



CryoModel: A Cryostat Thermal Performance Simulation Tool

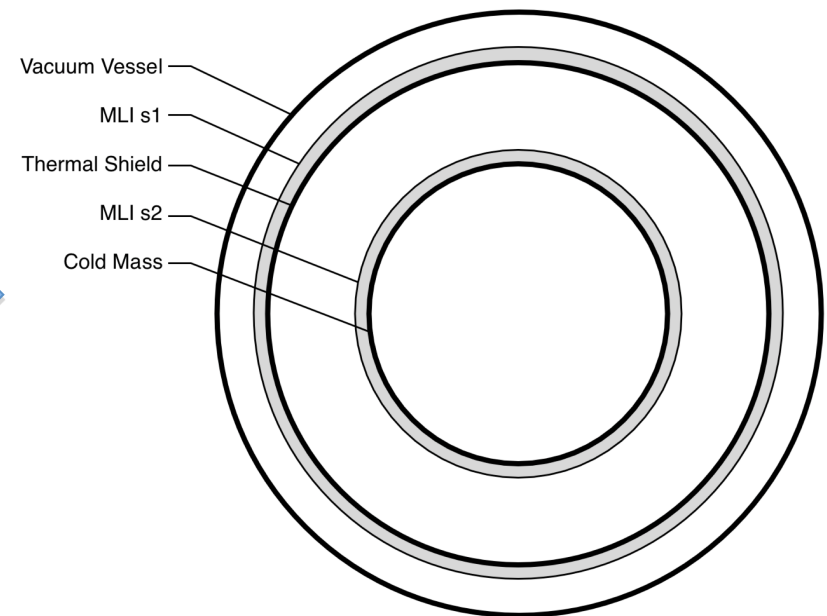
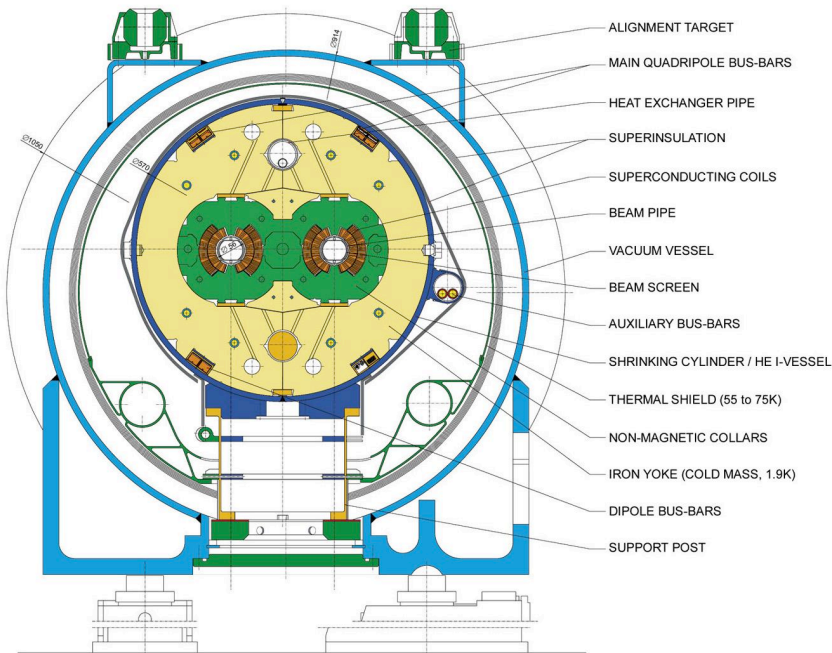
David Perez Caparros



Cryostat Thermal Model (I)

LHC DIPOLE : STANDARD CROSS-SECTION

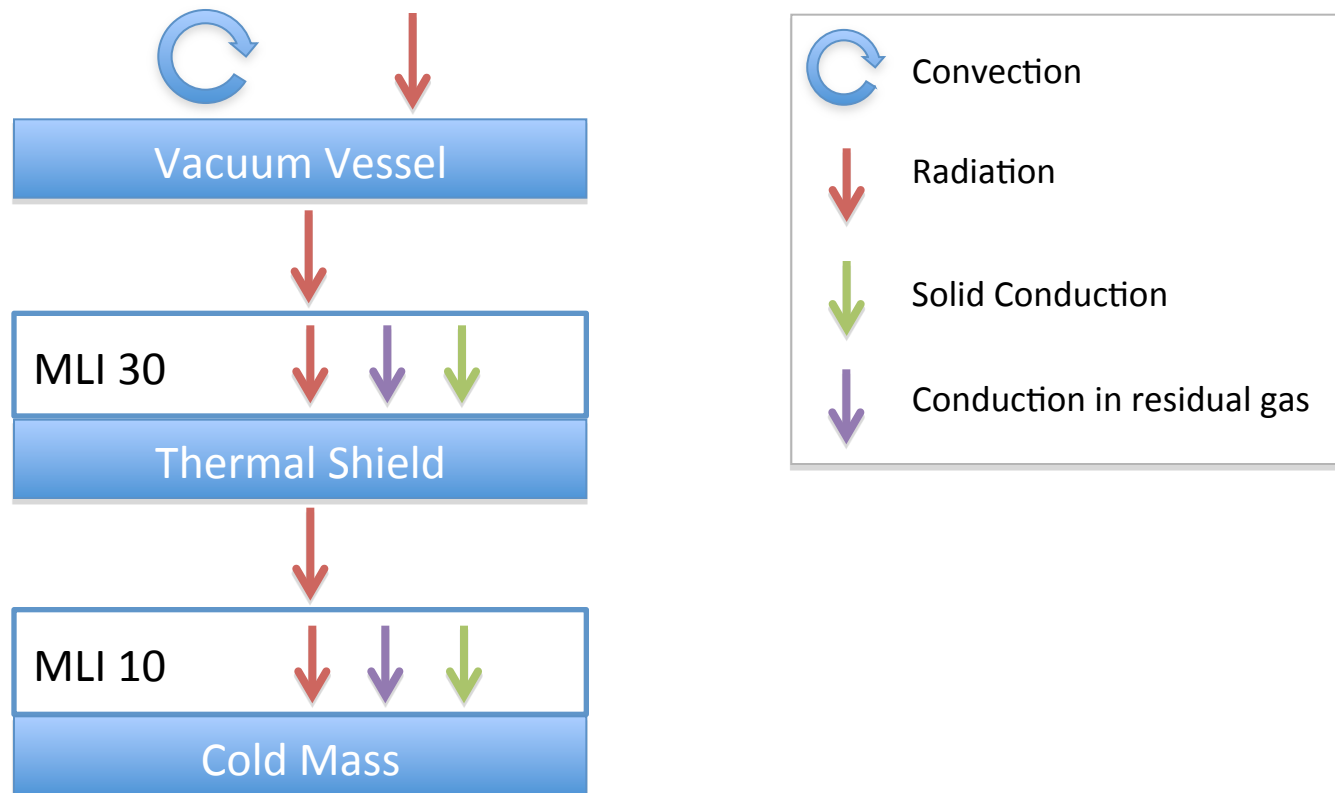
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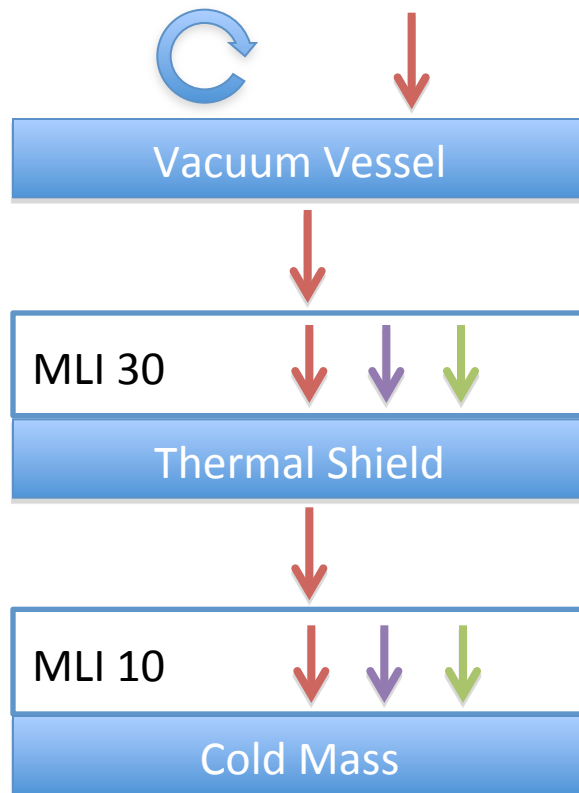
Cryostat Thermal Model (II)

