2-D thermal response calculations of the liquid lithium divertor on NSTX

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Introduction

The liquid lithium divertor (LLD) in NSTX was installed for particle and impurity control in NSTX. The structure and thermal properties of materials in the LLD make its thermal response under plasma heating more complicated than relatively thick graphite tiles. In this work, analysis tools currently used have been investigated for use with the LLD, and a new computational tool, DFLUX, has been developed for full 2-D thermal response of NSTX PFCs,

Steps to calculate the temperature on the LLD include:
υ Calculating the heat flux from the temperature of graphite by solving the heat conduction equation with 2D numerical code(DFLUX)
o Choosing reasonable heat transmission coefficient to get physically acceptable heat flux data.
o Assuming toroidal symmetry, project heat flux load on graphite to the LLD
o Solving the Enthalpy formulation of phase change problem with Gauss-Seidel method.

Temperature calculation requires:
o A believable heat flux on graphite
o Appropriate boundary condition
o An accurate description of the LLD components
o Consideration of the latent heat of fusion for lithium
o Temperature dependence of material thermal properties

Contents
o Introduction the method of Li enthalpy
o Calculation of physically reasonable heat flux
o Analysis the ability which endure the heat load for the LLD, and compared the ATJ graphite
o Compared the temperature data between Li enthalpy and dual-band IR data.

LLD in NSTX

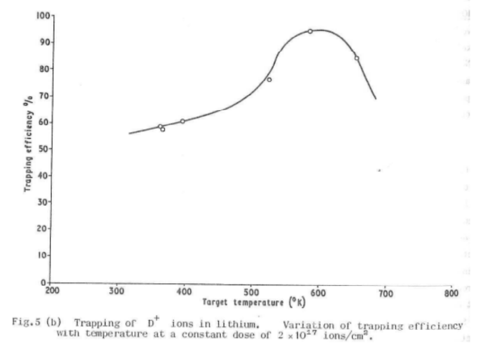
o Four LLD plates extending toroidally around the outer divertor, ATJ graphite compose the gap between two LLD plate.

o The heat flux on LLD is difficult to calculate, due to the phase change, unknown thickness of lithium and the complicated structure of LLD. The heat flux can be easily calculated from ATJ graphite.

Lithium retain deuterium

o Lithium was used to reducing the recycling, however, the best efficiency to retain the deuterium is in a limited window of Temperature. 200-400°C is reasonable temperature range to produce a lower recycling surface(R. Majeski, AIP Conf. Proc.Volume 1237, pp. 122-137 (2010))

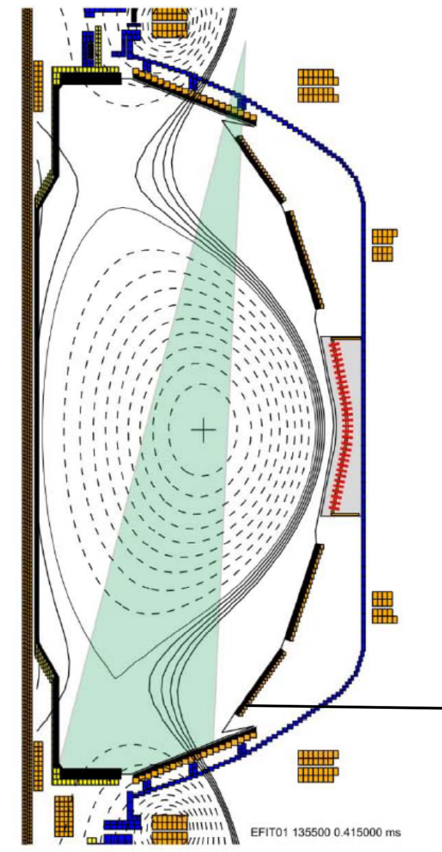
o Avoiding the high temperature is necessary to prevent the deuterium desorption



[Leonid E. Zakharov, LLD Design Meeting, PPPL, 2007]

