



EN

Engineering Department

# Crab Cavity Cryomodules: Thermal Aspects

**F. Carra, R. Bonomi**

with inputs from O. Capatina, L. Alberty Vieira, R. Leuxe, T. Renaglia, K. Brodzinski, M. Navarro Tapia, S. Verdú Andrés, and many others

**LHC-CC13: 6th LHC Crab Cavity Workshop  
CERN, Geneva, Switzerland – 10.12.2013**



# Outline

EN

Engineering Department

- Principles of cryogenic vessel insulation
- Crab Cavity cryomodules
  - Heat losses balance
  - Thermal calculations
- Conclusions





# Outline

EN

Engineering Department

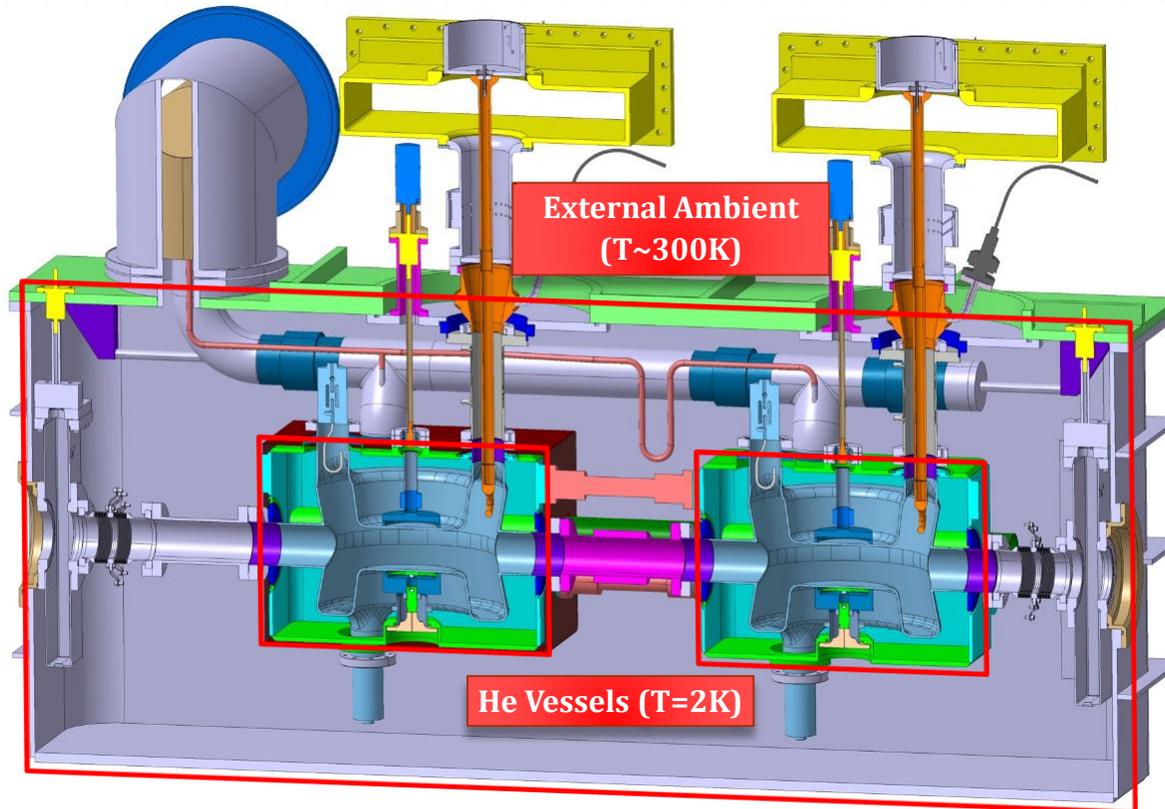
- **Principles of cryostat insulation**
- Crab Cavity cryomodules
  - Heat losses balance
  - Thermal calculations
- Conclusions



# Thermal exchange in a cryostat

- Vessels at cryogenic temperature can exchange heat with the external ambient in three ways:

1. Convection
2. Radiation
3. Conduction



- Additional heat losses can be generated by **joule effect** (RF current inside cavities, couplers, HOM/LOM, ...)

