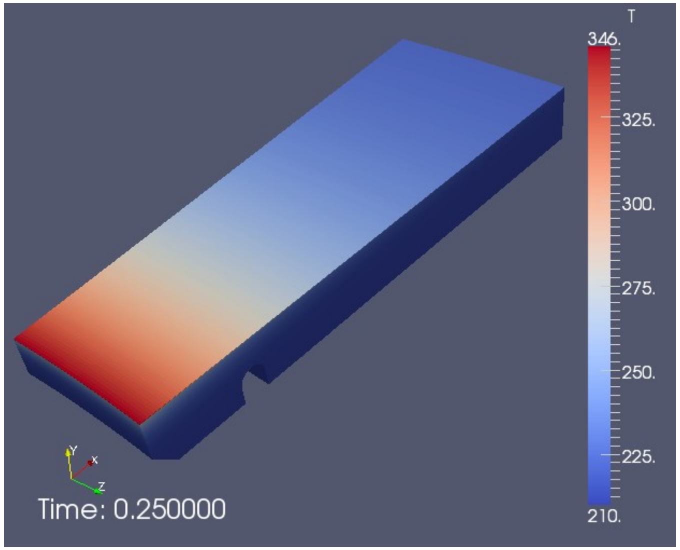
Allain, J. Nucl. Matl., **313-316** (2003)

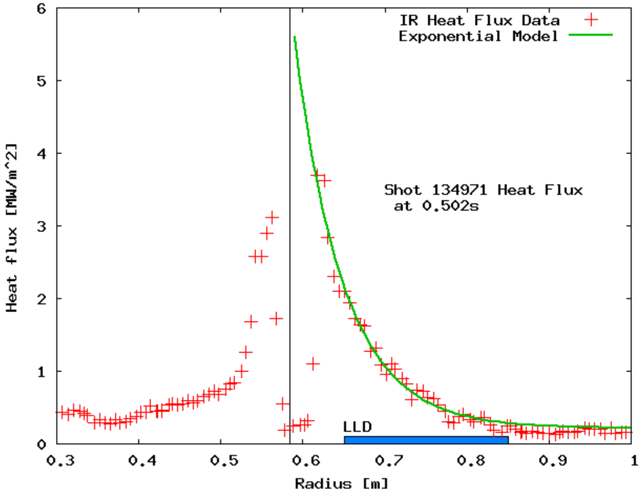


Doerner, J. Nucl. Matl., **290-293** (2001)

Working model for LLD temperature rise

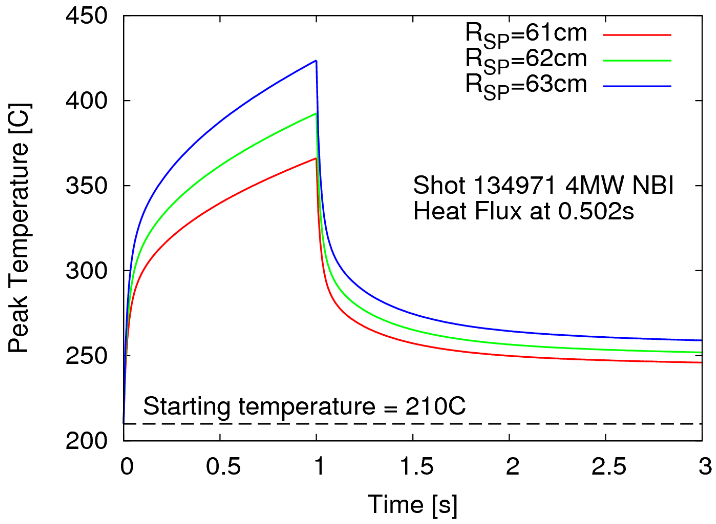
- LLD model implemented
  - Using OpenFOAM computational system to perform thermal analysis
  - Using IR heat flux measurements for input (J. Kallman and R. Maingi)
  - LLD geometry and materials used (additional porous material model based on Jaworski **JNM** 2008)
- Boundary conditions and other details
  - Insulated back surfaces
  - Axisymmetric wedge modeled solving r-z heat transport
  - Radiative (with b.b. properties) and evaporative cooling of the front-face (both largely negligible)
  - Temperature dependent material properties (Cu, SS316, Mo, Li)
- End result is time history of temperature throughout the LLD, current metrics:
  - Maximum plate temperature
  - Total mass flux

