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CERN HSE Occupational Health & Safety and Environmental Protection unit

KIT Karlsruhe Institute of Technology

Measurement of heat flux in multi-layer insulated helium cryostats after loss of insulating vacuum

C1Or2A-07 – Applications: Safety and Instrumentation

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Outline

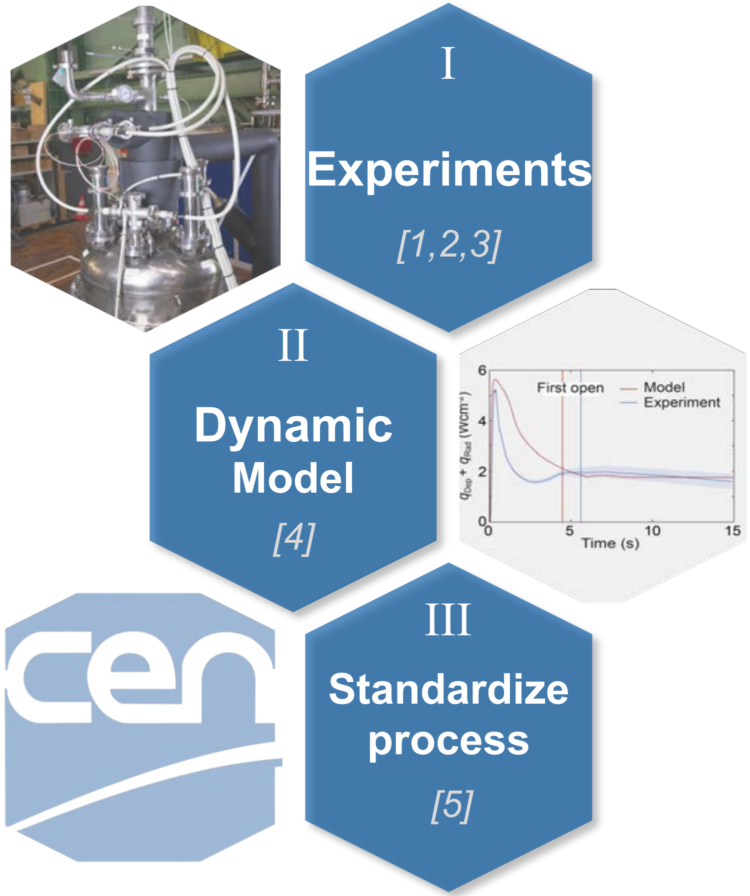
- Motivation
- Experimental setup
- Heat transfer mechanism
- Results & Discussion
- Summary & Outlook

PICARD

Pressure Increase in Cryostats and Analysis of Relief Devices

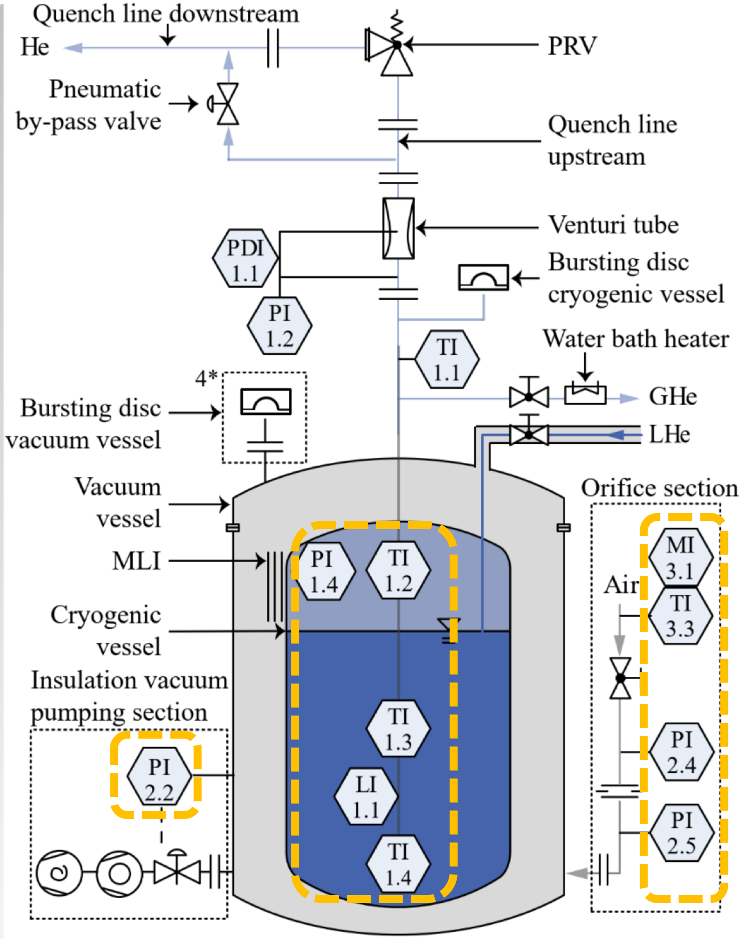
Motivation

- Profound understanding of the dimensioning process of Pressure Relief Devices (PRD)
  - Thermodynamic process tailored to the application;
  - Uniform & detailed understanding of heat transfer mechanisms.
- Compare with existing data for continuous improvement of the 'state-of-the-art'
- Emphasis on heat flux in multi-layer insulated (MLI) helium cryostats after loss of insulating vacuum (LIV)