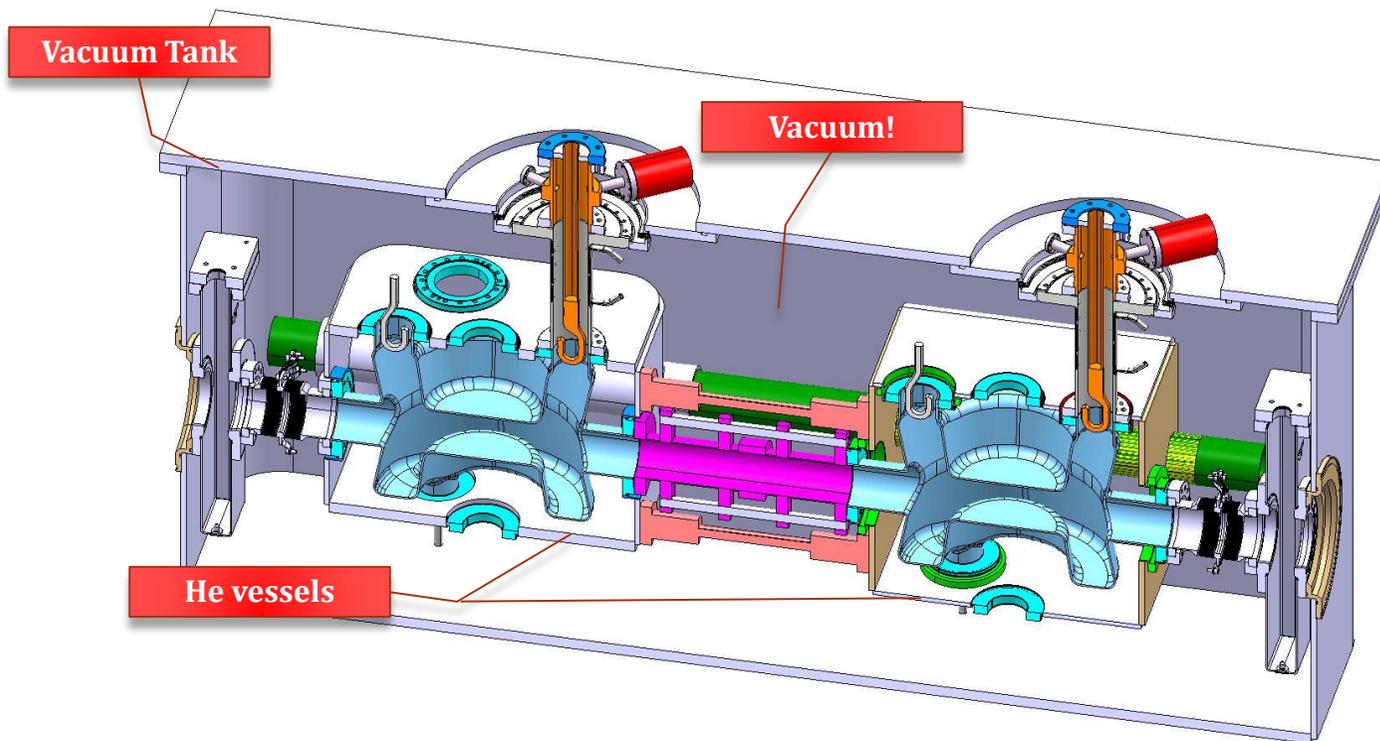
**Objective: minimize thermal losses to 2K bath**

- COP @ 2 K ~ **990**  $W_{el}/W_{th}$
- COP @ 4.5 K ~ 210  $W_{el}/W_{th}$
- COP @ 50 K ~ 16  $W_{el}/W_{th}$

# Thermal exchange in a cryostat

## 1. Heat losses by convection

- Removed by positioning the He vessels inside a vacuum tank

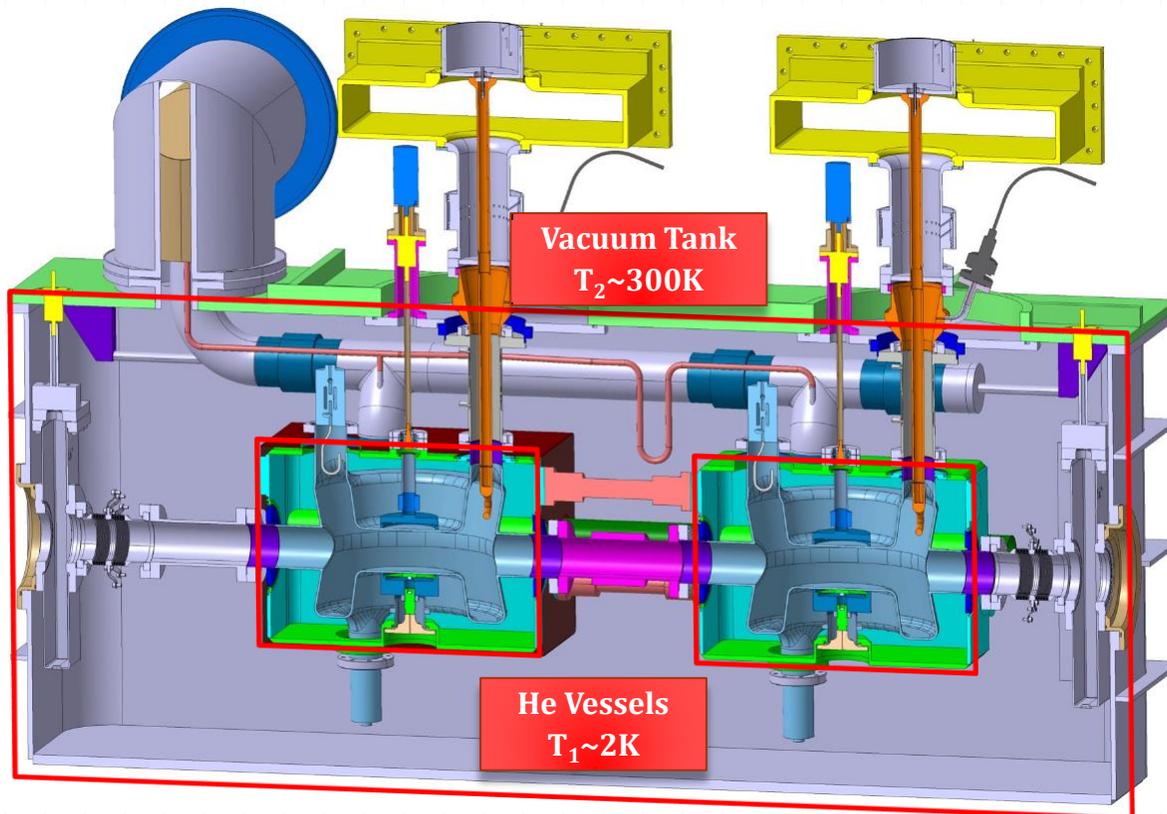


# Thermal exchange in a cryostat

## 2. Heat losses by radiation

- Exchange surface to surface: inner vacuum tank faces to outer He vessel faces

$$Q \propto \epsilon_1, \epsilon_2, (T_2^4 - T_1^4)$$



- $\epsilon_1, T_1$  : emissivity and temperature of the He vessel outer faces
- $\epsilon_2, T_2$  : emissivity and temperature of the vacuum vessel inner faces