Natural Warm-up





Mathematical Model (I)



$$\dot{Q}_{w,vv}(T_{vv}) = \dot{Q}_{rad} + \dot{Q}_{conv} = \sigma \bar{A}_{vv} E_1 (T_{wall}^4 - T_{vv}^4) + h_C \bar{A}_{vv} (T_{wall} - T_{vv})$$

$$\dot{Q}_{vv,s1}(T_{vv}, T_{s1}) = \dot{Q}_{rad} = \sigma \bar{A}_{s1} E_2 (T_{vv}^4 - T_{s1}^4)$$

$$\dot{Q}_{s1,ts}(T_{s1}, T_{ts}) = \dot{Q}_{vv,s1}(T_{vv}, T_{s1}) = \dot{Q}_{MLI30}$$

$$\dot{Q}_{ts,s2}(T_{ts}, T_{s2}) = \dot{Q}_{rad} = \sigma \bar{A}_{s2} E_3 (T_{ts}^4 - T_{s2}^4)$$

$$\dot{Q}_{s2,cm}(T_{s2}, T_{cm}) = \dot{Q}_{ts,s2}(T_{ts}, T_{s2}) = \dot{Q}_{MLI10}$$

σ : Stefan-Boltzmann constant

T : temperature [K]

Q : heat flux [W/m]

h_C : natural conv factor

E : emissivity factor

w : tunnel wall

vv : vacuum vessel

$s1$: MLI 30

ts : thermal shield

$s2$: MLI 10

cm : cold mass



Mathematical Model (II)

$$M_{vv} C_{p_{vv}} (T_{vv}) \frac{\partial T_{vv}}{\partial t} = \dot{Q}_{w,vv} (T_{vv}) - \dot{Q}_{vv,s1} (T_{vv}, T_{s1})$$
$$M_{ts} C_{p_{ts}} (T_{ts}) \frac{\partial T_{ts}}{\partial t} = \dot{Q}_{s1,ts} (T_{s1}, T_{ts}) - \dot{Q}_{ts,s2} (T_{ts}, T_{s2})$$
$$M_{cm} C_{p_{cm}} (T_{cm}) \frac{\partial T_{cm}}{\partial t} = \dot{Q}_{s2,cm} (T_{s2}, T_{cm})$$
$$\dot{Q}_{vv,s1} = \dot{Q}_{s1,ts}$$
$$\dot{Q}_{ts,s2} = \dot{Q}_{s2,cm}$$

M: mass [kg/m]

Cp: specific heat [J/(kg K)]

T: temperature [K]

Q: heat flux [W/m]

w: tunnel wall

vv: vacuum vessel

s1: MLI 30

ts: thermal shield

s2: MLI 10

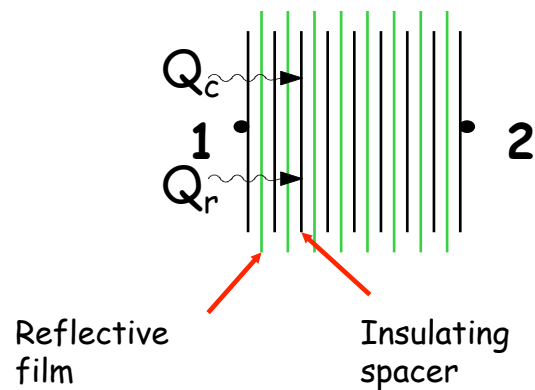
cm: cold mass



Heat Flux through MLI. Simple Model

$$\dot{q} = \frac{\alpha_S}{N_S} \frac{T_c + T_w}{2} (T_w - T_c) + \frac{\beta_S}{N_S} (T_w^4 - T_c^4)$$

N: number of reflective layers
 α : average thermal conductivity
 β : average emissivity



Model based on empirical data

LHC prototype cryostats at 10^{-4} Pa:

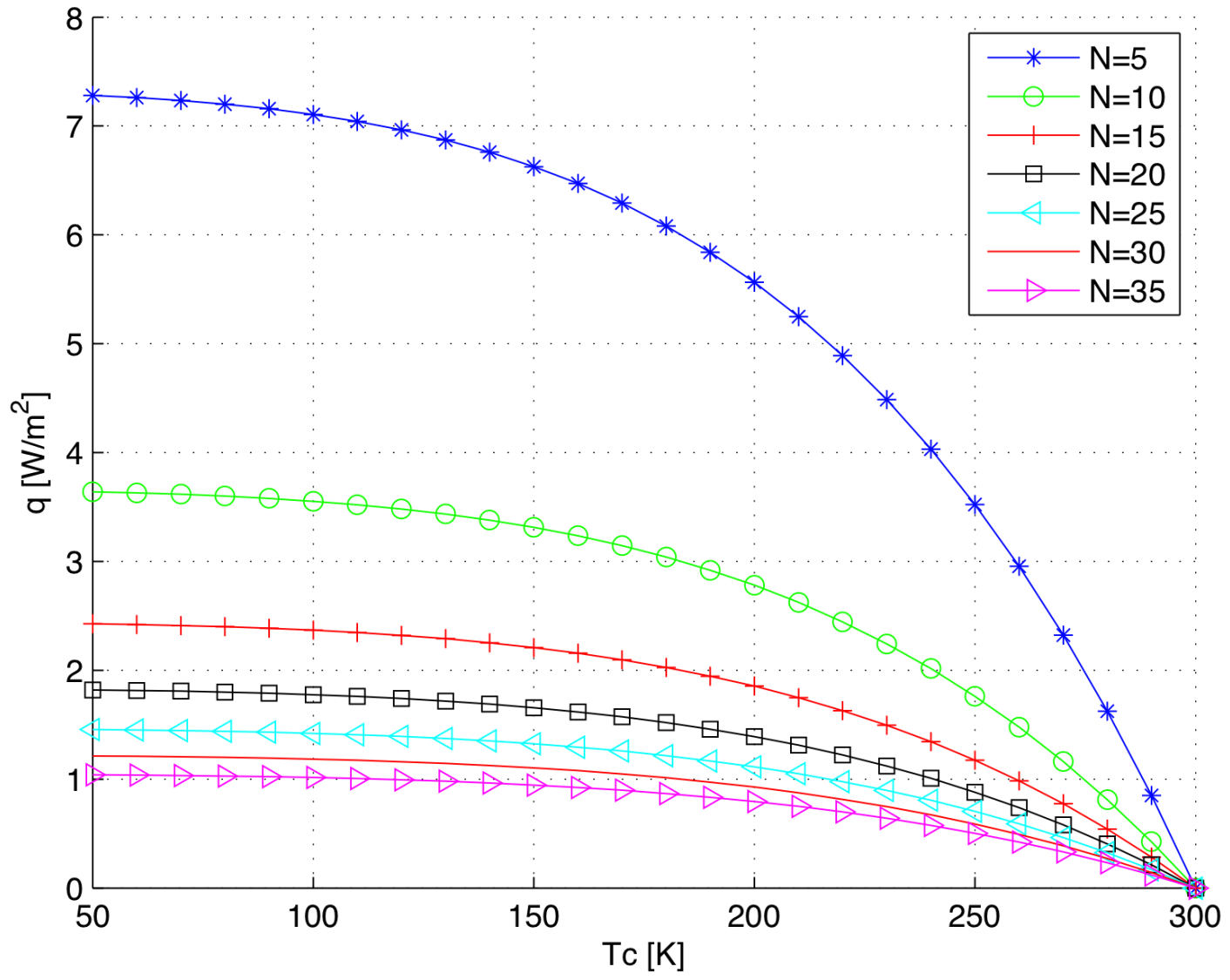
- 300-80K, MLI 30, $q=1.2$ W/m²
- 80-4.5K, MLI 10, $q=0.06$ W/m²