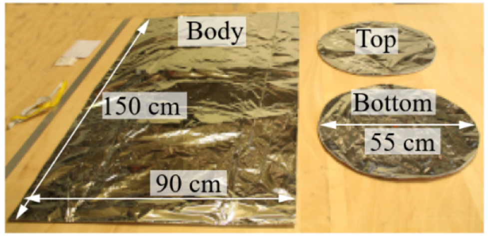


Experimental setup

PICARD P&ID



MLI Installation



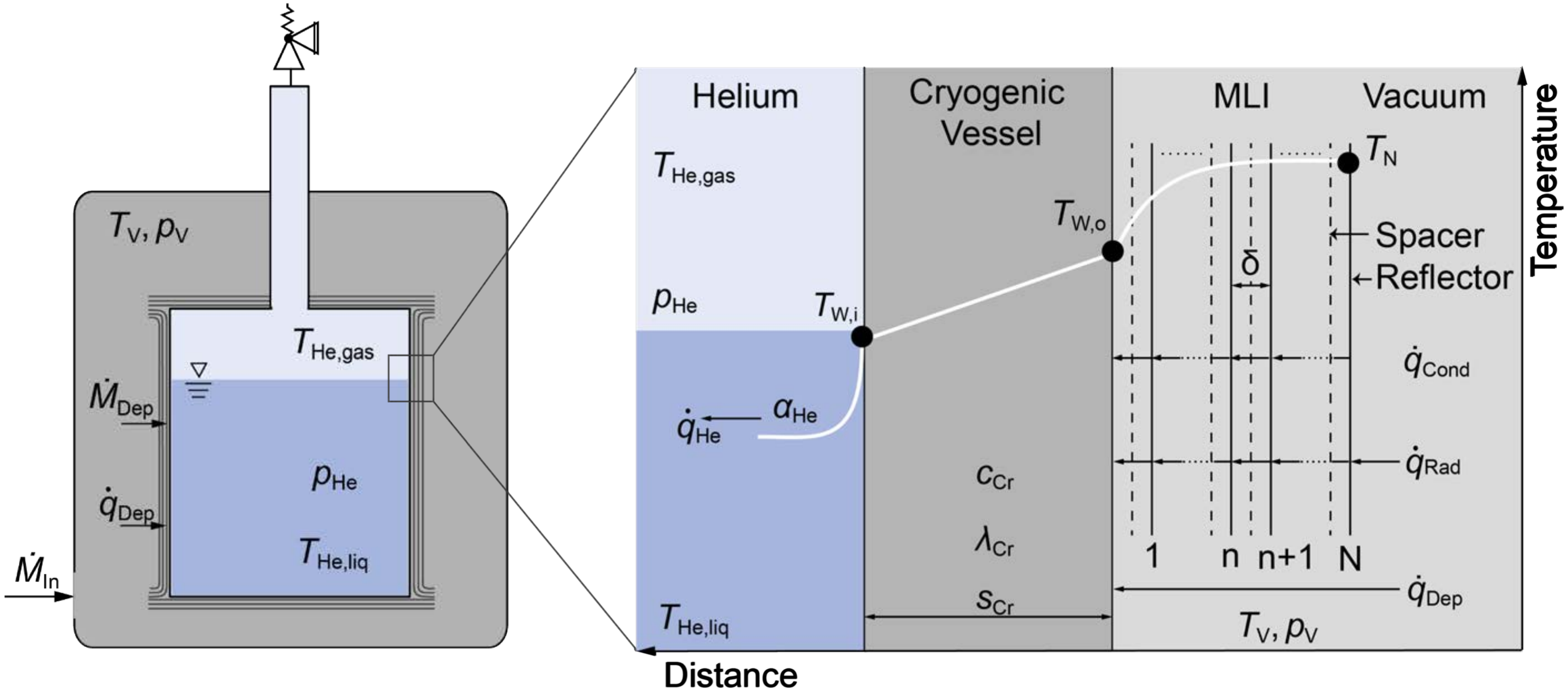
Characteristics

Type	N_{Layer}	Thickness (µm)		Perforation holes (mm)	
		δ_R	δ_S	ϕ	Grid
1	12	6	55	2	50
2	1	18	-	6	200
3	10	12	55	4	150

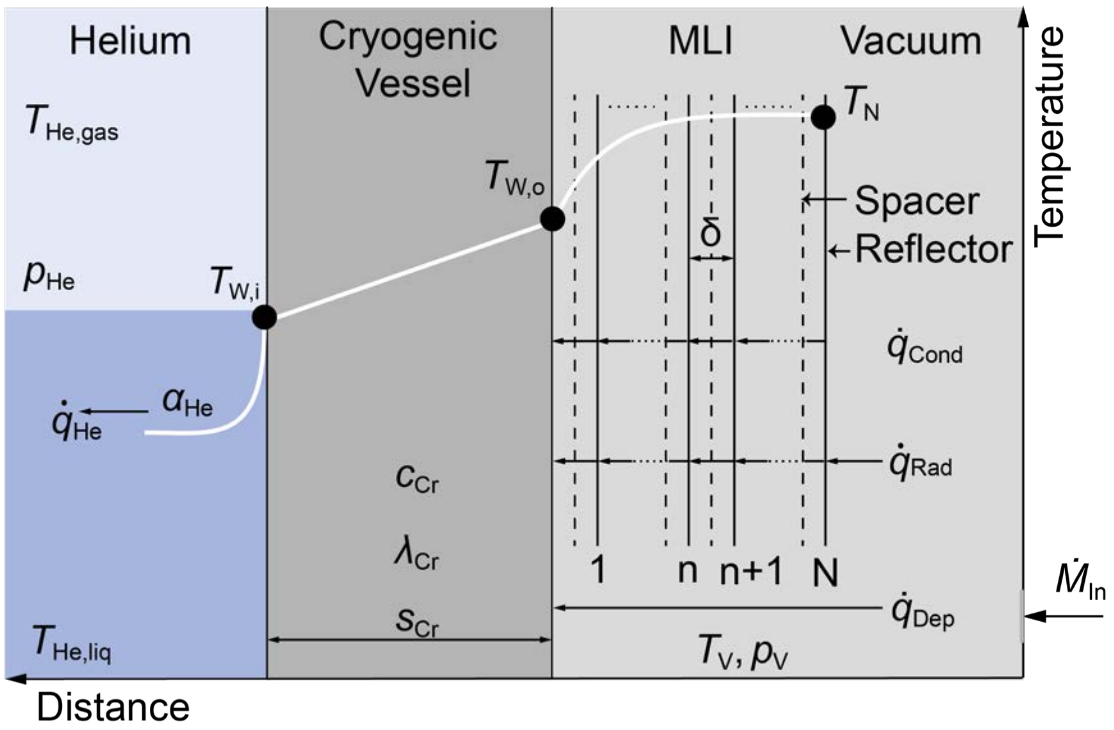
Layer density: 10 cm^{-1}

Thermal bridges warm-cold layers avoided using aluminum adhesive

Heat transfer mechanism



Heat transfer mechanism



1D heat transfer equation for cryogenic wall temperature ($T_{w,i}$ & $T_{w,o}$)