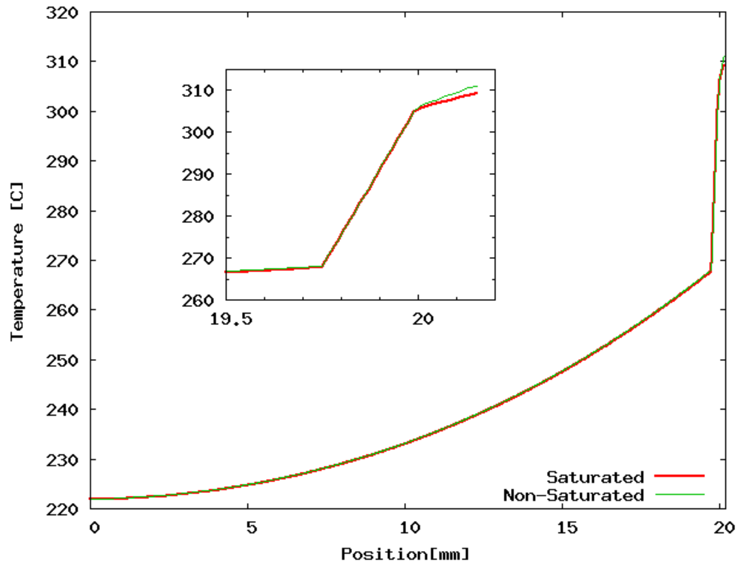




Strike point position is significant

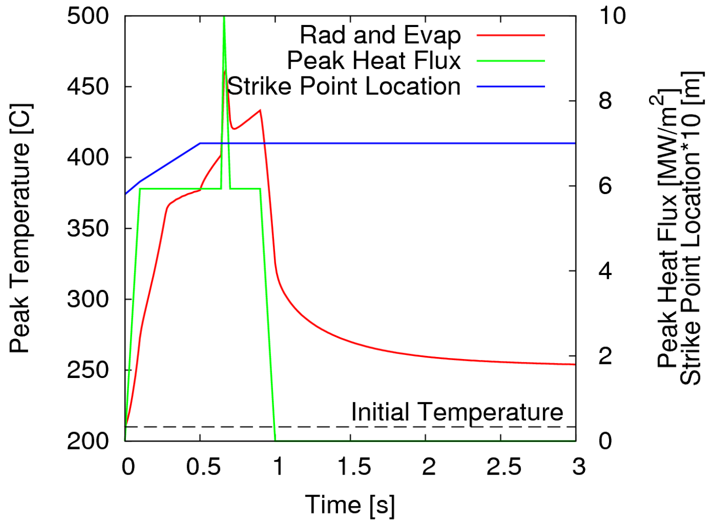
- Same heat flux profile – shifted over 2 cm
  - SOL heat flux gradient significant leading to sensitivity of position control
  - LLD bulk temperature rise could provide calorimetry data immediately following a shot
- Temperature rise dominated by two factors
  - Most temperature rise occurs in stainless steel chemical barrier (old news)
  - Porous layer has little effect on temperature whether filled with lithium or empty
  - Time history dominated by copper diffusivity (great conductor)