# Thermal exchange in a cryostat

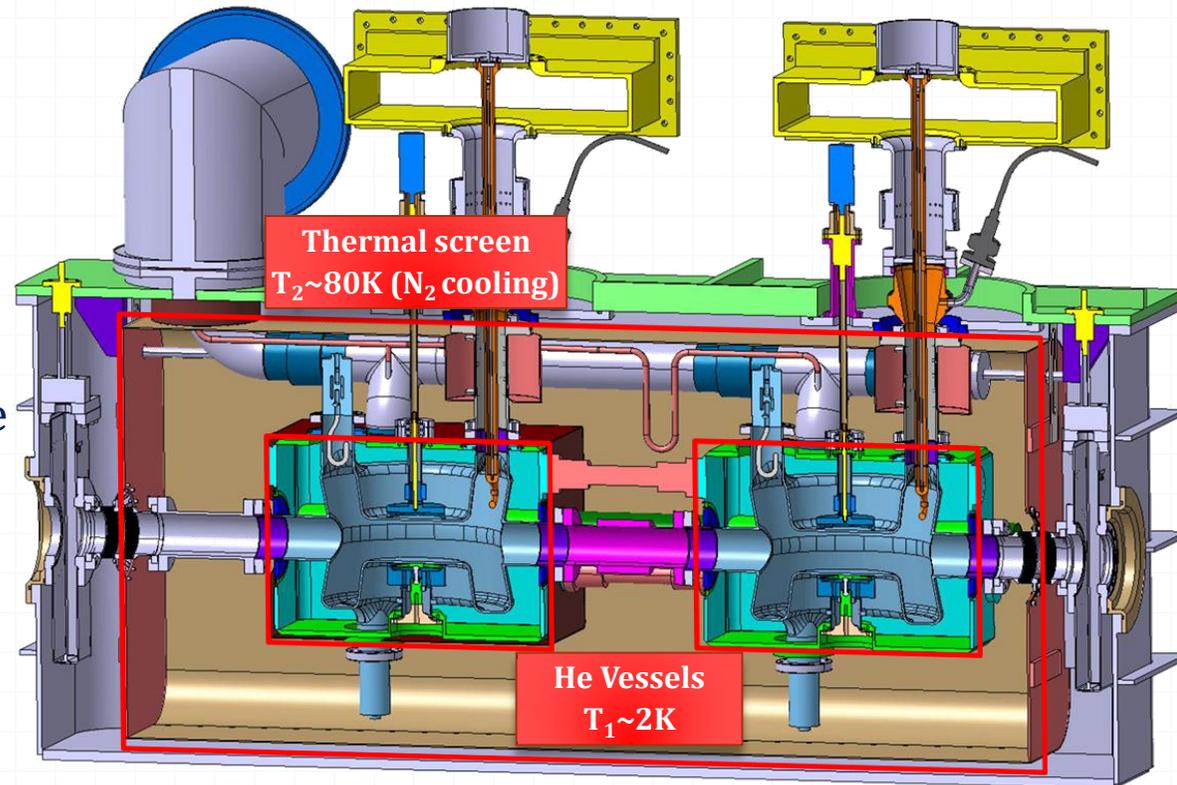
## 2. Heat losses by radiation

$$Q \propto \epsilon_1, \epsilon_2, (T_2^4 - T_1^4)$$

- Two ways to minimize Q:

- Decrease  $T_2^4 - T_1^4$
- Decrease  $\epsilon_1$  and  $\epsilon_2$

- $T_1$  fixed (2K)
- $T_2$  is decreased adding a **thermal screen** between the He vessel and the vacuum tank
- In the formula,  $T_2$  is now the **temperature of the thermal screen**, which is directly cooled (e.g. with nitrogen @80K)



# Thermal exchange in a cryostat

## 2. Heat losses by radiation

$$Q \propto \epsilon_1, \epsilon_2, (T_2^4 - T_1^4)$$

- The emissivity of the thermal screen and the He vessel is minimized by covering the radiating surfaces with **Multi-Layer Insulators (MLI)**.