- Deposition heat flux : Enthalpy balance – $f(\dot{M}_{in}, p_v)$
- Thermal radiation : Stefan-Boltzmann equation
- Thermal conduction MLI : Fourier equation (radial)
- Thermal conduction wall : Fourier equation
- Heat transfer in helium : Convective heat transfer

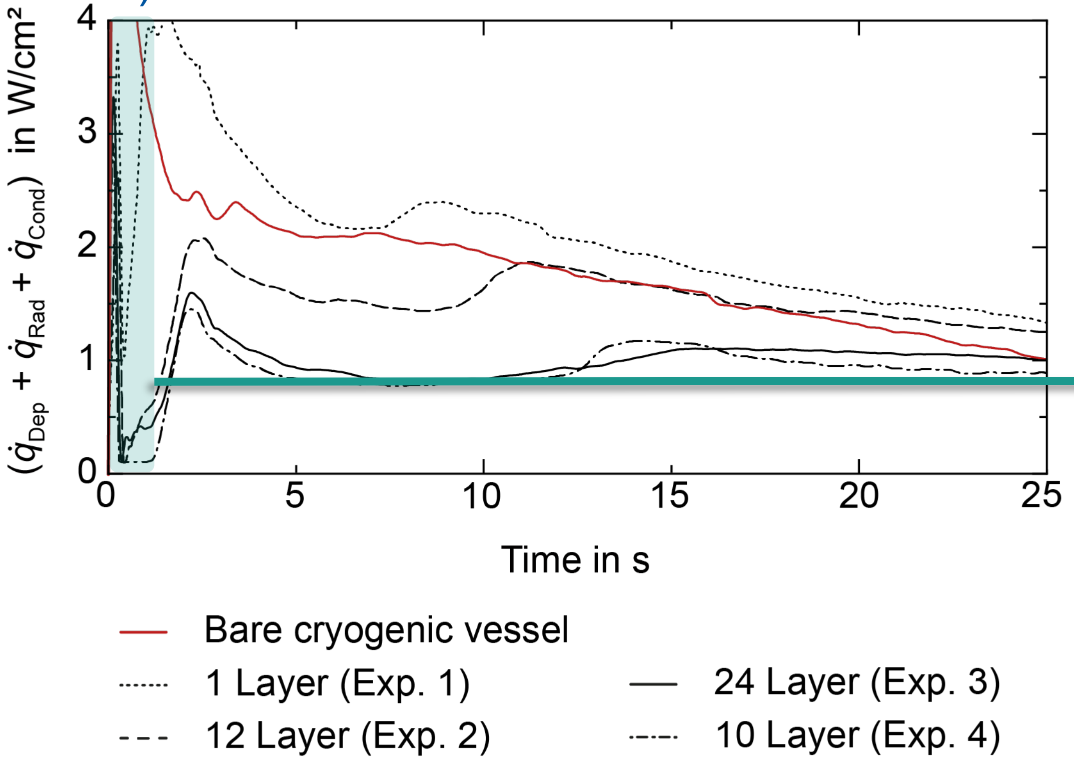
Note:

- Vacuum vessel: Convective heat transfer neglected due to low Grashof numbers
- Deposition: Solid air enthalpies included (ideal mixture of N_2, O_2, Ar, and water)

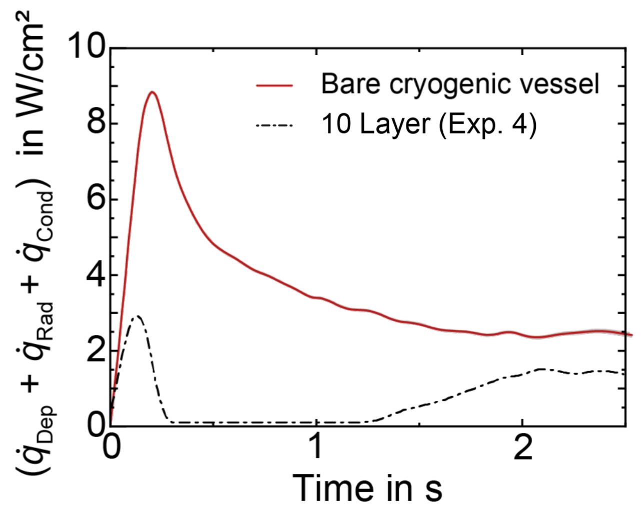
Results – Heat Flux

Vacuum

1)