$$\alpha_S = 1.401 \cdot 10^{-4} [W / m^2 K^2]$$

$$\beta_S = 3.741 \cdot 10^{-9} [W / m^2 K^4]$$

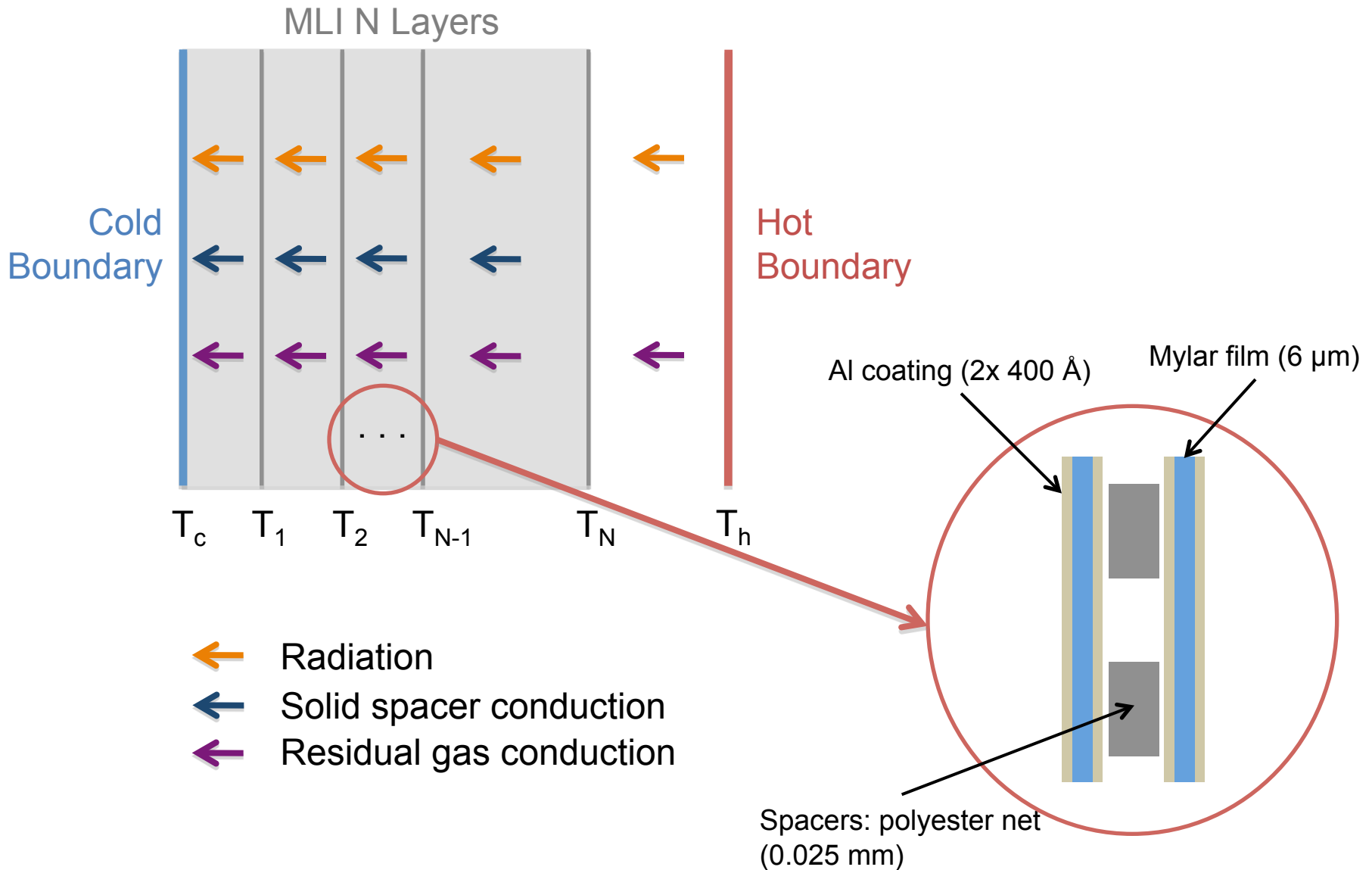


Calculated Heat Flux through MLI from 300K to T_c at 10^{-4} Pa



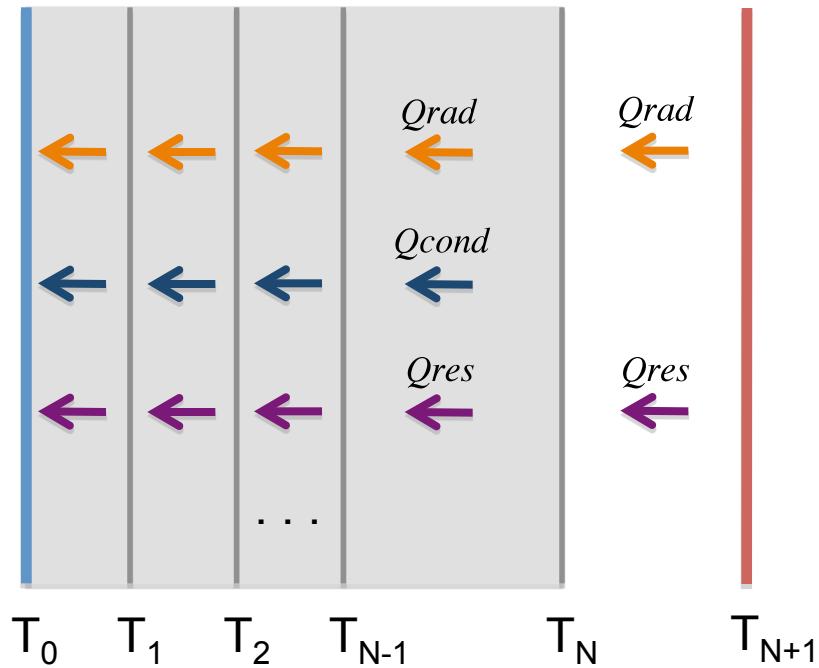


MLI structure and heat transfer scheme





MLI layer to layer model



Set of N+1 equations

N: number of MLI layers

$$\left\{ \begin{array}{l} \dot{Q} = \dot{Q}_{rad}_{1 \rightarrow 0} + \dot{Q}_{cond}_{1 \rightarrow 0} + \dot{Q}_{res}_{1 \rightarrow 0} \\ \dot{Q} = \dot{Q}_{rad}_{2 \rightarrow 1} + \dot{Q}_{cond}_{2 \rightarrow 1} + \dot{Q}_{res}_{2 \rightarrow 1} \\ \dot{Q} = \dot{Q}_{rad}_{3 \rightarrow 2} + \dot{Q}_{cond}_{3 \rightarrow 2} + \dot{Q}_{res}_{3 \rightarrow 2} \\ \dots \\ \dot{Q} = \dot{Q}_{rad}_{N \rightarrow N-1} + \dot{Q}_{cond}_{N \rightarrow N-1} + \dot{Q}_{res}_{N \rightarrow N-1} \\ \dot{Q} = \dot{Q}_{rad}_{N+1 \rightarrow N} + \dot{Q}_{res}_{N+1 \rightarrow N} \end{array} \right.$$



MLI layer to layer (I): Radiation

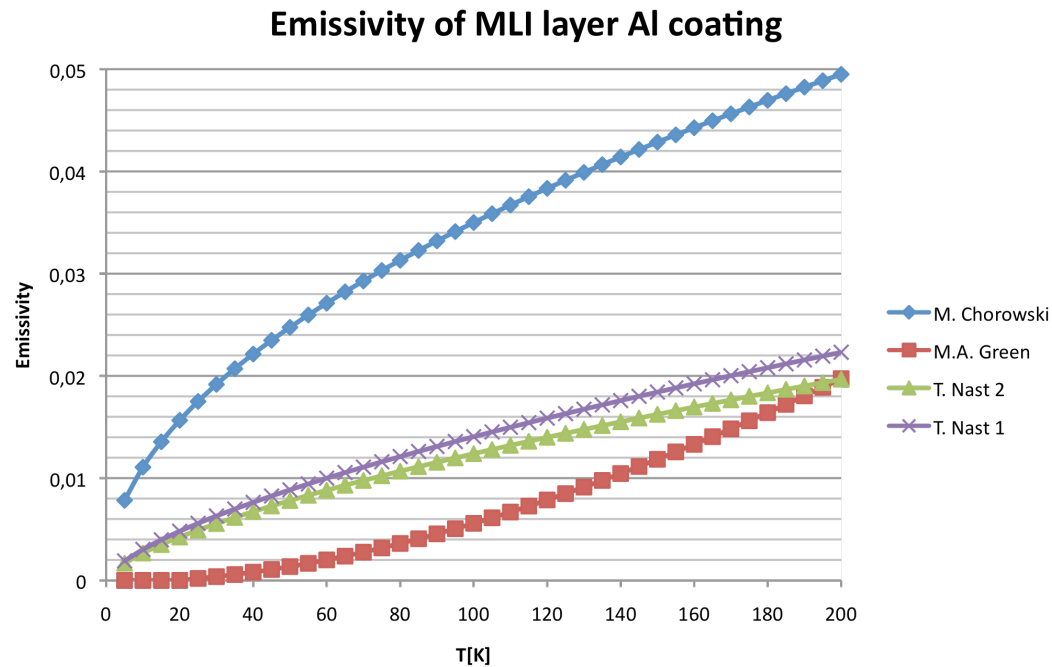
$$q_{rad} = \sigma \cdot E(\varepsilon, A) \cdot (T_h^4 - T_c^4) \quad [W / m^2]$$

σ : Stefan-Boltzmann constant

$E(\varepsilon, A)$: Emissivity factor

T_h : Hot boundary temperature [K]

T_c : Cold boundary temperature [K]





MLI layer to layer (II): Conduction in residual gas

$$q_{res} = \alpha \cdot \underbrace{\left(\frac{\gamma + 1}{\gamma - 1} \right) \left(\frac{R}{8\pi} \right)^{0.5} \frac{1}{(MT)^{0.5}}}_{\Omega} P (T_h - T_c) \quad [W / m^2]$$

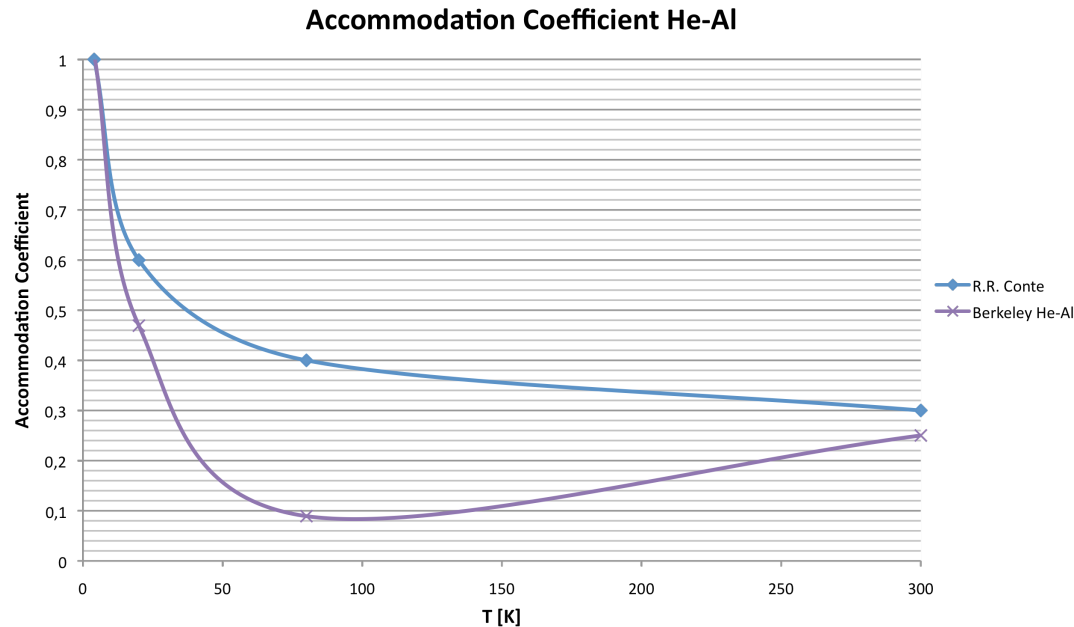
$\Omega=0.028$ (Helium gas)