- 1 k
- Re
- Sp
- St
- cl
- Co
- Av

C. Mag  
arc, fr  
2008.



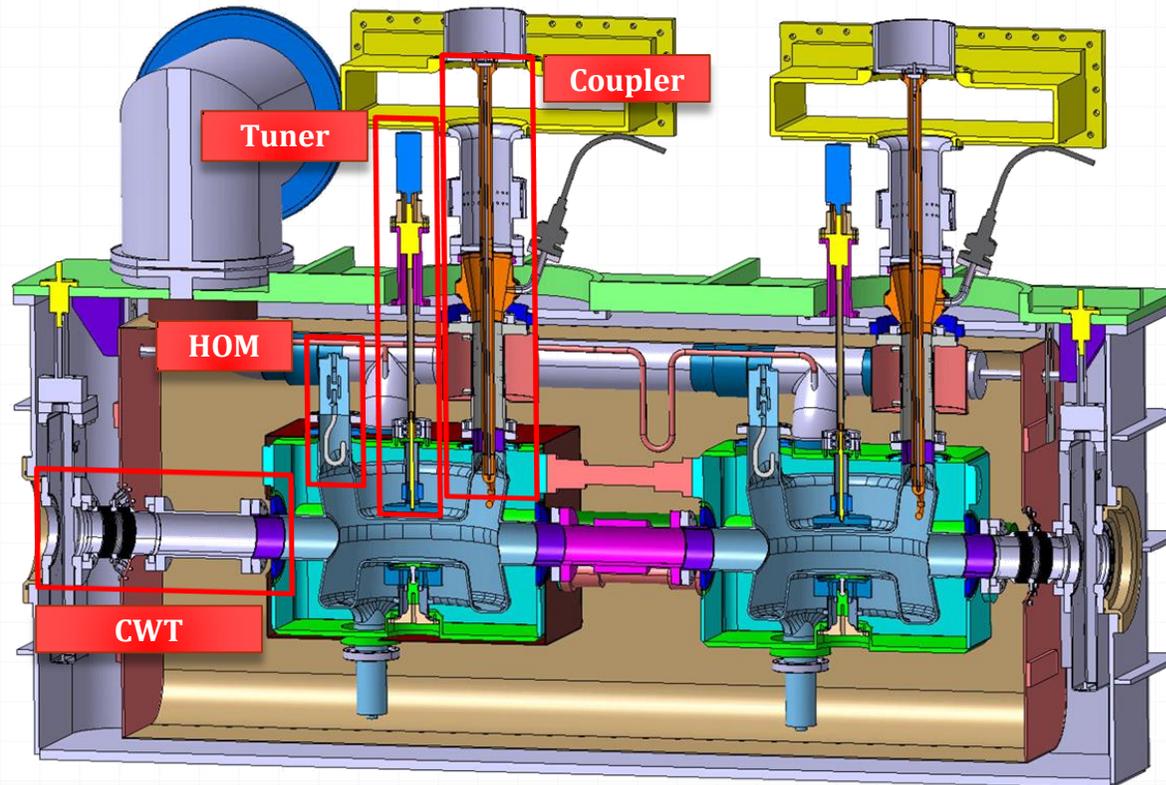
lm  
d quality

0.1 W/m<sup>2</sup>  
in the LHC  
t Note 409,

# Thermal exchange in a cryostat

## 3. Heat losses by conduction

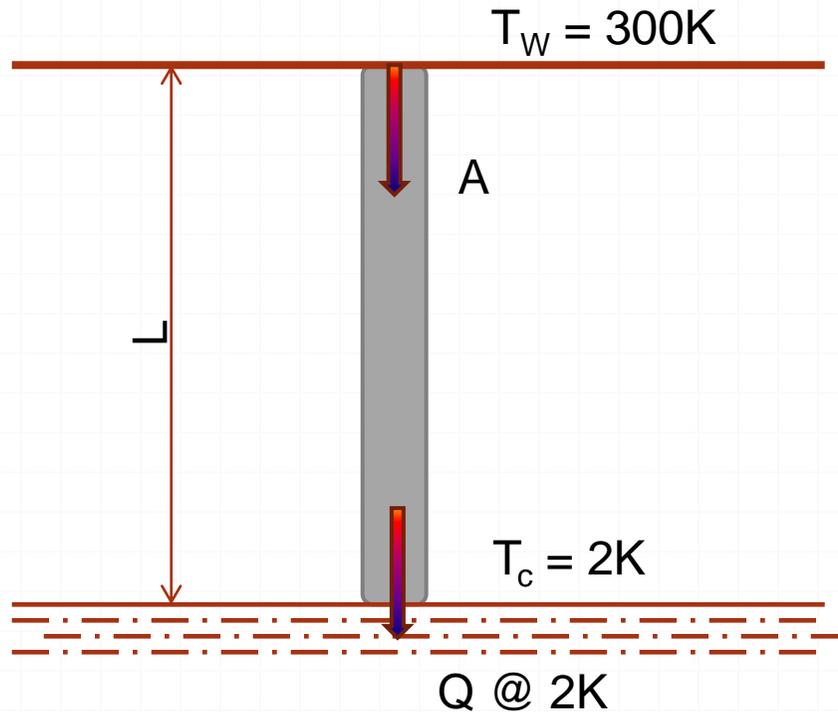
- Heat can be transmitted by conduction to the cold mass **through all the connections with surrounding systems at higher temperature** (external ambient, vacuum vessel, thermal screen, magnetic screen, ...)
- Connections:** power coupler, HOM/LOM, cables & instrumentation, supports, cold-warm transitions, tuners, etc.



# Thermal exchange in a cryostat

## 3. Heat losses by conduction: example (generic connection)

### A) Pure conduction



$$Q_{2K} := \frac{A}{L} \cdot \int_{T_c}^{T_w} k(T) dT$$

- **A, L:** conductor section and length
- **k:** thermal conductivity, as a function of temperature