Dual-band IR camera

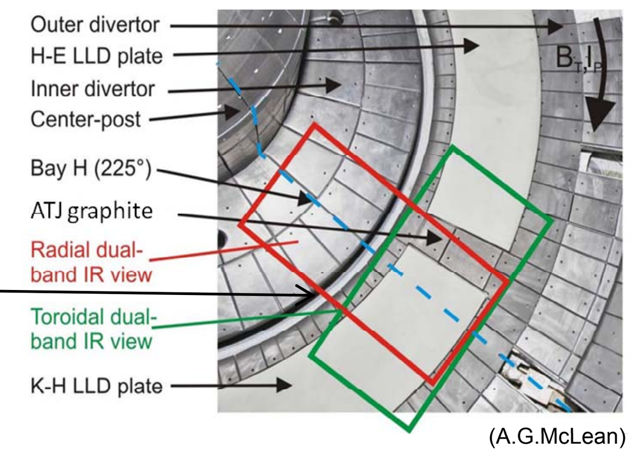
NSTX dual-band IR camera field of view



Dual band IR diagnostic parameter

frequency	wavelength	Spatial resolution
1.6khz	4-6μm & 7-10μm	4.5mm

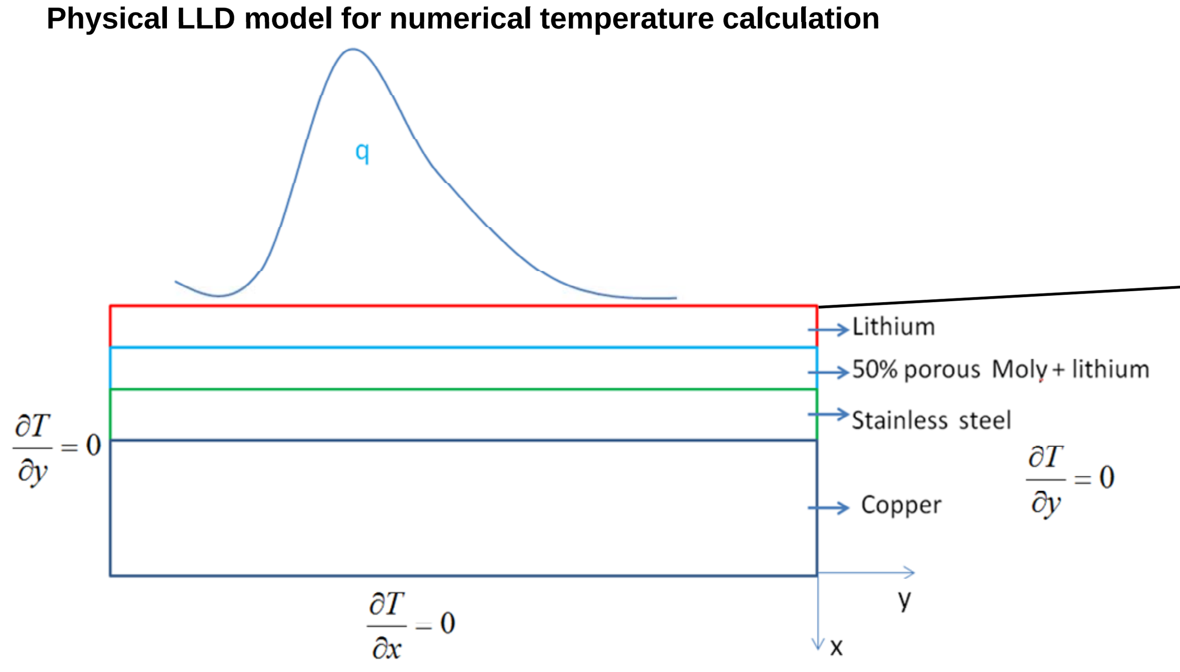
oNSTX IR Field of view contain LLD and ATJ graphite which the same radius position as LLD.
υ The dual band IR camera integrated two IR regions, reduce the influence of the emissivity setting compared with the single band IR camera (see A.G.McLean PP9-00069)