α : Accommodation Coefficient

P : Residual gas pressure [Pa]

T_h : Hot boundary temperature [K]

T_c : Cold boundary temperature [K]





MLI layer to layer (III): Solid conduction through spacers

$$q_{cond} = \frac{k_s}{t} \cdot (T_h - T_c) \quad [W / m^2]$$

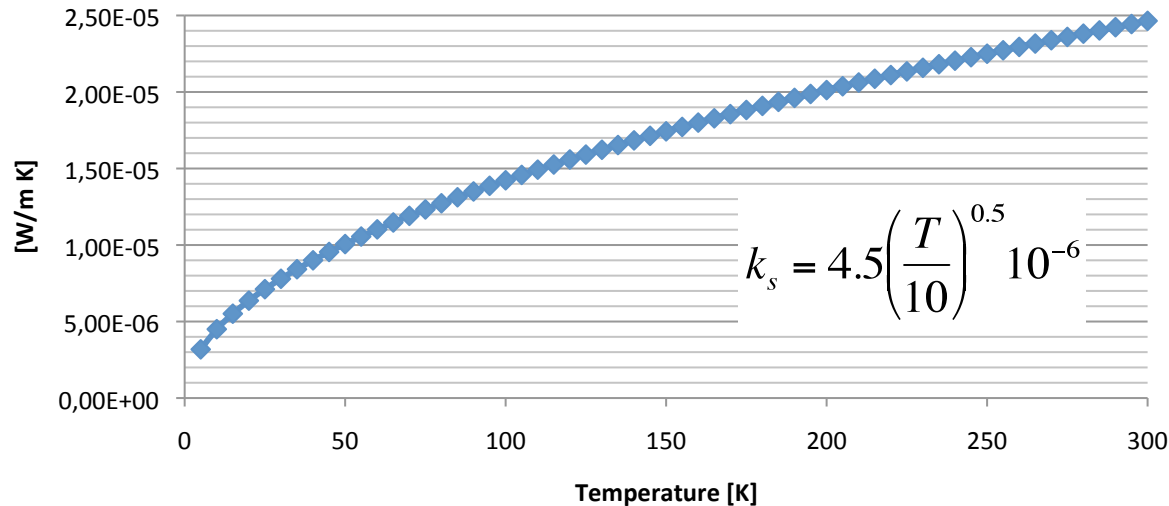
k_s : Effective spacer thermal conductivity [W/m K]

t : Spacer thickness [m]

T_h : Hot boundary temperature [K]

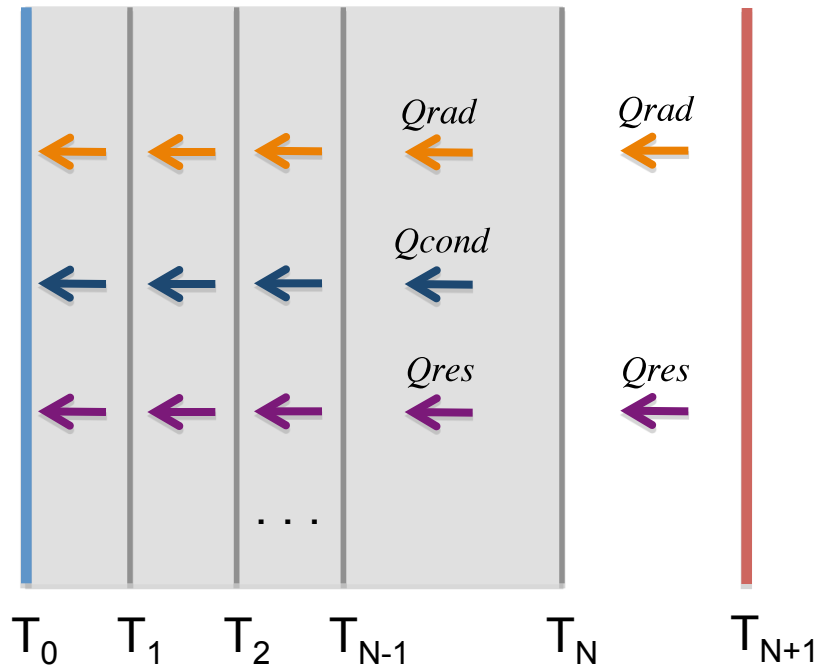
T_c : Cold boundary temperature [K]

Fiberglass Spacer Effective Thermal Conductivity





MLI layer to layer model



Set of N+1 equations

N: number of MLI layers

$$\left\{ \begin{array}{l} \dot{Q} = \dot{Q}_{rad_{1 \rightarrow 0}} + \dot{Q}_{cond_{1 \rightarrow 0}} + \dot{Q}_{res_{1 \rightarrow 0}} \\ \dot{Q} = \dot{Q}_{rad_{2 \rightarrow 1}} + \dot{Q}_{cond_{2 \rightarrow 1}} + \dot{Q}_{res_{2 \rightarrow 1}} \\ \dot{Q} = \dot{Q}_{rad_{3 \rightarrow 2}} + \dot{Q}_{cond_{3 \rightarrow 2}} + \dot{Q}_{res_{3 \rightarrow 2}} \\ \dots \\ \dot{Q} = \dot{Q}_{rad_{N \rightarrow N-1}} + \dot{Q}_{cond_{N \rightarrow N-1}} + \dot{Q}_{res_{N \rightarrow N-1}} \\ \dot{Q} = \dot{Q}_{rad_{N+1 \rightarrow N}} + \dot{Q}_{res_{N+1 \rightarrow N}} \end{array} \right.$$



Mathematical Model

$$M_{vv} C_{p_{vv}} (T_{vv}) \frac{\partial T_{vv}}{\partial t} = \dot{Q}_{w,vv} (T_{vv}) - \dot{Q}_{vv,s1} (T_{vv}, T_{s1})$$
$$M_{ts} C_{p_{ts}} (T_{ts}) \frac{\partial T_{ts}}{\partial t} = \dot{Q}_{s1,ts} (T_{s1}, T_{ts}) - \dot{Q}_{ts,s2} (T_{ts}, T_{s2})$$
$$M_{cm} C_{p_{cm}} (T_{cm}) \frac{\partial T_{cm}}{\partial t} = \dot{Q}_{s2,cm} (T_{s2}, T_{cm})$$
$$\dot{Q}_{vv,s1} = \dot{Q}_{s1,ts}$$
$$\dot{Q}_{ts,s2} = \dot{Q}_{s2,cm}$$

M: mass [kg/m]

Cp: specific heat [J/(kg K)]

T: temperature [K]

Q: heat flux [W/m]

w: tunnel wall

vv: vacuum vessel

s1: MLI 30

ts: thermal shield

s2: MLI 10

cm: cold mass



Matlab Application. MLIGUI (I)

MLI model

Geometry

Hot Boundary Diameter [m]:

Cold Boundary Diameter [m]:

MLI

Number of MLI layers:

Spacer conductivity [W/m K]:

Spacer thickness [m]:

Hot Boundary emissivity:

Cold Boundary emissivity:

MLI film emissivity:

Test Conditions

Hot Boundary Temperature [K]:

Cold Boundary Temperature [K]:

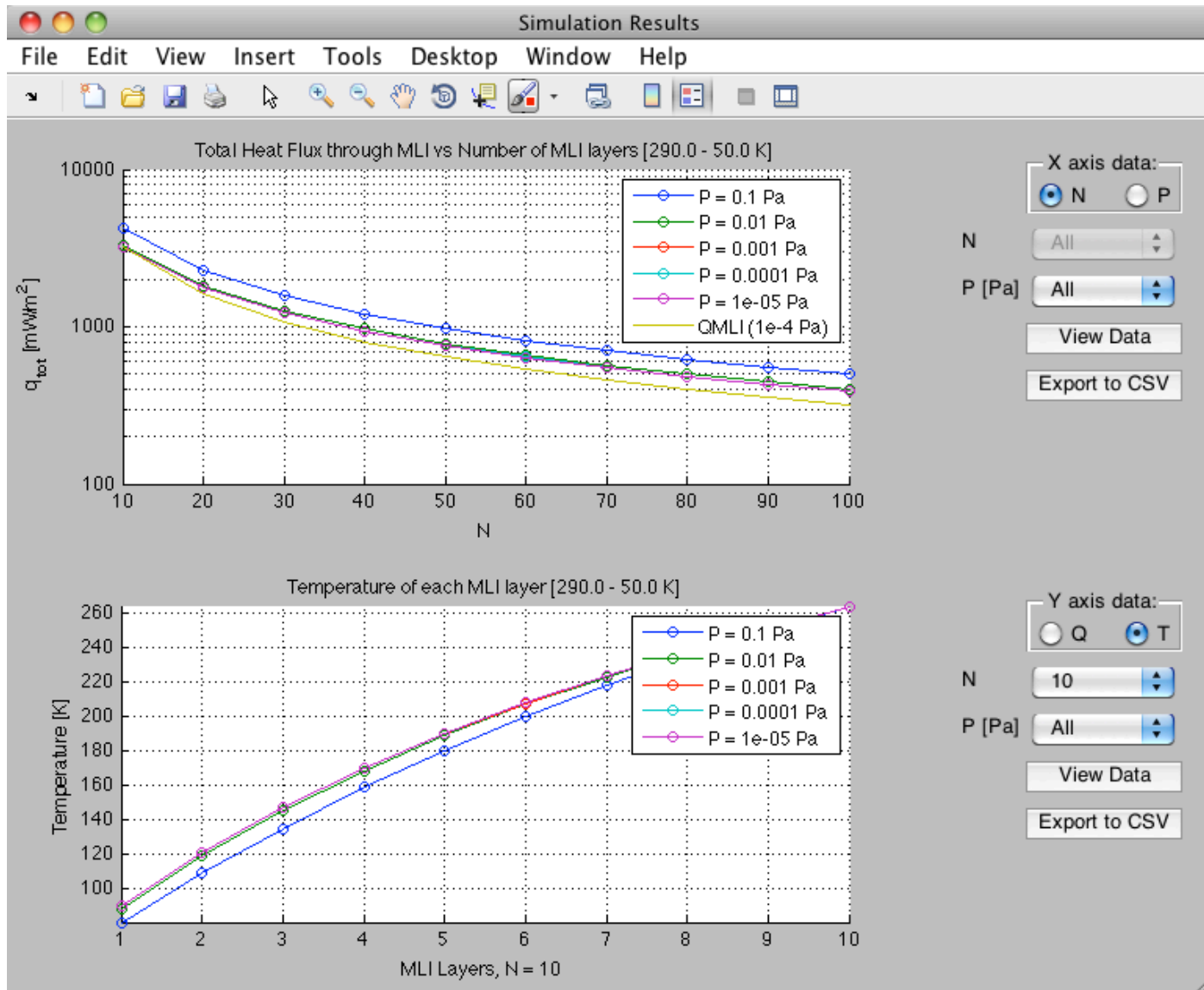
Residual Gas Pressure [Pa]:

Calculate

— Hot Boundary T=290.0 K
- - - MLI N=10
— Cold Boundary T=50.0 K

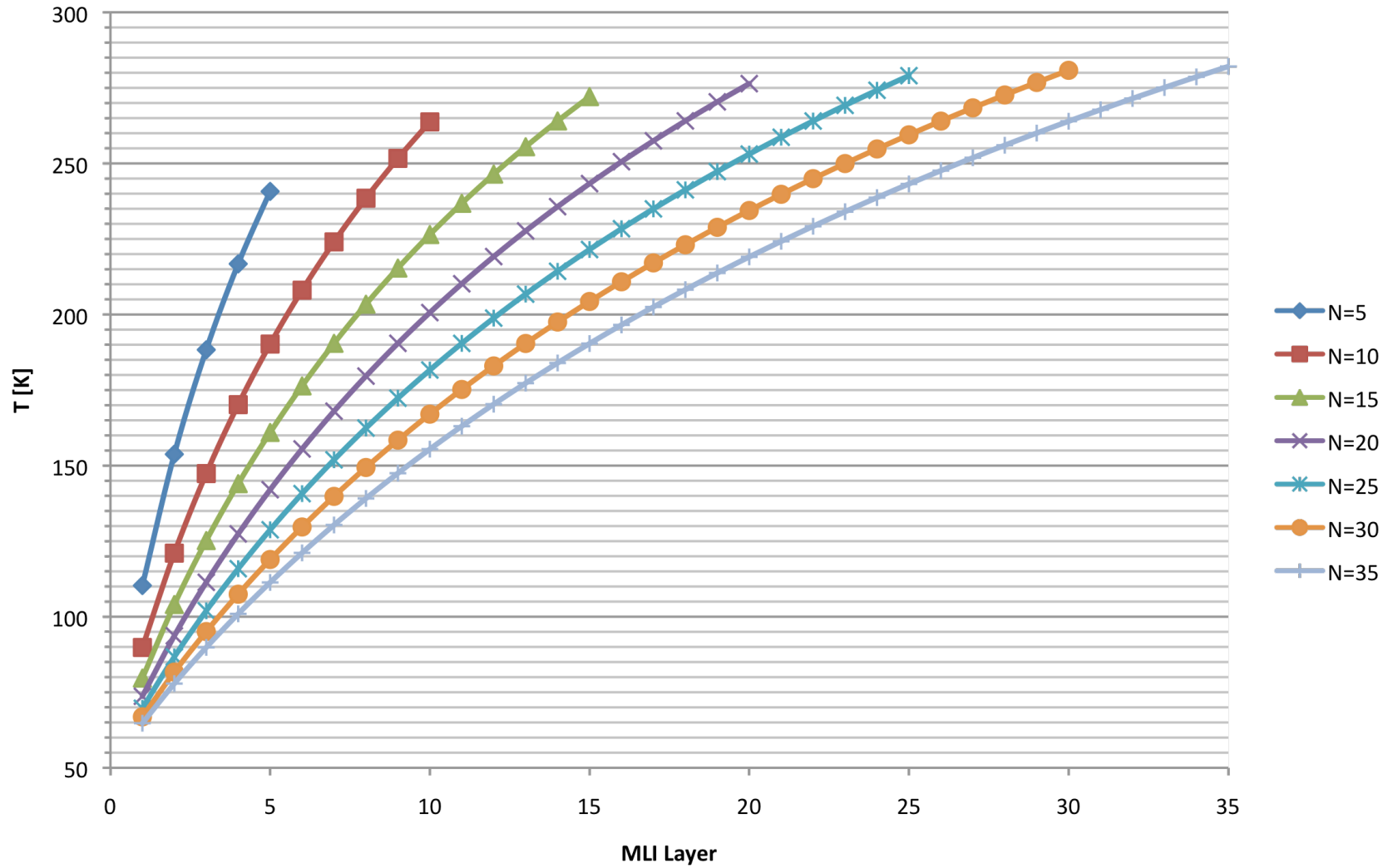


Matlab Application. MLIGUI (II)