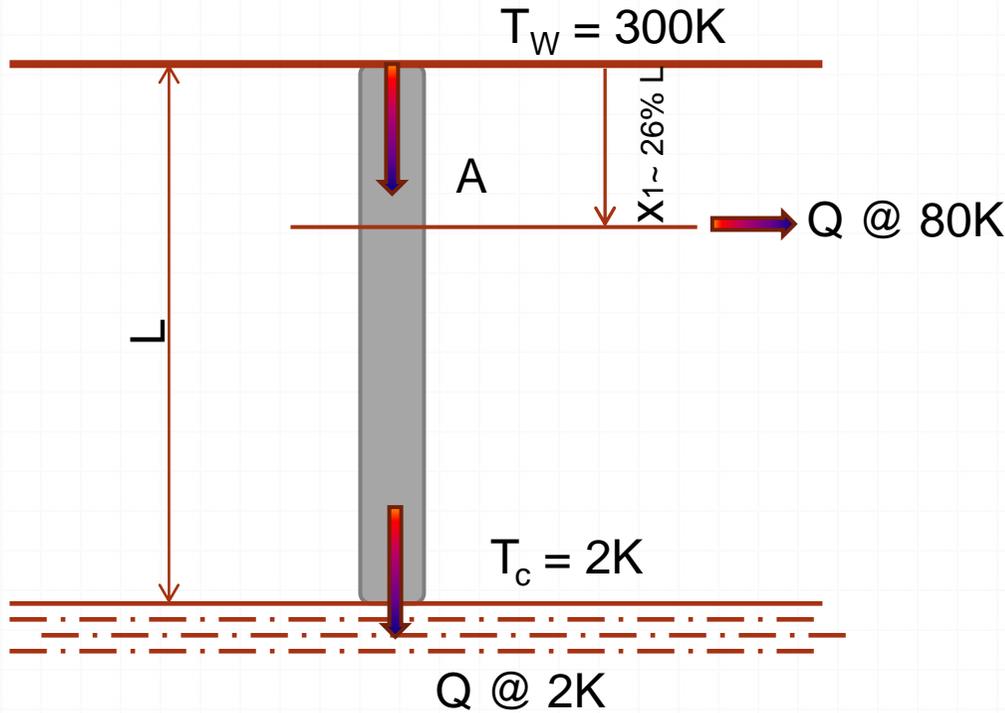
*Example: SPL coupler*

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	Vapors rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
<b>A) No intercept</b>	<b>11.6</b>	<b>11512</b>								<b>11512</b>

# Thermal exchange in a cryostat

## 3. Heat losses by conduction: example (generic connection)

### B) 1 Heat intercept @ 80K, in optimized position



Cost factors:

$$C1 = 16 \text{ W/W}$$

$$C3 = 990 \text{ W/W}$$

Example: SPL coupler

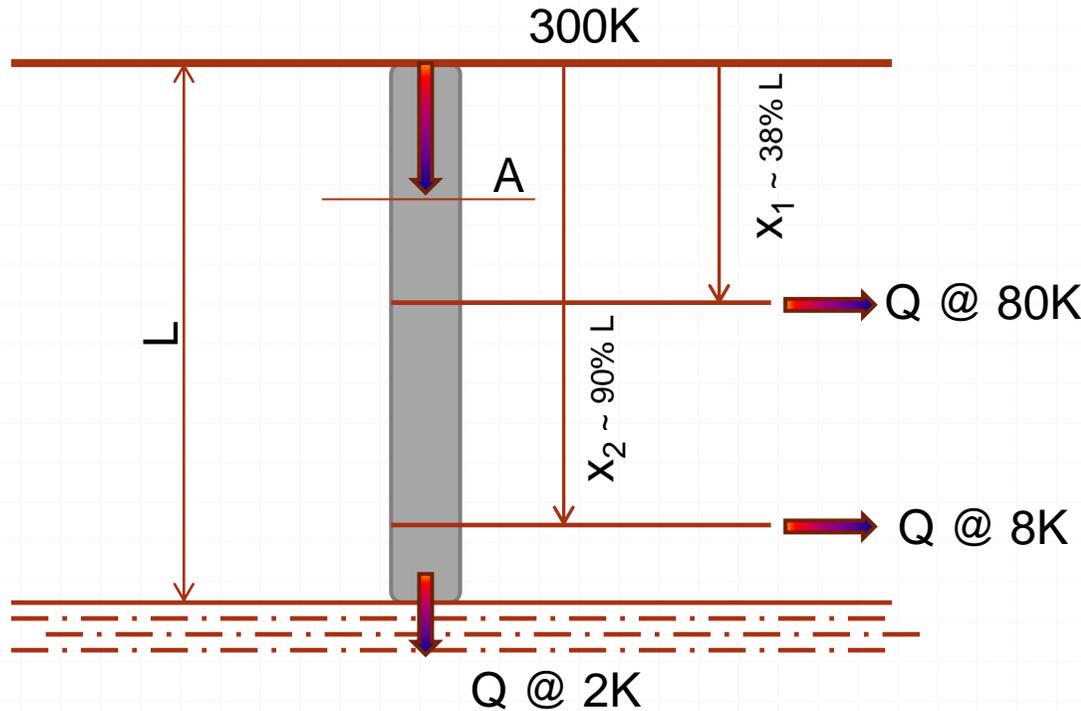
Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	Vapors rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.6	11512								11512
B) 1 optimized intercept @ 80K	1.8	1798			39	632				2430

# Thermal exchange in a cryostat

## 3. Heat losses by conduction: example (generic connection)

### C) 2 Heat intercepts @ 80K & 8K in optimized positions

Cost factors:  
 $C_1 = 16 \text{ w/w}$   
 $C_2 = 210 \text{ w/w}$   
 $C_3 = 990 \text{ w/w}$