(A.G.McLean)

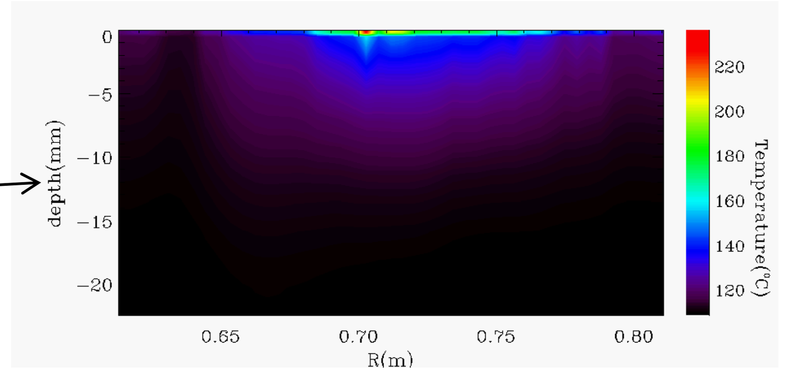
Li enthalpy

Physical LLD model for numerical temperature calculation



o The thickness of lithium is assumed to be 0.1 mm(unknown), 0.165 mm for porous moly, 0.24 mm for stainless steel, and 22 mm for copper.
o Implicit method is necessary to solve this equation with extremely thin lithium and moly.
o The temperature in copper is calculated with an explicit method to reduce cpu time.
o The surface boundary condition is heat flux calculated from ATJ graphite, which the same radius position as LLD

Temperature distribution in LLD



Solve the non-linear finite different equation with Gauss-Seidel method.

Equation $\rho \frac{\partial H}{\partial t} = \nabla(\kappa \nabla T)$

The relationship between temperature and enthalpy

$$T=\begin{cases}180.5+H/C, H<-C*e\\ 180.5+e(H-L)/(C*e+L/2), -C*e\le H\le C*e+L\\ 180.5+(H-L)/C, H>L\end{cases}$$

$$H(i,j)_{s+1}^{(m+1)\Delta t}=\frac{H^{m\Delta t}+(\Delta t/((\Delta y)^2\cdot\rho))(k(i-1,j)\cdot T(i-1,j)_{s+1}^{(m+1)\Delta t}+k(i+1,j)\cdot T(i+1,j)_{s}^{(m+1)\Delta t}) +(\Delta t/((\Delta x)^2\cdot\rho))(k(i,j-1)\cdot T(i,j-1)_{s+1}^{(m+1)\Delta t}+k(i,j+1)\cdot T(i,j+1)_{s}^{(m+1)\Delta t})+\alpha_s^{(m+1)\Delta t}}{\beta_s^{(m+1)\Delta t}}$$

Where

$$\alpha_s^{(m+1)\Delta t}=\begin{cases}0, H\le -C*e\\ ((\Delta t/((\Delta y)^2*\rho)(k(i-1,j)+k(i+1,j))+(\Delta t/((\Delta x)^2*\rho)(k(i,j+1)+k(i,j-1)))*e*L/(2(C*e+L/2), -C*e\le H\le C*e+L\\ ((\Delta t/((\Delta y)^2*\rho)(k(i-1,j)+k(i+1,j))+(\Delta t/((\Delta x)^2*\rho)(k(i,j+1)+k(i,j-1)))*L/C, H>L+C*e\end{cases}$$