Temperature of MLI layers [290K - 50K]





Matlab Application. CryoModel (I)

Cryostat Thermal Performance

File Edit View Insert Tools Desktop Window Help

Geometry

Tunnel Diameter [m]: 4 Thermal Shield Diameter [m]: 0.78
Vacuum Vessel Diameter [m]: 0.914 Cold Mass Diameter [m]: 0.57

Insulation

Number of layers MLI s1: 30 Number of layers MLI s2: 10
Spacer thickness MLI s1 [m]: 0.0003 Spacer thickness MLI s2 [m]: 0.0003
MLI shield emissivity: 0.0035*T^{0.5}
 Use layer to layer MLI model
Spacer conductivity s1 [W/m K]: 4.5*((T/10)^{0.5})*1e-6
Spacer conductivity s2 [W/m K]: 4.5*((T/10)^{0.5})*1e-6

Materials

Cold Mass Thermal Shield Vacuum Vessel

Iron [1566 kg/m]
304 Stainless Steel [163 kg/m]
Helium [4 kg/m]
OFCH Copper [82.52 kg/m]

1100 Aluminium [kg/m]
Add Remove

Simulation Parameters

Sim Time: 90 Days
 Apply time scaling
Frequency: 1 Day
Algorithm: AVG

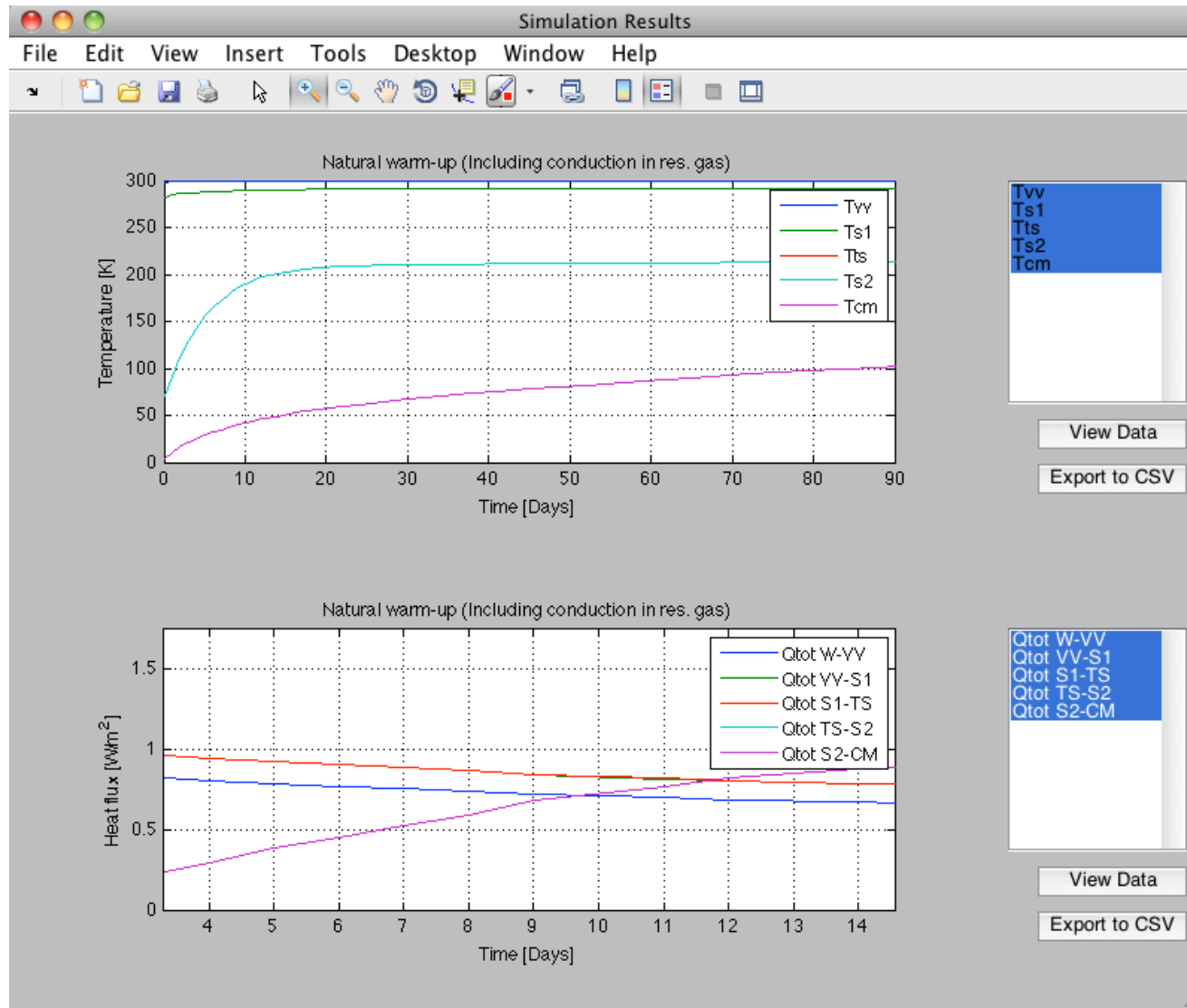
Initial Values and Conditions

Temperature of Tunnel Wall [K]: 300
Initial value of Vacuum Vessel Temp. [K]: 294
Initial value of Thermal Shield Temp. [K]: 65
Initial value of Cold Mass Temp. [K]: 1.9
Pressure [Pa]: 0.0001