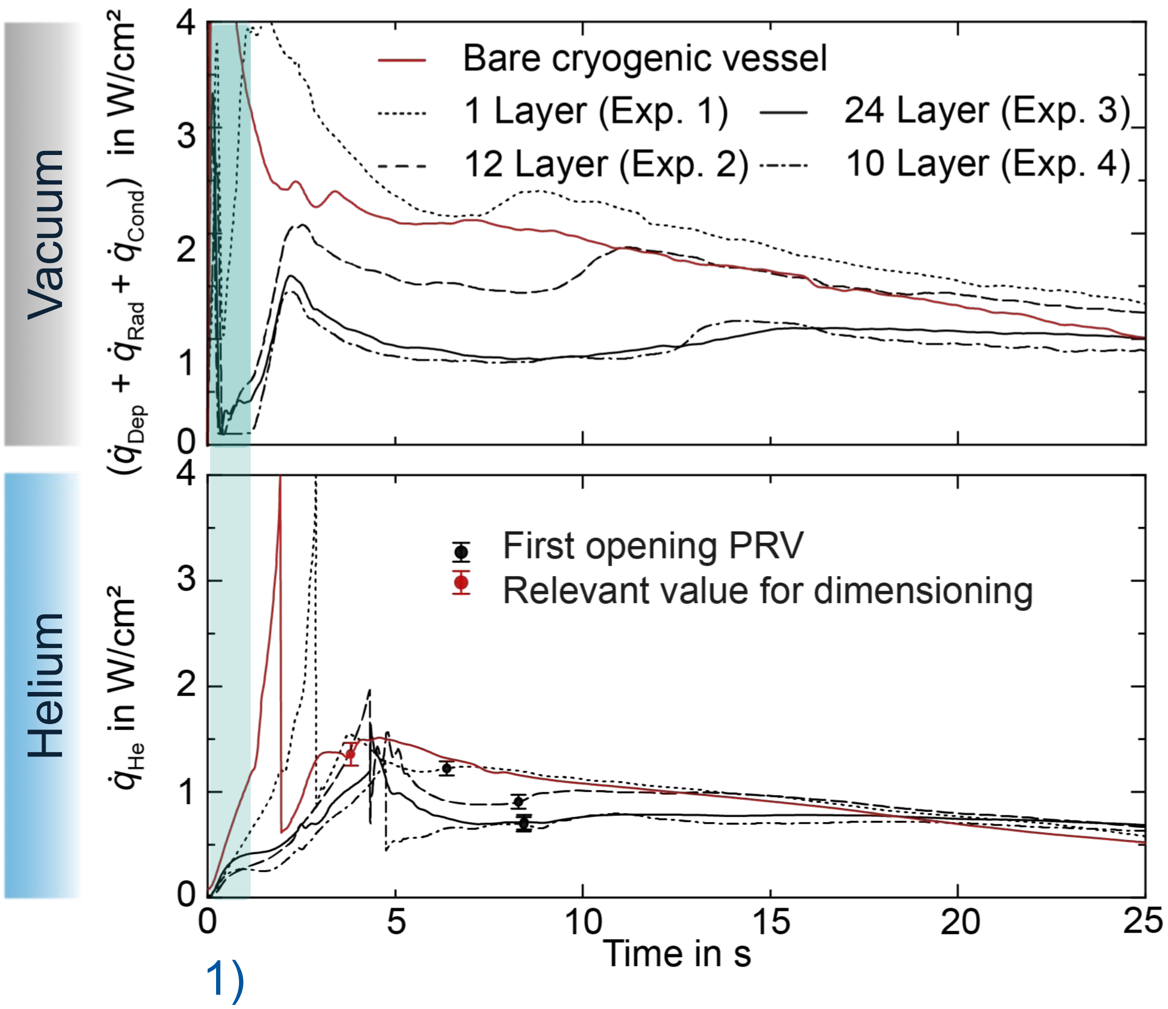
Zoom



Plot shape (MLI Experiments):

1) Influence on the flow resistance of the MLI blanket

Results – Heat Flux



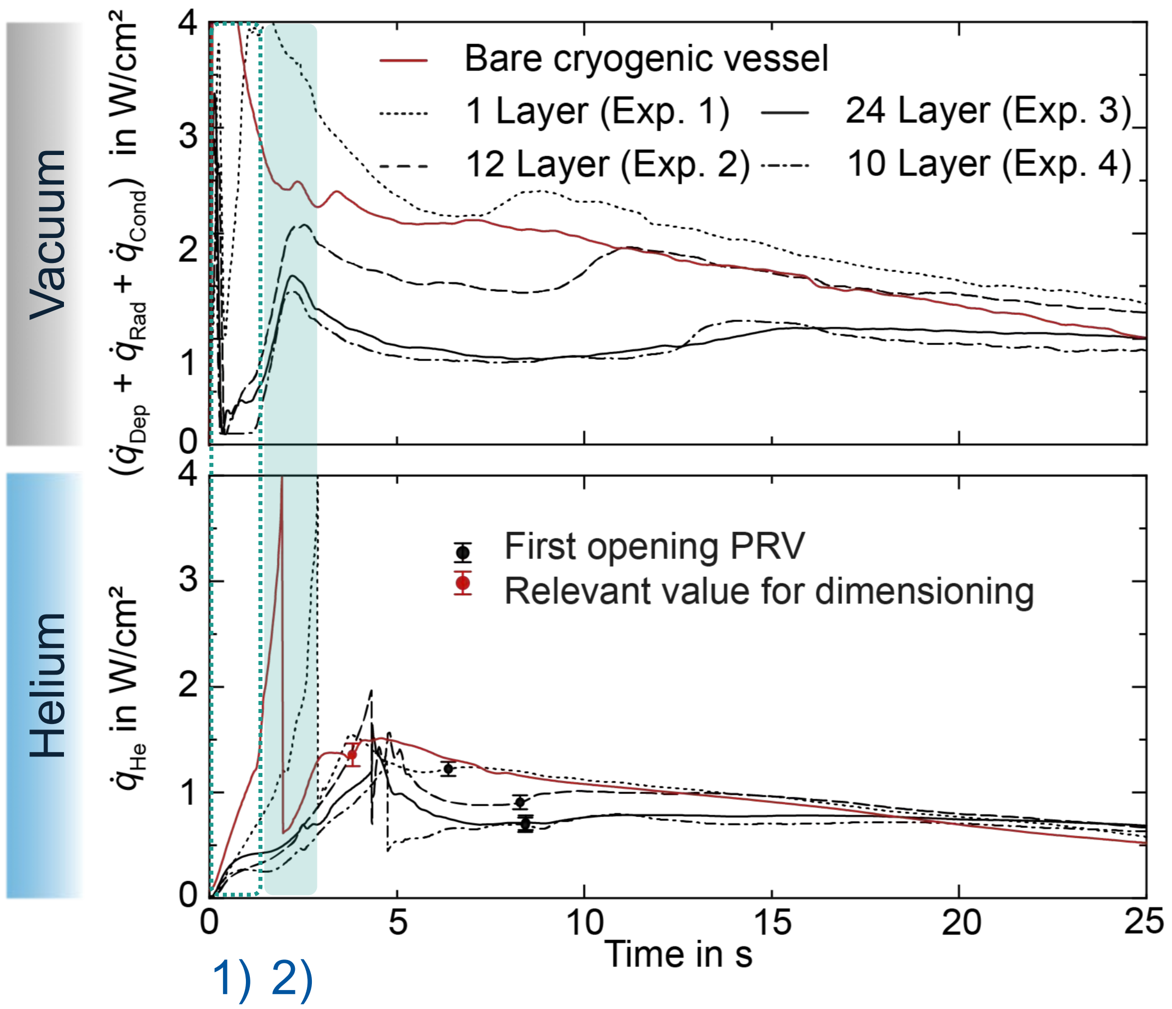
Plot shape (Vacuum space):