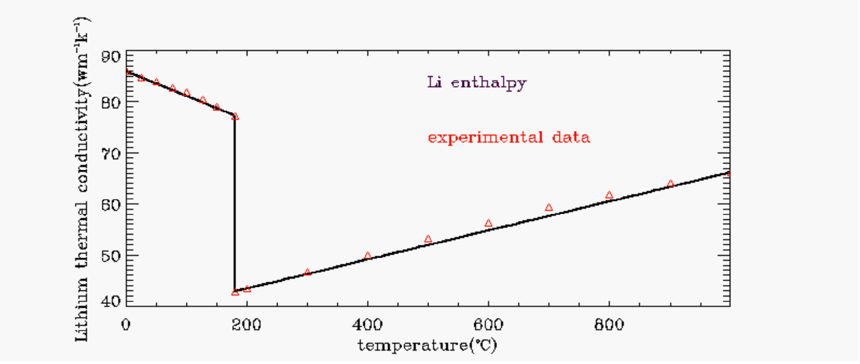
$$\beta_s^{(m+1)\Delta t}=\begin{cases}1+((\Delta t/((\Delta y)^2*\rho)(k(i-1,j)+k(i+1,j))+(\Delta t/((\Delta x)^2*\rho)(k(i,j+1)+k(i,j-1)))/C, H\le -C*e\\ 1+((\Delta t/((\Delta y)^2*\rho)(k(i-1,j)+k(i+1,j))+(\Delta t/((\Delta x)^2*\rho)(k(i,j+1)+k(i,j-1)))*e/(C*e+L/2), -C*e\le H\le C*e+L\\ 1+((\Delta t/((\Delta y)^2*\rho)(k(i-1,j)+k(i+1,j))+(\Delta t/((\Delta x)^2*\rho)(k(i,j+1)+k(i,j-1)))/C, H>L+C*e\end{cases}$$

[V.R.VOLLER, Journal of numerical of analysis(1985) 5, 201-204]

I, j represent the position, m represent the time step, s represent the Gauss seidel iteration

Thermal parameter in physical LLD model

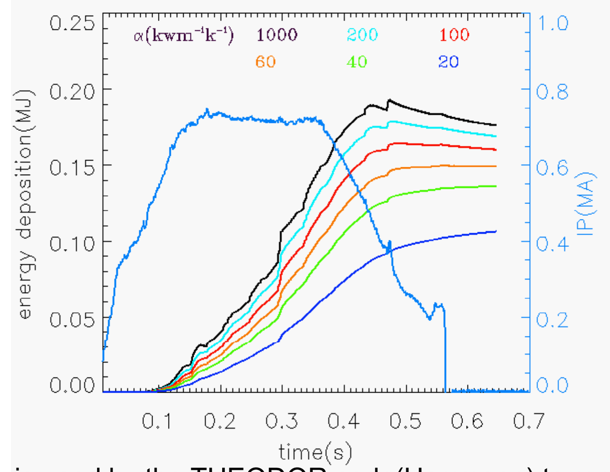
Lithium thermal conductivity in Li enthalpy(A.G.McLean)



50% porous moly thermal parameter

Material(180.5 °C)	ρ(kg/m³)	C(J/kg⁻¹k⁻¹)	K(w m⁻¹k⁻¹)	L(J/kg)
Lithium	534	4232	77.2	422000
molybdenum	10190	270	124	0
50% Porous moly&Li	5365	467	100.6	21000

Choose the α value for believable heat flux



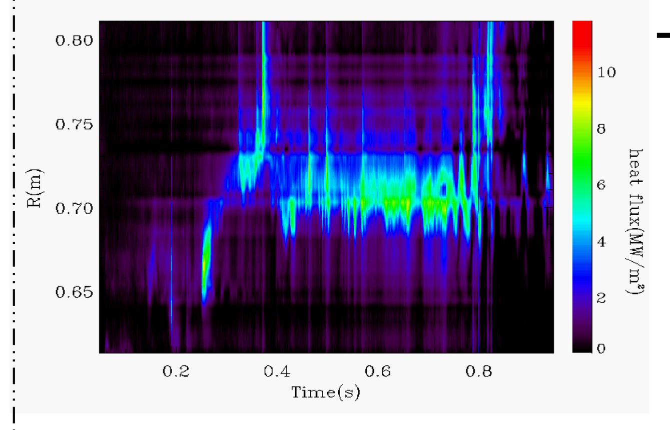
o An factor, α, is used by the THEODOR code(Herrmann) to represent heat transmission through loosely-held surface layers
o Without α, calculated heat flux after transient events can be <0
o The α value greatly affects the magnitude of calculated heat flux.
o DFLUX similarly solve the conduction equation to get the heat flux with surface temperature and appropriate boundary condition.
oThe heat transmission coefficient on a surface in DFLUX is calculated as