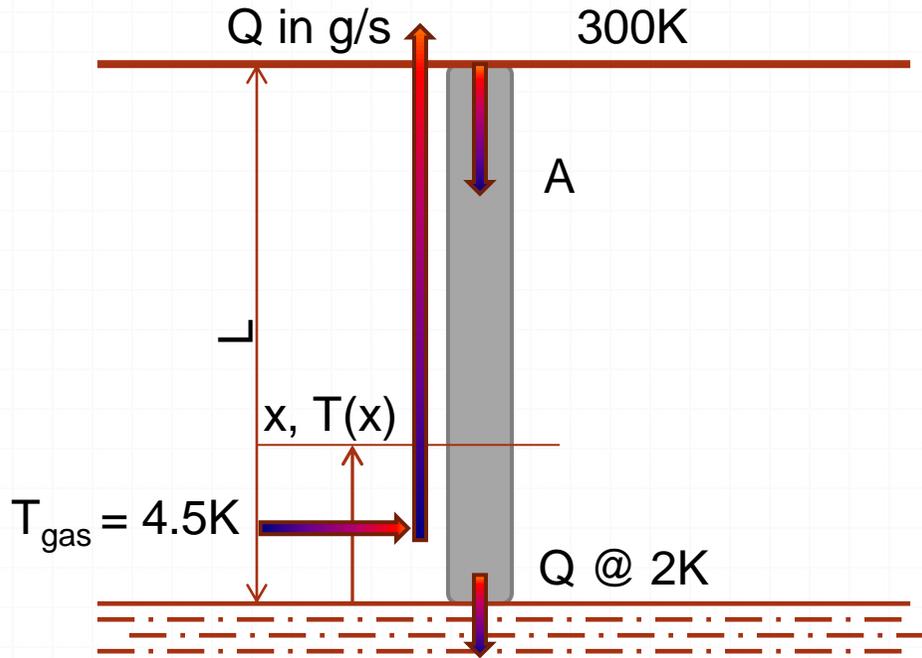
Example: SPL coupler

$$f(x_1, x_2) := \left( \frac{A}{x_1} \right) \cdot \left( \int_{80}^{300} k(T) dT \right) \cdot C_1 + \left[ \frac{A}{(x_2 - x_1)} \right] \cdot \left( \int_8^{80} k(T) dT \right) \cdot C_2 + \left[ \frac{A}{(L - x_2)} \right] \cdot \left( \int_2^8 k(T) dT \right) \cdot C_3$$

# Thermal exchange in a cryostat

## 3. Heat losses by conduction: example (generic connection)

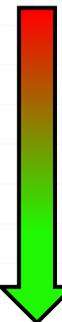
### D) He vapor cooling, 4.5K-300K



- Finite gas/wall film coefficient
- He gas temperature changing with x
- Usually solved by numerical or semi-analytical methods

Example: SPL coupler

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	Vapors rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.6	11512								11512
B) 1 optimized intercept @ 80K	1.8	1798			39	632				2430
C) 2 optimized intercepts @ 80K & 8K	0.1	128	2.64	581	26.8	429				1138
D) 4.5K vapor cooling	0.03	30.7					0.019	1.9	407	438





# Outline

EN

Engineering Department

- Principles of cryostat insulation
- **Crab Cavity cryomodules**
  - **Heat losses balance**
  - Thermal calculations
- Conclusions



# Crab cavity cryomodules: heat losses balance

HL per cryomodule		HL @2K [W]	HL @80K [W]	Comments
Static	Radiation (Cavity + Phase Sep. Cold surface + Thermal shield)	0.2	6.8	Rescaling from LHC: 0.1W/m <sup>2</sup> @cold mass 1.7W/m <sup>2</sup> @thermal shield
	CWT	3.0	12.6	1 heat interceptor not optimized
	Supporting system	0.2	3.3	HL@2K estimated from SPL
	RF couplers	2 x 2 = 4.0	2 x 50 = 100	For a tube thickness t = 3mm
	Cables & Instrumentation	1.0	0	Tentative
	Tuner	0.2	0	Not thermalized
	Other order modes	4x0.2 + 2x2 ~ 5.0	100	Max losses found in ODU cryostat: 4 small HOMs (4x0.2W @2K estimated from SPL) + 2 "chimneys" HOM (2x2W @2K for a thickness of 3 mm and a length outside He bath of 340 mm); @80K: 4x? + 2x45W
<b>Total Static</b>		<b>13.6</b>	<b>222.7</b>	
Dynamic	Deflecting mode	6.0	0	Tentative
	Beam current	0.5	0	Tentative
	RF couplers	2 x 2 = 4.0	2 x 5 = 10	For a tube thickness t = 3mm ; P <sub>avg</sub> = 100 kW
	Other order modes	0.6	10	for a P <sub>avg</sub> = 100 kW; f = 1000 MHz; @2K chimneys: 2x0.1 + small HOM (estimated from SPL): 4x0.1@2K; @80K: 4x?+2x4
<b>Total Dynamic</b>		<b>11.1</b>	<b>20</b>	
<b>Total losses</b>		<b>24.7</b>	<b>242.7</b>	

- **SPS configuration**; active cooling: **1 circuit @80K** (nitrogen)
- Estimation of total losses to 2K and 80K baths, Static & Dynamic (RF-induced)
- Thermal budget for SPS is limited (see K. Brodzinski's presentation)
- For each line, the **highest value between the 3 different cryomodules (BNL, UK, ODU)** has been entered
- Many design choices not frozen yet: thermal calculations performed are **parametric**
- Parameters are material, thickness & length of the connections, position of the heat intercepts @80K, etc.
- **Mechanical calculations ongoing on the proposed solutions**



# Outline

EN

Engineering Department

- Principles of cryostat insulation
- **Crab Cavity cryomodules**
  - Heat losses balance
  - **Thermal calculations**
- Conclusions