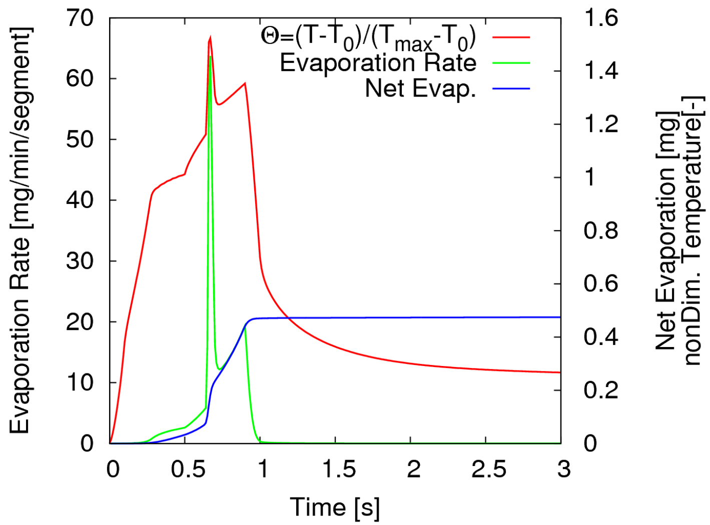




Evaporation with a toy strike-point sweep and ELM

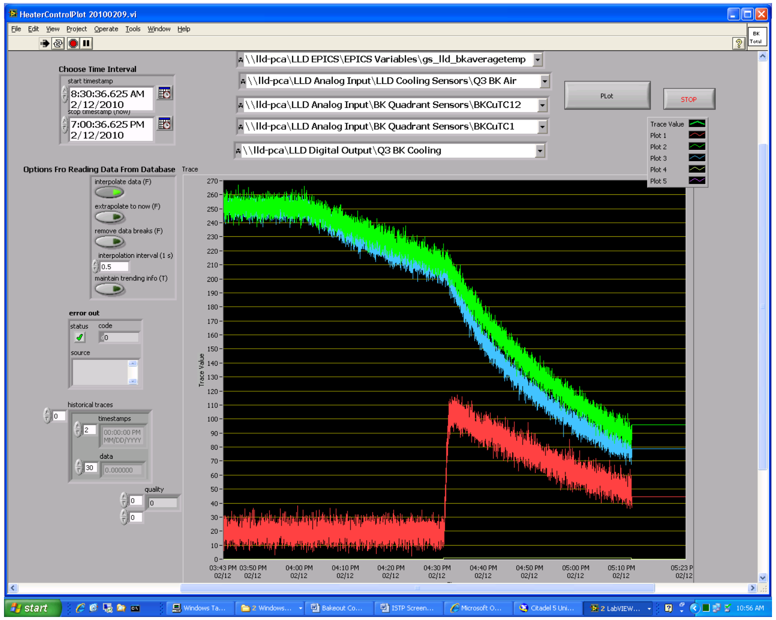
- Toy heat flux implemented for testing
  - Time varying peak heat flux
  - Strike point sweep and hold
  - “ELM” with profile widening and peak increase
  - Ramp-down
- Surface radiation and evaporation
  - Negligible effects from a heat transfer stand point
  - Radiation at 500C is ~0.02MW/m2 from a blackbody source, evaporation is even less
  - No coupling to plasma heat flux built into this model
- Is there a limit set on peak LLD temperature?
  - Integral of evaporated flux modest despite exceeding 375C “limit”



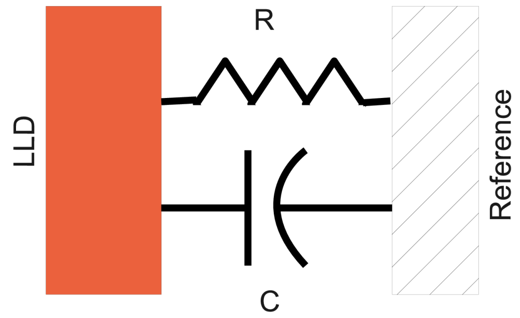


Ratcheting calculations based on LLD ISTP

- LLD ISTP provided valuable data for thermal modeling
  - ISTP maintained temperature at ~250C for 5 hours for heater test
  - Period of unforced cooldown
  - Period of gas cooling
- Standard analysis method applied: thermal resistances
  - Treats system as lumped elements with electrical analogues
  - Time scales of minutes makes lumped element approach logical
  - Capacitance determined by LLD materials and geometry
  - Resistance is an unknown parameter determined by thermal decay curves → system identification