$$q_s=\alpha\cdot(T_s-T_{bulk})$$

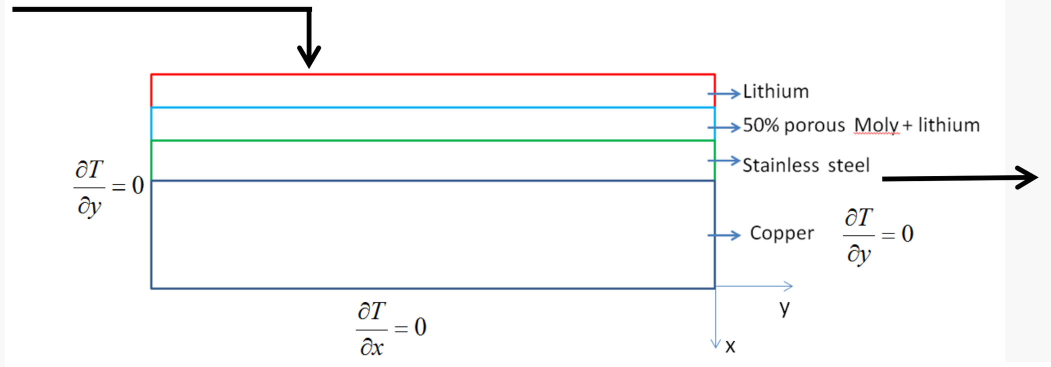
o Technique: Choose the α value to keep the energy deposition constant after discharge when q=0

Energy balance of Li enthalpy

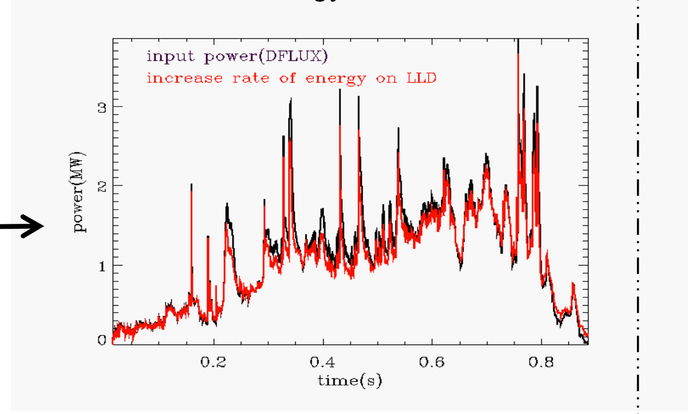
Divertor heat flux distribution on graphite