# Crab cavity cryomodules: thermal calculations

EN

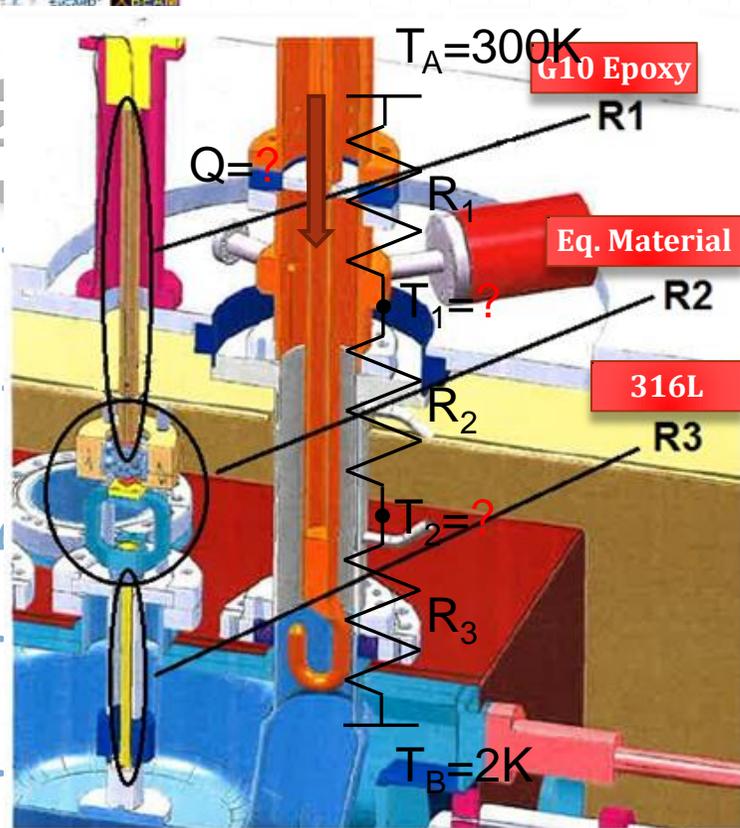
Engineering Department

- Main methods to evaluate the thermal exchange through connections between cold mass and surrounding systems are:
  - **Analytical**
  - **Semi-analytical**
  - **Numerical** (ANSYS, HFSS/ANSYS coupling for dynamic losses)
  
- In the next slides, one example for each method is shown (applied on crab cavity cryomodule components):
  1. **BNL cavity tuner**: Analytical & Numerical
  2. **ODU high-order mode coupler**: Semi-analytical
  3. **BNL power coupler**: Numerical (HFSS/ANSYS coupling)



# Crab cavity cryomodules: thermal calculations

## 1. BNL cavity tuner: Analytical



Series circuit

3 Equations, 3 Unknowns

$$Q = \left[ \frac{A_1}{L_1} \cdot \left( \int_{T_1}^{T_A} K_1(T) dT \right) \right] = \left[ \frac{A_2}{L_2} \cdot \left( \int_{T_2}^{T_1} K_2(T) dT \right) \right] = \left[ \frac{A_3}{L_3} \cdot \left( \int_{T_B}^{T_2} K_3(T) dT \right) \right]$$

- The analytical estimation of  $R_2$  is quite difficult (different materials, piezoelectric component, contact resistance with bearings, ...)
- **Conservative assumption:  $R_2 = 0$**  (it will be verified numerically)
- This means  $T_1 = T_2 \rightarrow$  **2 equations, 2 unknowns**
- Easy to solve: material properties, sections and lengths are known

$$Q = \frac{A_1}{L_1} \cdot \left( \int_{T_1}^{T_A} K_1(T) dT \right) = \frac{A_3}{L_3} \cdot \left( \int_{T_B}^{T_1} K_3(T) dT \right) \longrightarrow T_1 = 61.3 \text{ K}, Q = 0.07 \text{ W/tuner}$$

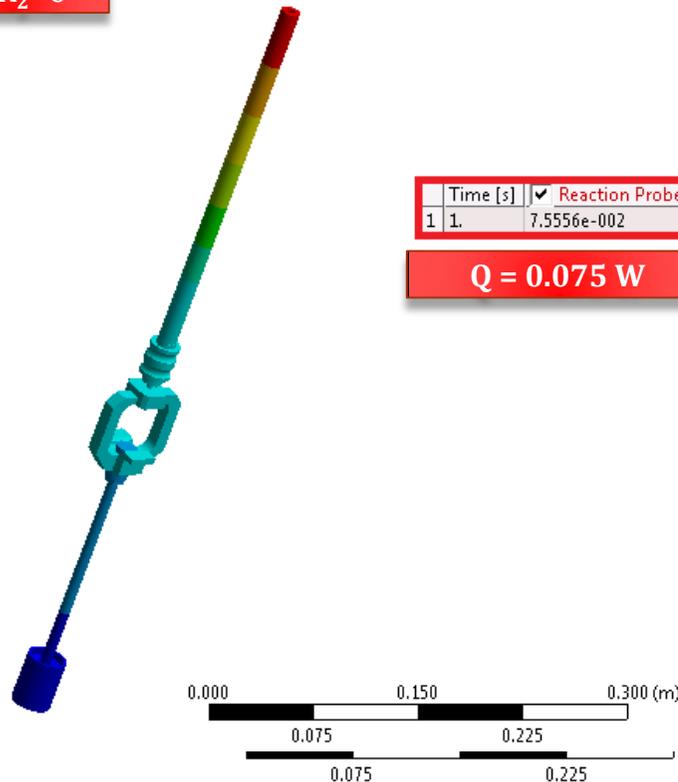
# Crab cavity cryomodules: thermal calculations

## 1. BNL cavity tuner: Numerical (ANSYS)

- Two goals: A) verify the analytical calculation with  $R_2=0$ ; B): evaluate  $R_2$  and its influence of the thermal flux to He bath.

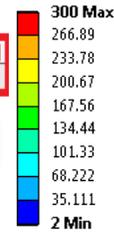
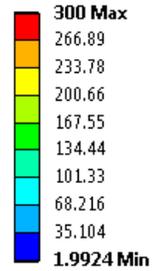
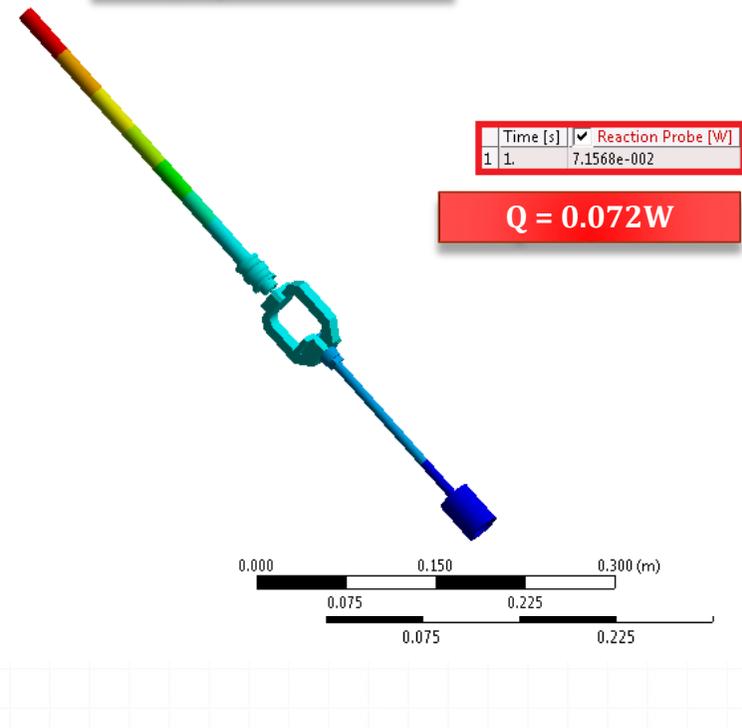
C: Analytical Benchmarking  
 Temperature  
 Type: Temperature  
 Unit: K  
 Time: 1  
 08/12/2013 13:06