1) Influence on the flow resistance of the MLI blanket

Plot shape (Helium):

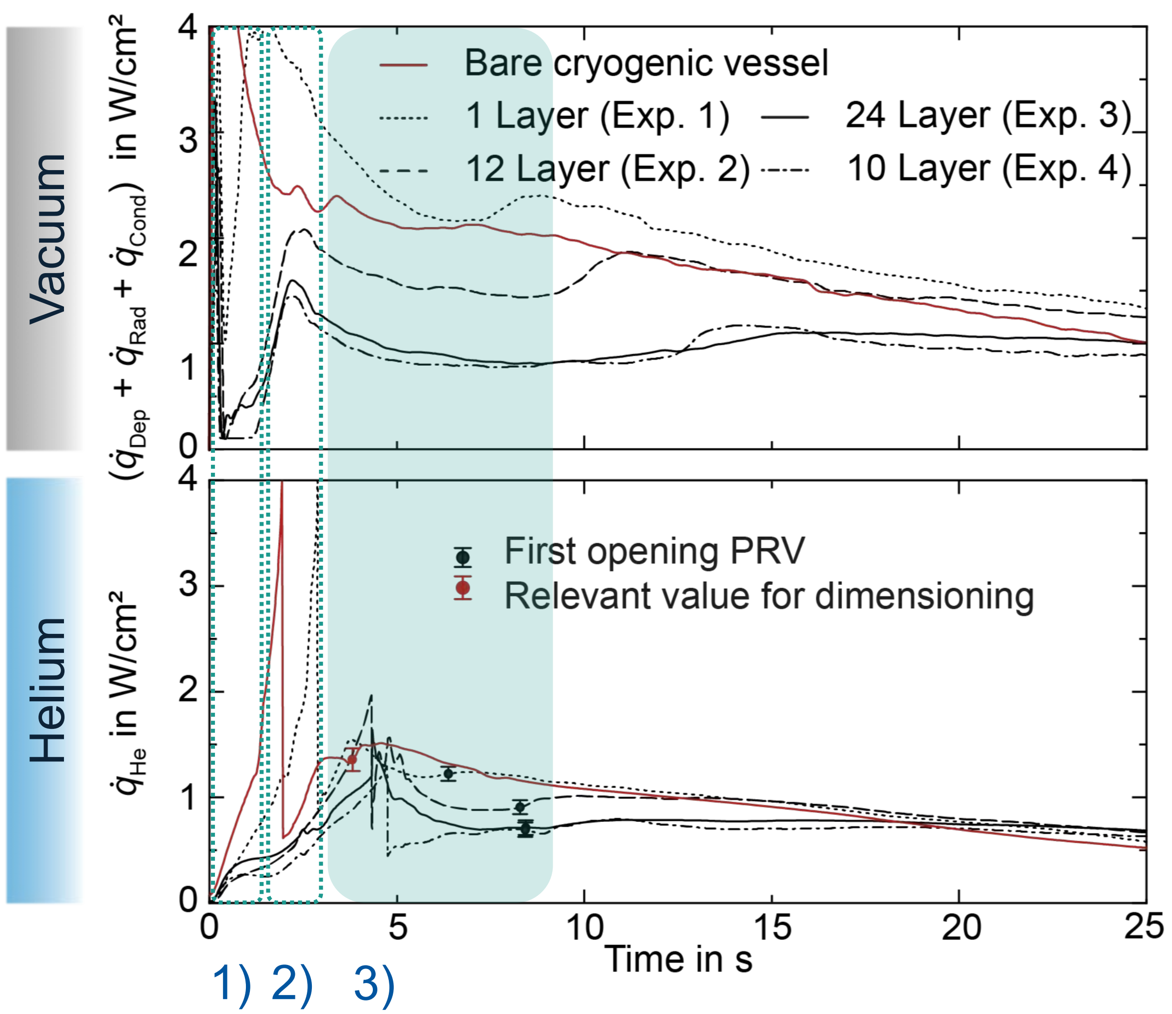
1) $\dot{q}_{He}$ small due to film boiling

Results – Heat Flux



- Plot shape (Vacuum space):
  1) Influence on the flow resistance of the MLI blanket
  2) **Increase of heat flux to peak due to p_v ≈ atm**
- Plot shape (Helium):
  1) $\dot{q}_{He}$ small due to film boiling
  2) **Peak due to property data in vicinity of p_{Crit}**