LLD model



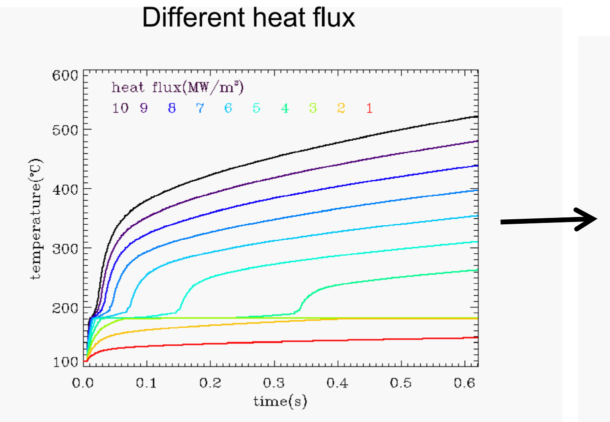
Energy balance

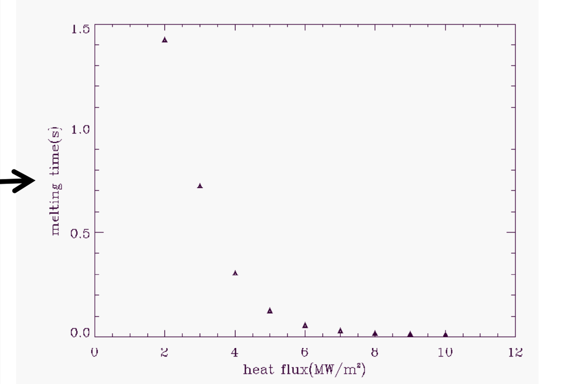


Analysis

Thermal response of the LLD under constant heat flux

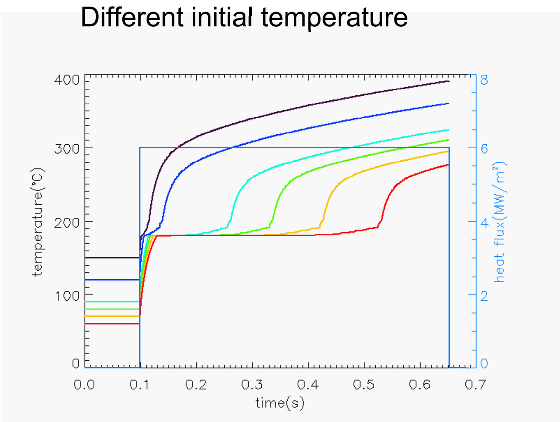
Different heat flux

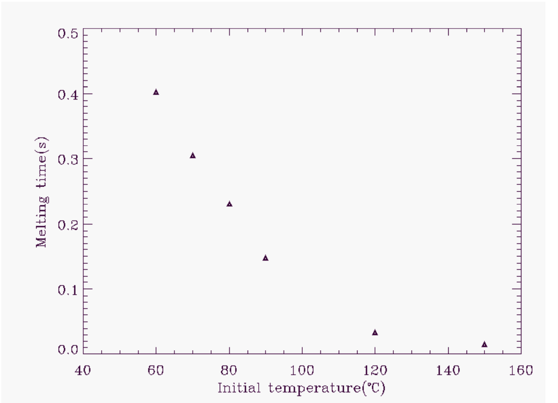




o The time of fusion will sharply increase with lower heat flux
o 126 ms for 5 MW/m² heat flux
o 11 ms for 10 MW /m² heat flux

Different initial temperature

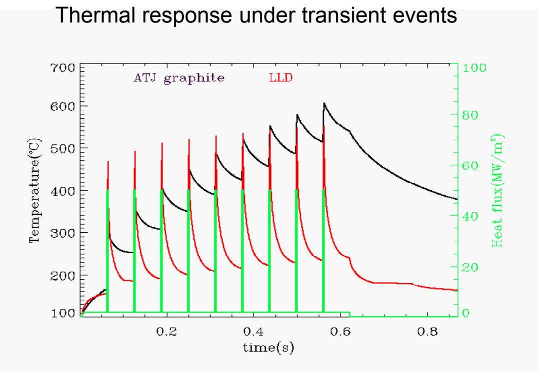




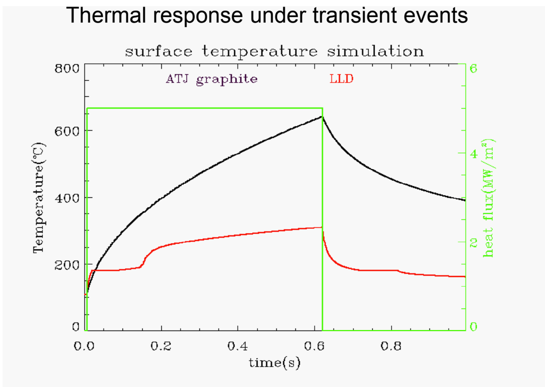
o The time of fusion will sharply increase with lower initial temperature
o 402 ms for 60° C initial temperature
o 15 ms for 150° C heat flux initial temperature