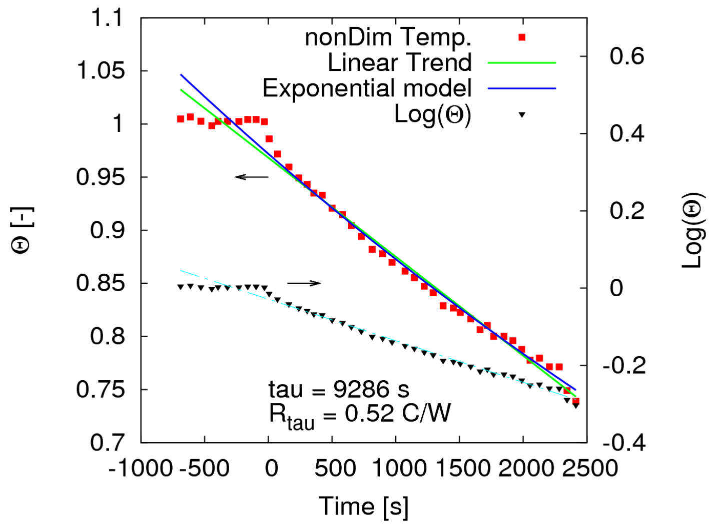


H. Schneider and T. Plumb



Unforced cooling system identification

- About 400W cooling during unforced period
  - Long time constant
  - Distinguishing exact system behavior difficult without more data
- Two power loss models available
  - Conduction (linear with temperature difference)
  - Radiation (T^4 dependence)
  - Real system is a linear combination of the two, but
  - Not enough data to distinguish
- Relevant parameters extracted for the two extreme cases
  - Case 1: all radiation
  - Case 2: all conduction



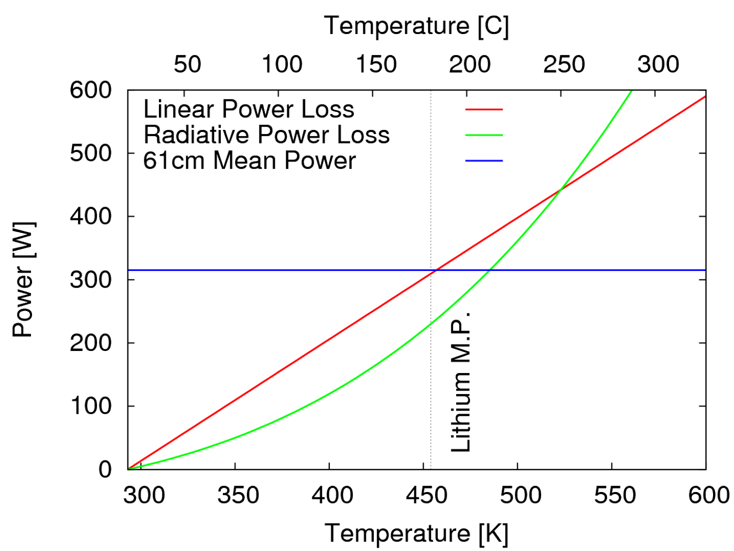
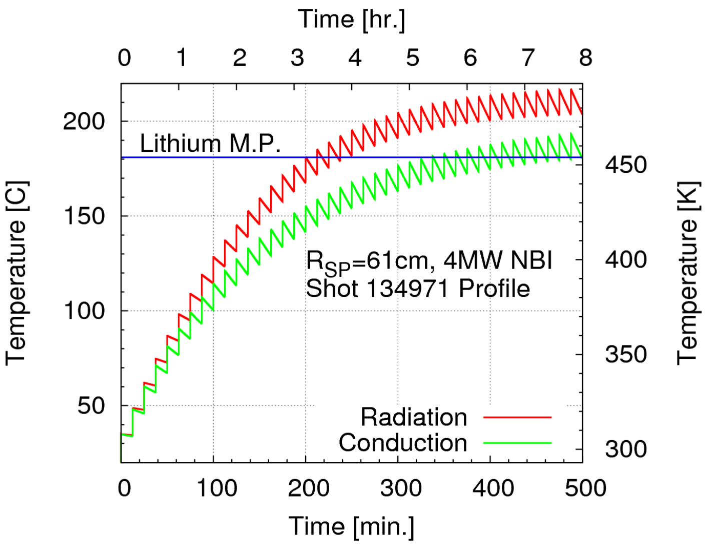
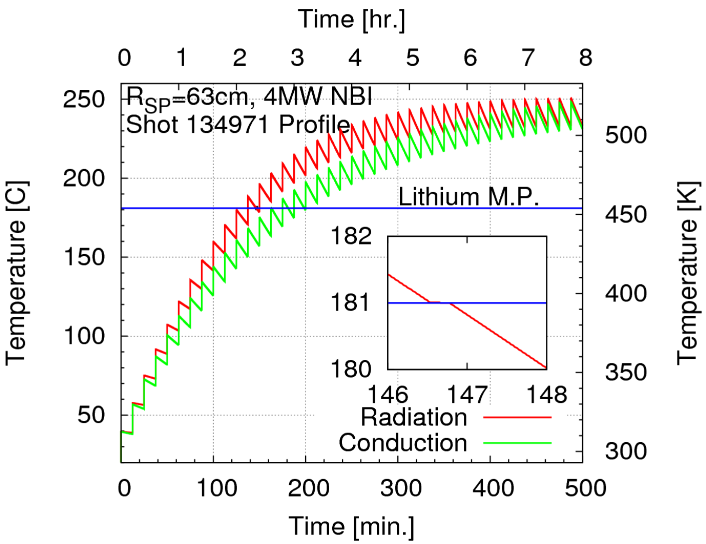