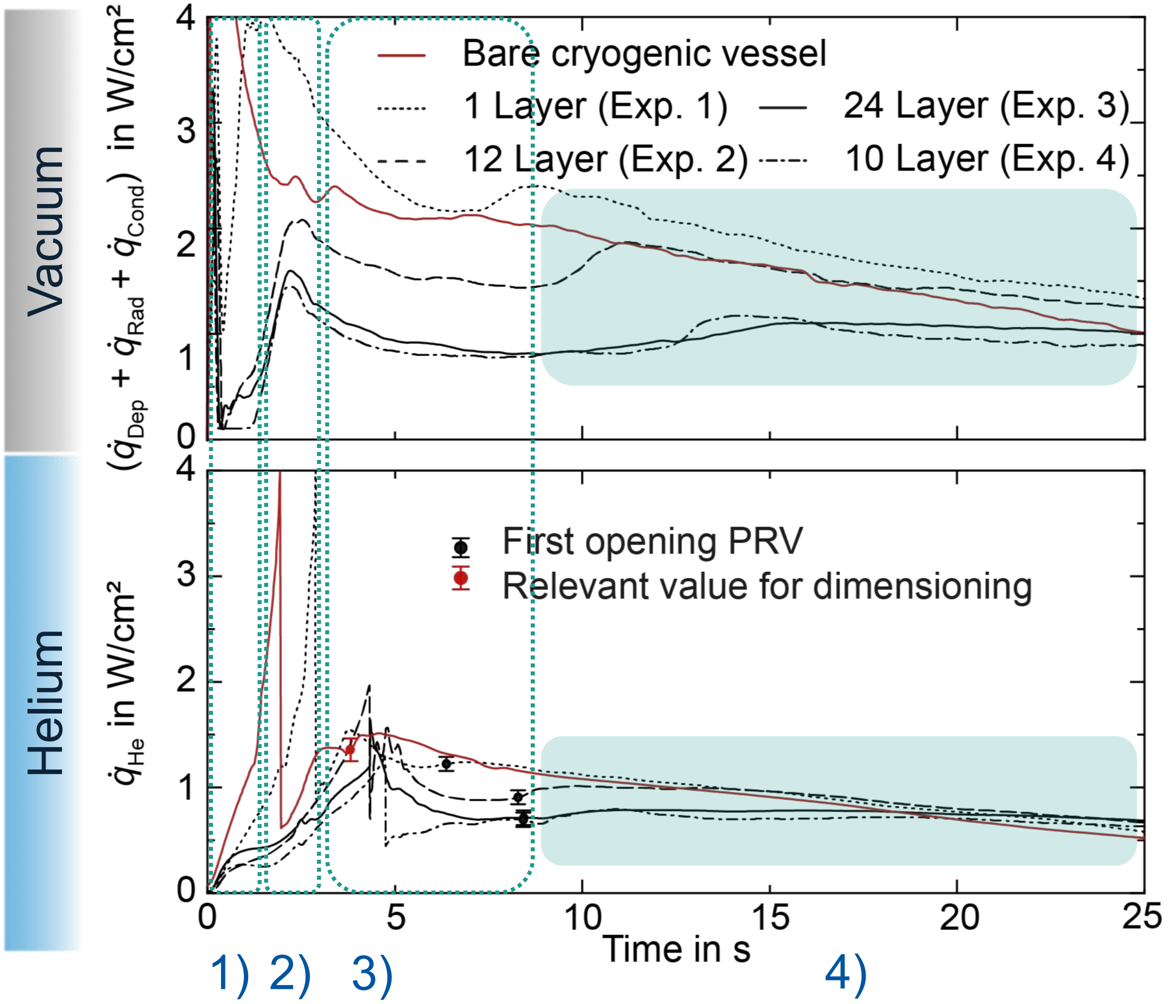
Results – Heat Flux



- Plot shape (Vacuum space):
  1) Influence on the flow resistance of the MLI blanket
  2) Increase of heat flux to peak due to $p_v \approx$ atm
  3) **First opening of PRD**

- Plot shape (Helium):
  1) $\dot{q}_{He}$ small due to film boiling
  2) Peak due to property data in vicinity of p_{Crit}
  3) **Free convection**
     First opening of the PRD –
     <u>Heat flux relevant for dimensioning</u>
     From ~ 1.2 – 0.7 W/cm²

Results – Heat Flux



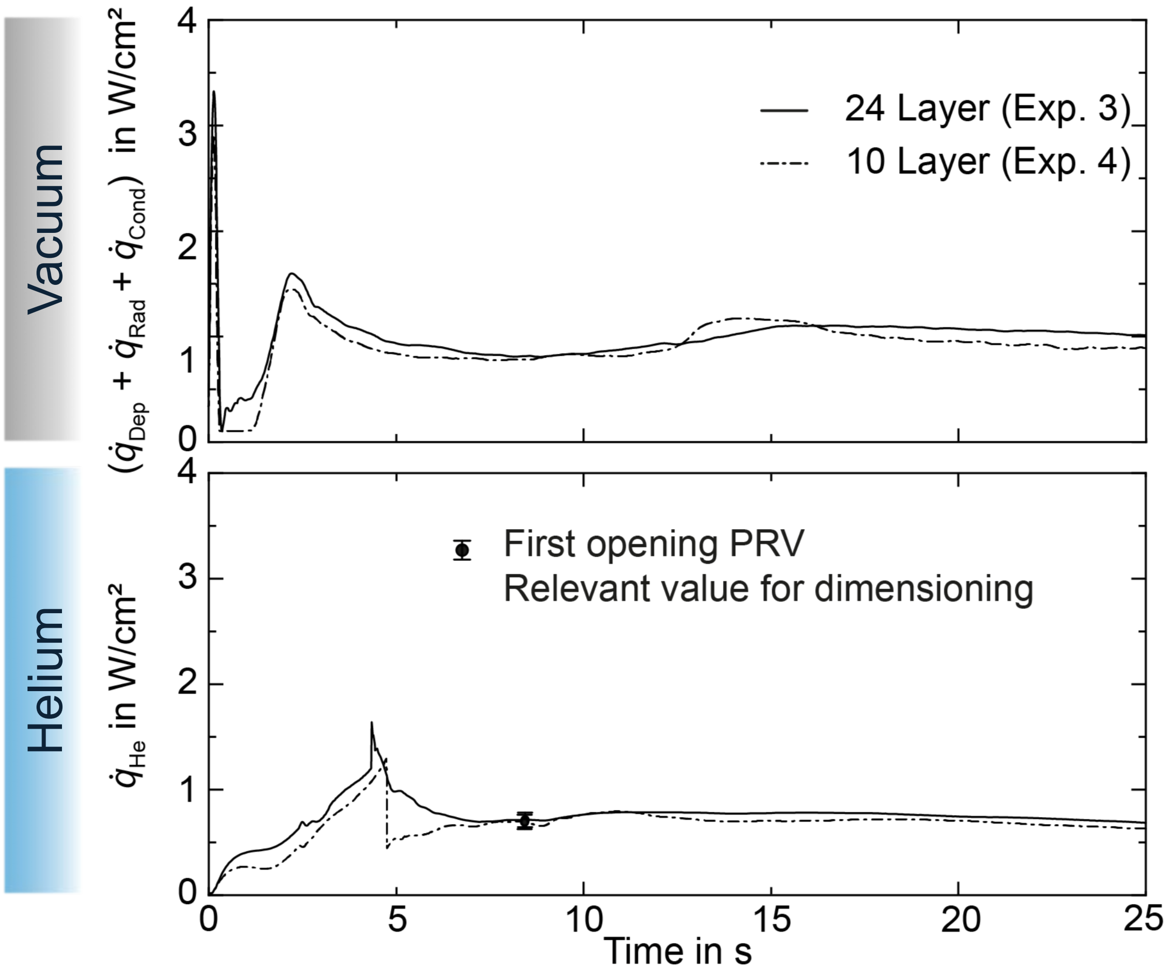
Plot shape (Vacuum Space):