Thermal response comparison between the LLD and ATJ graphite

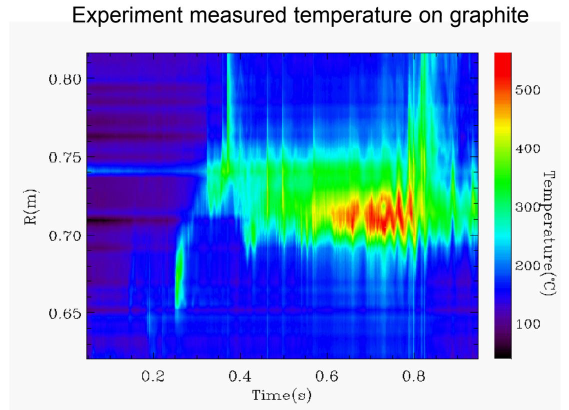
Thermal response under transient events



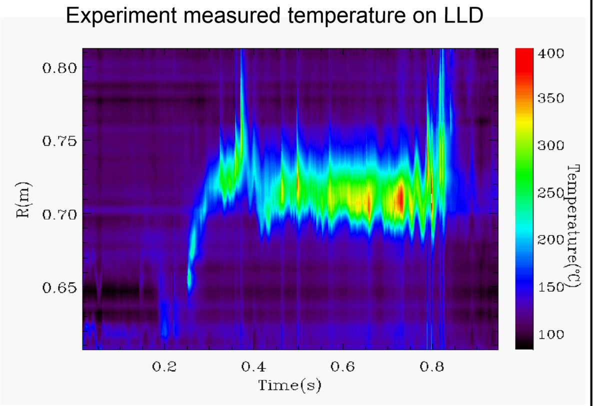
Thermal response under transient events



Experiment measured temperature on graphite



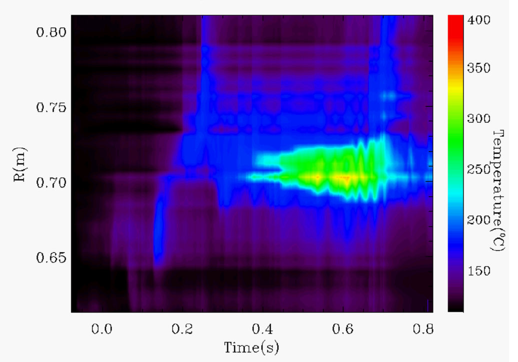
Experiment measured temperature on LLD



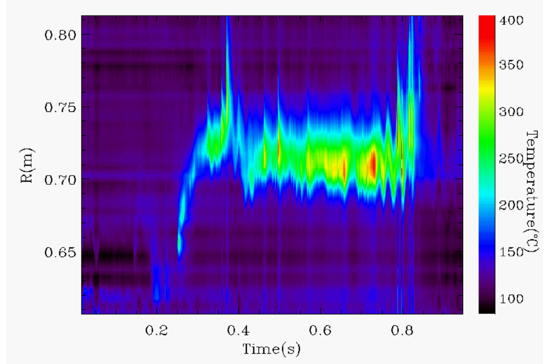
o The temperature on ATJ graphite increases faster than the LLD under steady state heat flux.
o However, the temperature increases faster on the LLD than on ATJ graphite under transient heat flux.
oThe temperature on LLD increase by about 300°C after 3 ms with 50 MW/m², heat flux, and only 100°C for ATJ graphite.
oThe peak temperature on the LLD will be higher than on graphite during an initial transient event, but smaller following the fast transient.
o Experimental data indicated the temperature on ATJ graphite is higher than LLD