Start Simulation

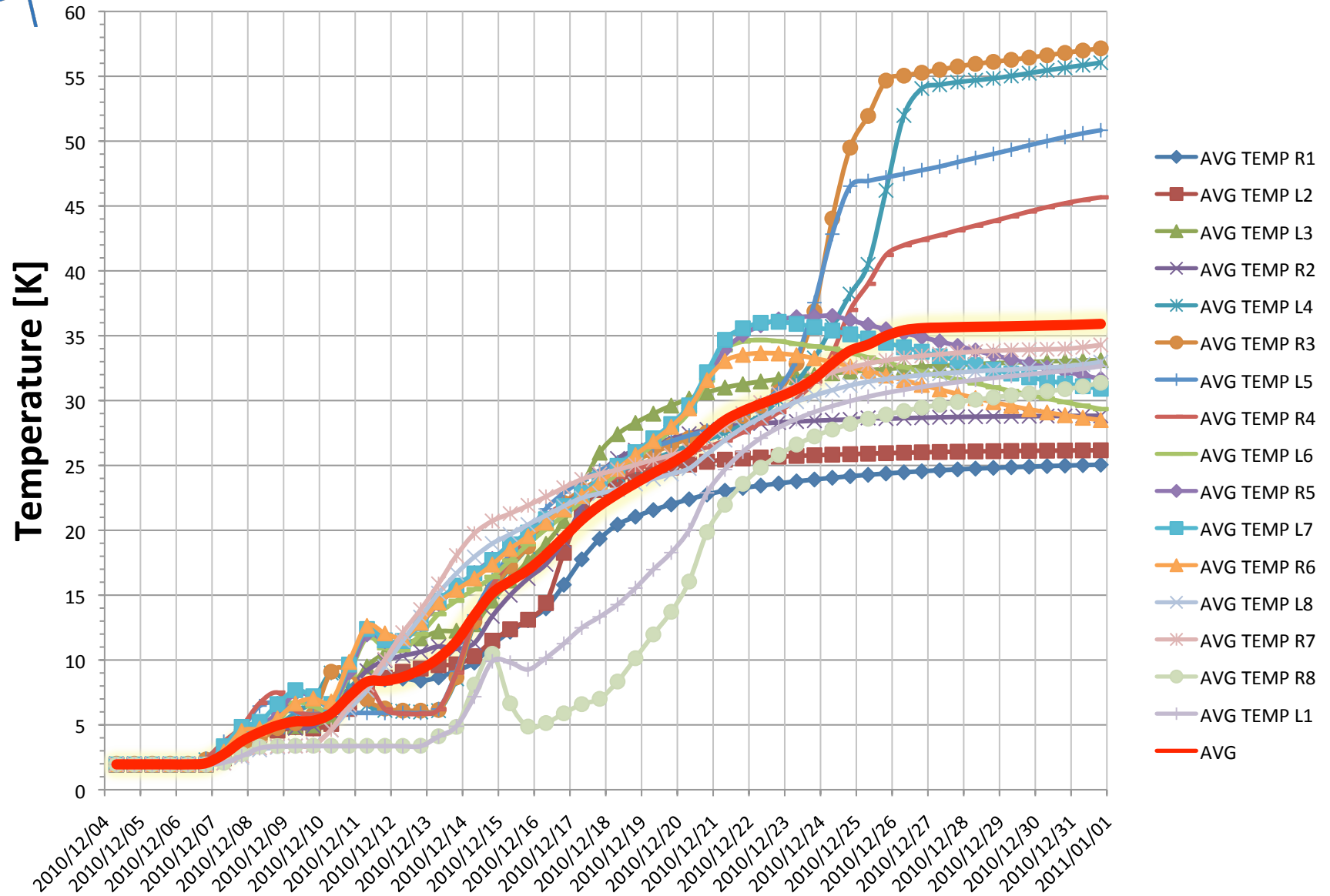


Matlab Application. CryoModel (II)



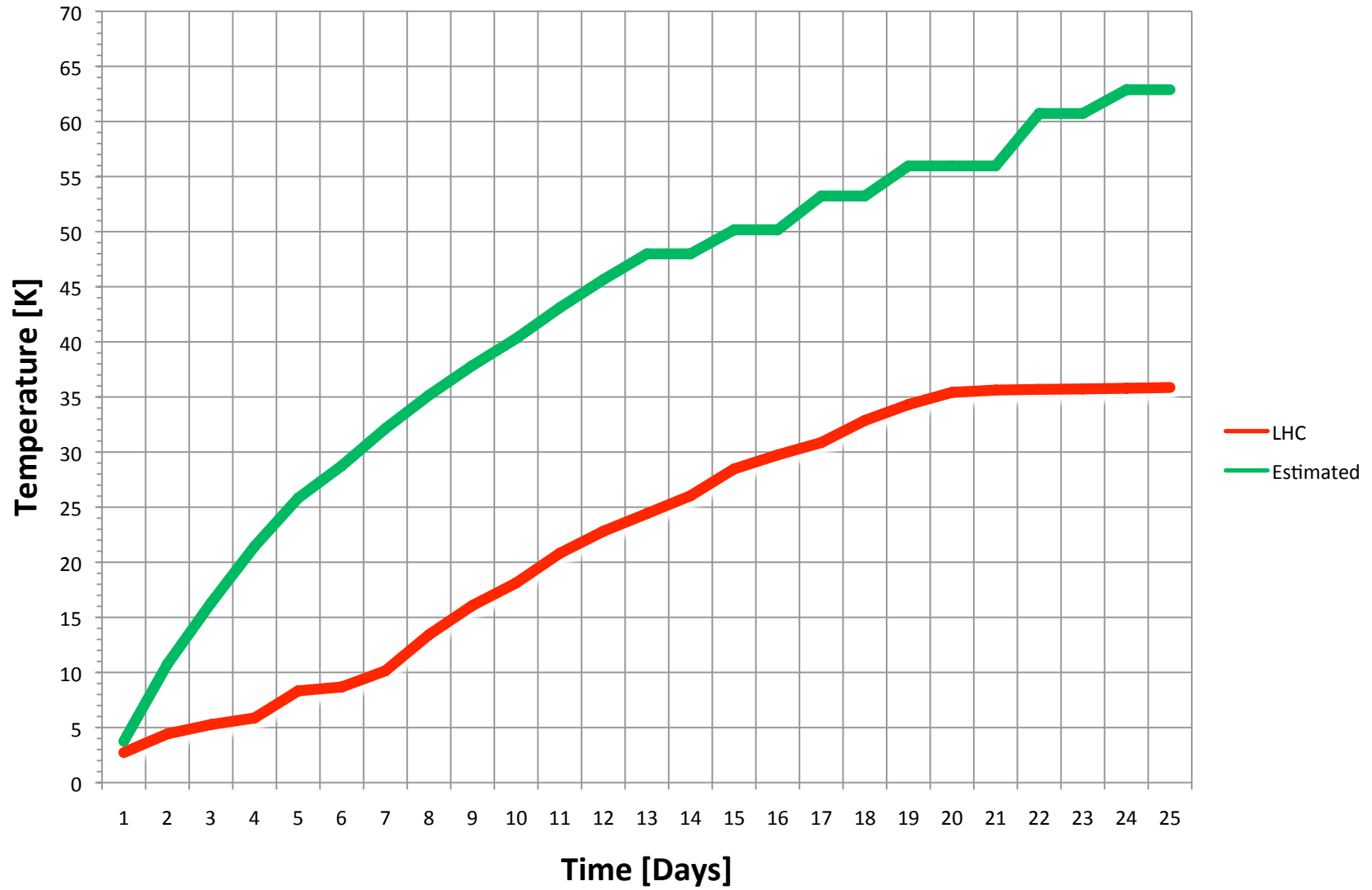


LHC AVG COLD MASS TEMPs WINTER SHUT-DOWN (2010)





Cold Mass Temperature: Estimated vs LHC data





Demo



Q&A