1) Influence on the flow resistance of the MLI blanket
2) Increase of heat flux to peak due to $p_v \approx$ atm
3) First opening of PRV
4) **Heat flux limited by cryopumping effect**

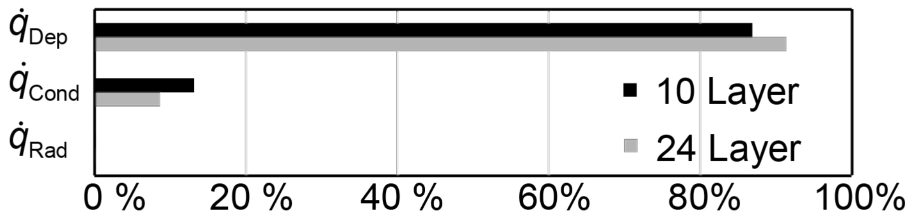
Plot shape (Helium):

1) $\dot{q}_{He}$ small due to film boiling
2) Peak due to property data in vicinity of p_{Crit}
3) Free convection
   First opening of the PRD –
   Heat flux relevant for dimensioning
   - *From ~ 1.2 – 0.7 W/cm²*
4) **Heat flux quasi-independent of the MLI type**

Results – Exp. 3 *vs* Exp. 4



- $\dot{q}_{Dep}$ - predominant heat transfer mechanism



- $\dot{q}_{He} < \dot{q}_{Vacuum}$
  Heat transfer limited by Helium ($Bi < 1$)

- 24 layers Type 1 *vs* 10 layers Type 3
  - Similar heat flux values. Why?

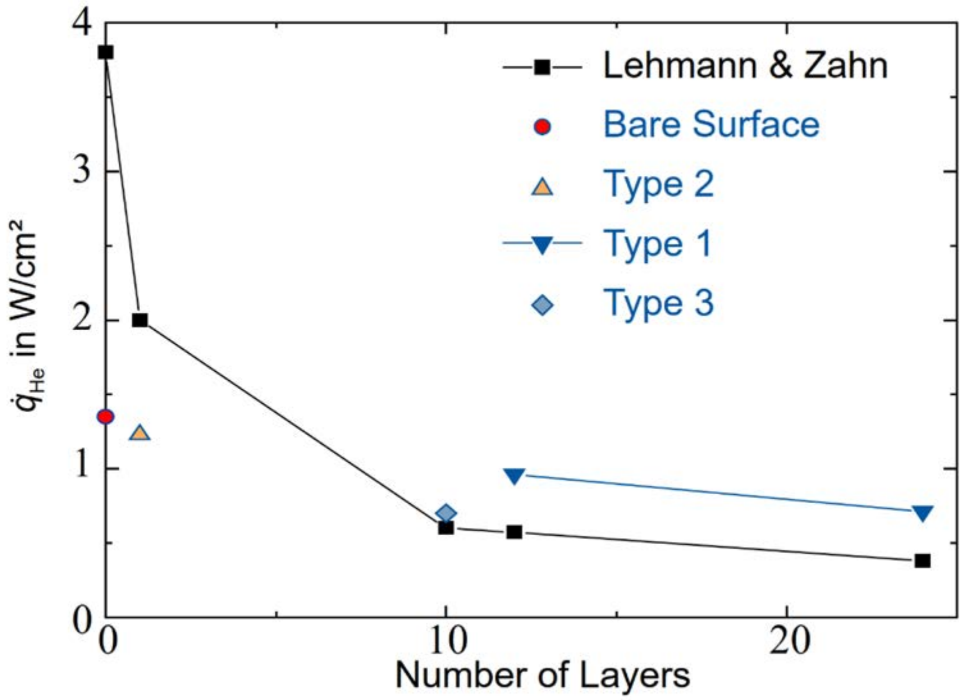
Type	N_{Layer}	Thickness (µm) δ_R	Thickness (µm) δ_S	Perforation holes (mm) ϕ	Perforation holes (mm) Grid	Free Perforation area (mm² / m² MLI)
1	12	6	55	2	50	**1250**
3	10	12	55	4	150	**550**

Results

Comparison with literature

N_{Layers}	Reference	Heat flux (W/cm^2)
0	Lehmann & Zahn [12]	3.8
	PICARD	1.4
1	Lehmann & Zahn [12]	2.0
	PICARD	1.2
10	Lehmann & Zahn [12]	0.6
	PICARD	0.7
12	Lehmann & Zahn [12]	0.59*
	PICARD	1.0
24	Lehmann & Zahn [12]	0.38*
	PICARD	0.7

**extrapolated*



- 12 layer blankets – higher values
- Bare & 1 Layer – lower values

Summary and Outlook

Summary

- Experiments performed at PICARD with MLI
- Effect of multi-layer insulated helium cryostats was measured and evaluated
- Influence on manufacturing characteristics of the MLI demonstrated (e.g. perforation holes)
- Relevant heat flux for dimensioning of PRD discussed
- Results differ from literature – higher heat flux for Type 1 MLI

Outlook

- Further experimental investigations on types of MLI
- Investigate the possibility of an ‘equivalent’ MLI resistance in the dynamic model
- Evaluation of model uncertainty (Bayesian approach)