Calculated temperature with different thickness of lithium compare with dual band IR data

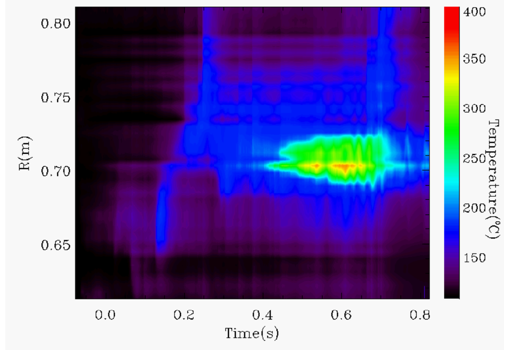
0.1mm



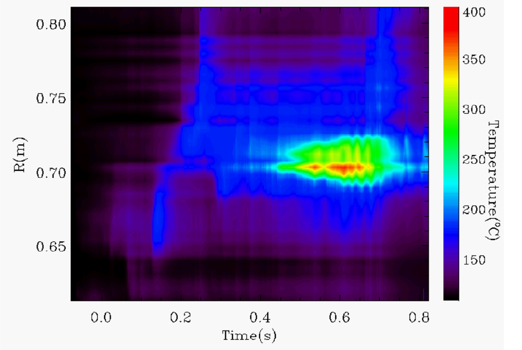
dual band IR data



0.2mm



0.4mm

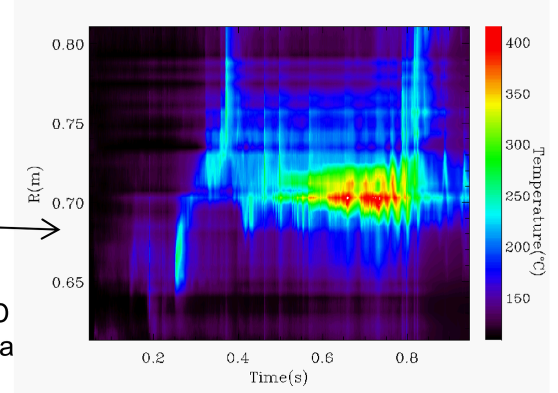


Consider a possible heat transmission Coefficient on LLD

Thermal response under transient events

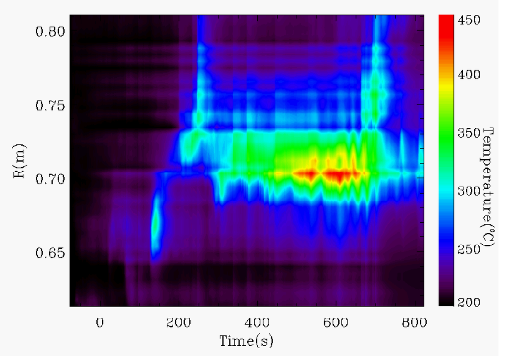
$$T_s=T_{Li\_enthalpy}+q/\alpha$$

α was set to 100k, the T_s is closer to the LLD temperature measured by dual-band IR camera



Another initial temperature for LLD management

The initial temperature was assumed to 200 °C, the lithium has been melted, project the same heat load to the LLD, the temperature of LLD will be More than 700k, which may be not good temperature range to control the recycling



Summary

υ The Li enthalpy code allow the temperature calculation with a phase change problem
υ A criteria to choose the α value: Modify α until the energy deposition with q=0 (after the discharge) is kept constant.
υ The temperature on the LLD if found to increase slower than graphite under steady state heat flux, and faster under transient heat flux.
υ The melting time decreases exponentially with increasing heat flux
υ The initial temperature on LLD significantly affect the melting time
υ The LLD surface temperature changes little with a variable thickness of lithium under a specific heat flux
o Beneficial since the Li layer thickness changes dynamically and is not measured
o It is necessary consider a heat transmission coefficient to make the T_s closer to the dual-band IR data.