Plate ratcheting without forced air cooling

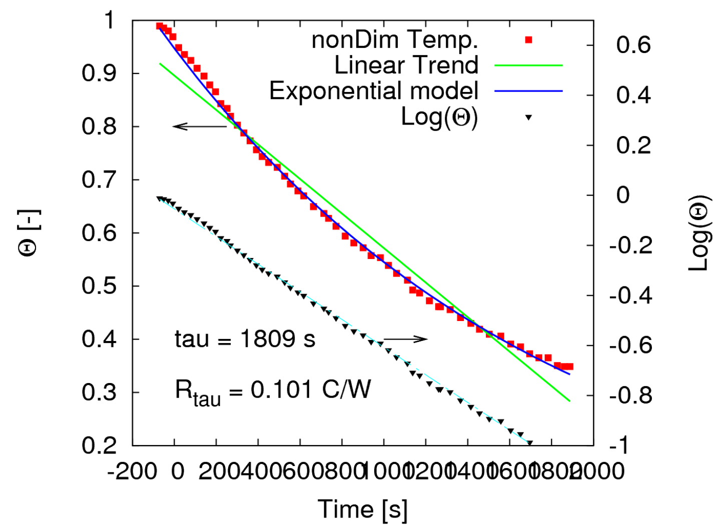
- Power balance method for calculating temperature
  - Net power in per shot based on heat flux
  - 12.5 minute shot cycle with unforced cooling
  - Porous layer assumed 100% saturated for thermal properties
- Kallman heat flux (134971, 4MW NBI) profile used
  - Strike point varied from 61cm to 63 cm
  - Shot duration assumed to be 1 full second with constant heat flux during shot
  - Both scenarios can reach lithium melting point, but require significant time investment
- Liquefaction will occur in the middle of a shot before starting temperature reaches lithium M.P.

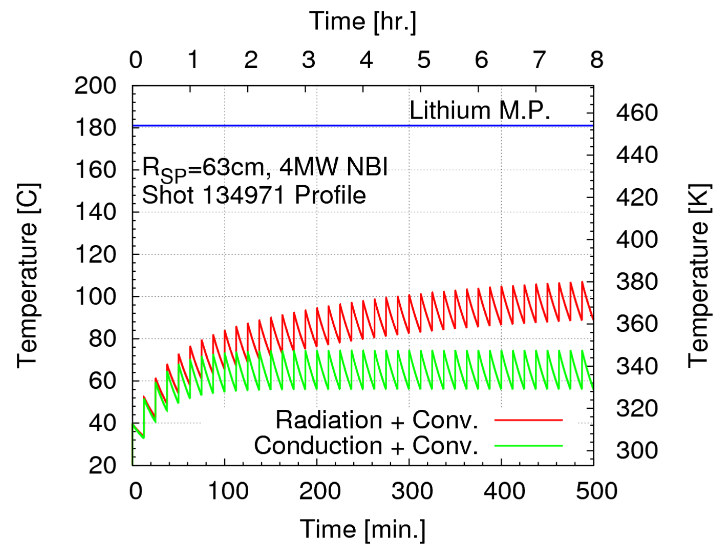




System ID and ratcheting with forced cooling

- Forced cooling data displays expected behavior
  - Gas cooling much more effective
  - Shorter time constant indicates much lower thermal resistance
- Plate ratcheting repeated for 63 cm strike point
  - Thermal resistance model includes both radiation and convection or
  - Conduction and convection
  - Both indicate the expected “cool” LLD conditions will be below lithium M.P.





Summary and next steps

- Temperature dependent plasma-material interaction effects are a reality of lithium systems
  - Thermal model created to aid analysis by providing link between machine operation (strike point location, heat flux profile, ELMy?) and LLD temperature
  - Additional outcome has been operations support such as ratcheting calculations
- Model validation will be necessary once operations begin
  - Several diagnostics useful to this effort:
  - embedded TCs,
  - IR cameras,
  - probe array
- Next step: link local plasma parameters via probe array and local temperature of the LLD to unravel PMI