Thank you for your attention

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References

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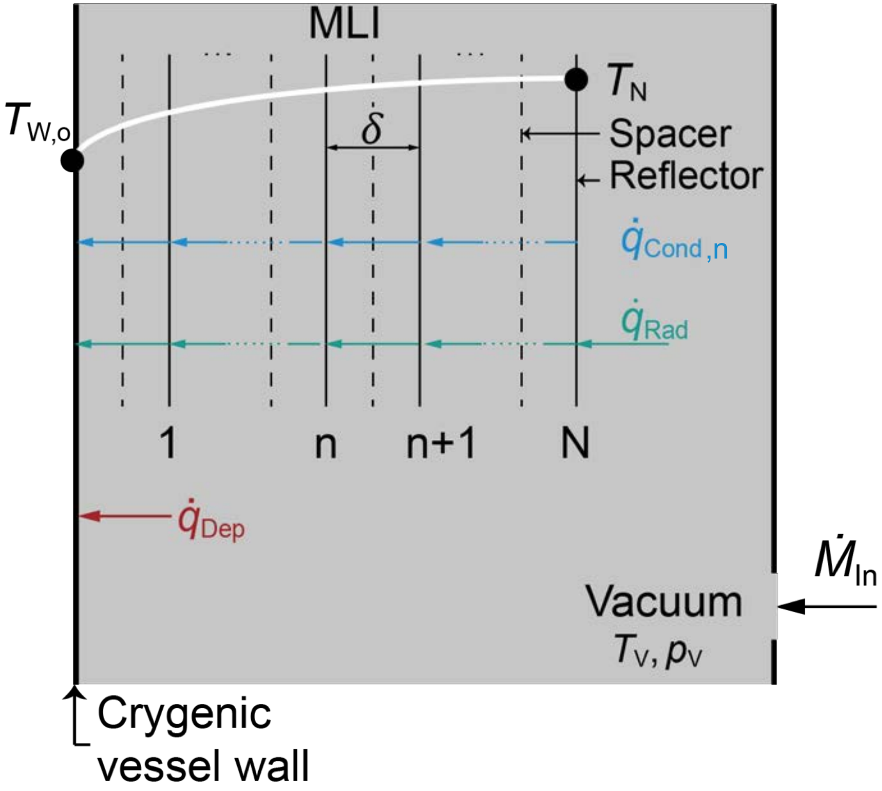
Spare Slides

Heat transfer mechanism - MLI



Density: 10 layers / cm

$\dot{q}_{Cond,n}$: Residual gas & solid thermal conduction *(n ; n+1)*

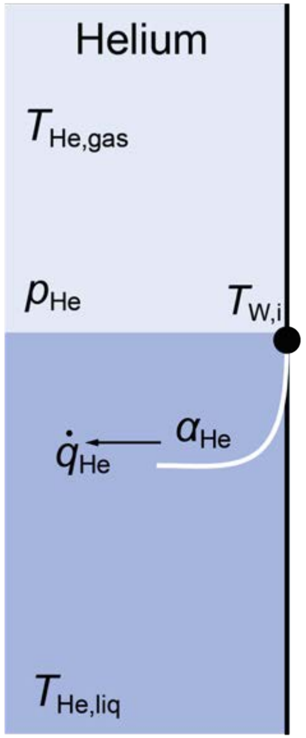
- Total thermal resistance derived from [6] , including:
  - Gaseous air, spacer and the reflective screens

$\dot{q}_{Rad}$: Radiated heat considering *N* reflective MLI layers as grey emitters. Emissivity values:

- ϵ_V = 0.8 – vacuum vessel (oxidized SS)
- ϵ_{Cr} = 0.07 – helium vessel (electro-polished SS)
- ϵ_{MLI} = 0.04 – reflector (electro-polished Al)

$\dot{q}_{Dep}$: Measured based on mass flow of venting air and rise in vacuum pressure [7]

Heat transfer mechanism - Helium



$\dot{q}_{He}$: Heat transfer coefficient α_{He} depends on thermodynamic state and fluid phase

- Correlations subcritical state:

  A_{Cr} in contact with liquid α_{He} - pool boiling [8,9]

  A_{Cr} in contact with gas α_{He} - free convection [10]

- Correlations supercritical state:

  α_{He} - free convection [11]

Formulas

- Cryo wall temperatures: $\frac{dT_{W,o}}{dt} = \frac{A_{Cr}}{c_{Cr} \cdot M_{Cr}} \cdot (\dot{q}_{Dep} + \dot{q}_{Rad} + \dot{q}_{Con} - \dot{q}_{\lambda,W})$; $\frac{dT_{W,i}}{dt} = \frac{A_{Cr}}{c_{Cr} \cdot M_{Cr}} \cdot (\dot{q}_{\lambda,W} - \dot{q}_{He})$
- Stefan-Boltzmann: $\dot{q}_{Rad} = \sigma \cdot \left(T_V^4 - T_W^4\right) \cdot \left(\left(\frac{1}{\epsilon_{Cr}} + \frac{1}{\epsilon_{MLI}} - 1 \right) + (N-1) \cdot \left(\frac{2}{\epsilon_{MLI}} - 1 \right) + \left(\frac{1}{\epsilon_{MLI}} + \frac{1}{\epsilon_V} - 1 \right) \right)^{-1}$
- Fourier (cryo wall): $\dot{q}_{\lambda,W} = \frac{\lambda_{Cr}}{s_{Cr}} \cdot (T_{W,o} - T_{W,i})$
- Fourier (MLI): $\dot{q}_{Cond,n} = \frac{(r_{n+1} - r_n) \cdot (T_{n+1} - T_n)}{r_n \cdot \left(R_g + \frac{R_s \cdot R_s'}{R_s + R_s'} + R_r \right) \cdot \ln\left(\frac{r_{n+1}}{r_n} \right)}$
- Convective heat flux to He: $\dot{q}_{He} = \alpha_{He} \cdot (T_{W,i} - T_{He})$
- Deposition heat flux: $\dot{q}_{Dep} = \frac{\dot{M}_{Dep}}{A_{Cr}} \cdot \left(h_{air}\left(p_{amb}, T_{amb}, \varphi_{amb}\right) - h_{air}\left(p_V, T_{W_o}, \varphi_{amb}\right) \right)$

Heat flux plot