A)  $R_2=0$



B: Steady-State Thermal  
 Temperature  
 Type: Temperature  
 Unit: K  
 Time: 1  
 08/12/2013 13:29

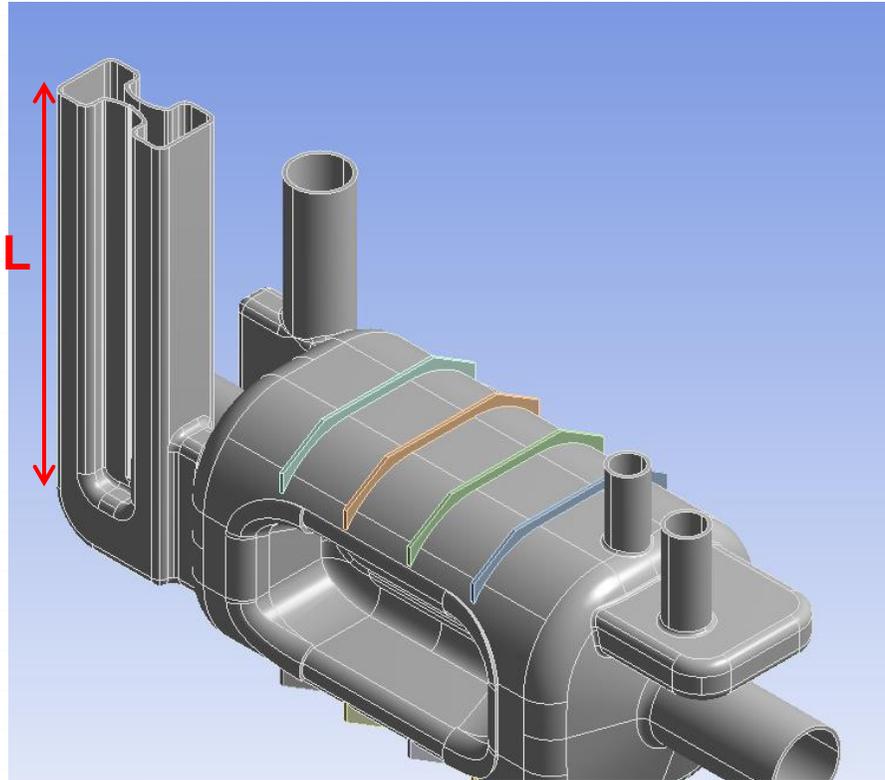
B)  $R_2$  considered



- Good accordance with the analytical calculation
- Effect of  $R_2$  on the heat flux to He bath  $\sim 5\%$ ; **Q  $\sim 0.1$  W/tuner**

# Crab cavity cryomodules: thermal calculations

## 2. ODU high-order mode coupler: Semi-analytical



- Copper-coated (4  $\mu\text{m}$ ) stainless steel wall
- Parametric calculation for different wall thicknesses and lengths  $L$  uncovered by the He bath
- With /without 80K heat intercept (optimized position)
- RF (estimation):  $P = 3 \text{ kW}$ ,  $f = 1000 \text{ MHz}$ ,  $Z = 50 \Omega$
- **Semi-analytical method:** continuum is discretized in elements and nodes
- Energy balance imposed to each element:

$$Q_{\text{condI}}(T_{w11}, T_{w12}) + P_{\text{rf}}(T_{w12}, 2) + Q_{\text{rad}}(T_{w12}, 2) = Q_{\text{condI}}(T_{w12}, T_{w13}) + Q_{\text{convI}}(T_{w12}, T_{g2}, h_{\text{gas}}, 2)$$

$$2 \quad Q_{\text{convI}}(T_{w12}, T_{g2}, h_{\text{gas}}, 2) + Q_{\text{convE}}(T_{wE2}, T_{g2}, h_{\text{gas}}, 2) = -Q_{\text{gas}}(T_{g1}, T_{g2})$$

$$Q_{\text{condE}}(T_{wE1}, T_{wE2}) = Q_{\text{condE}}(T_{wE2}, T_{wE3}) + Q_{\text{convE}}(T_{wE2}, T_{g2}, h_{\text{gas}}, 2)$$

# Crab cavity cryomodules: thermal calculations

## 2. ODU high-order mode coupler: Semi-analytical

- Contributions considered: conduction + dissipated power (when RF is on)

$$Q_{\text{cond}}(T_a, T_b) := - \int_{T_a}^{T_b} \frac{k(T) \cdot A}{dx} dT$$

$$P_{\text{rf}}(T_{\text{wall}}, i) := \frac{1}{2} \int_{x_i - \frac{dx}{2}}^{x_i + \frac{dx}{2}} I_{\text{eq}}(X)^2 \cdot R_{\text{wall}}(T_{\text{wall}}) dX$$

$$I(x) := I_0 \cdot 2 \cdot \sin\left(\frac{\omega}{c} \cdot x\right)$$

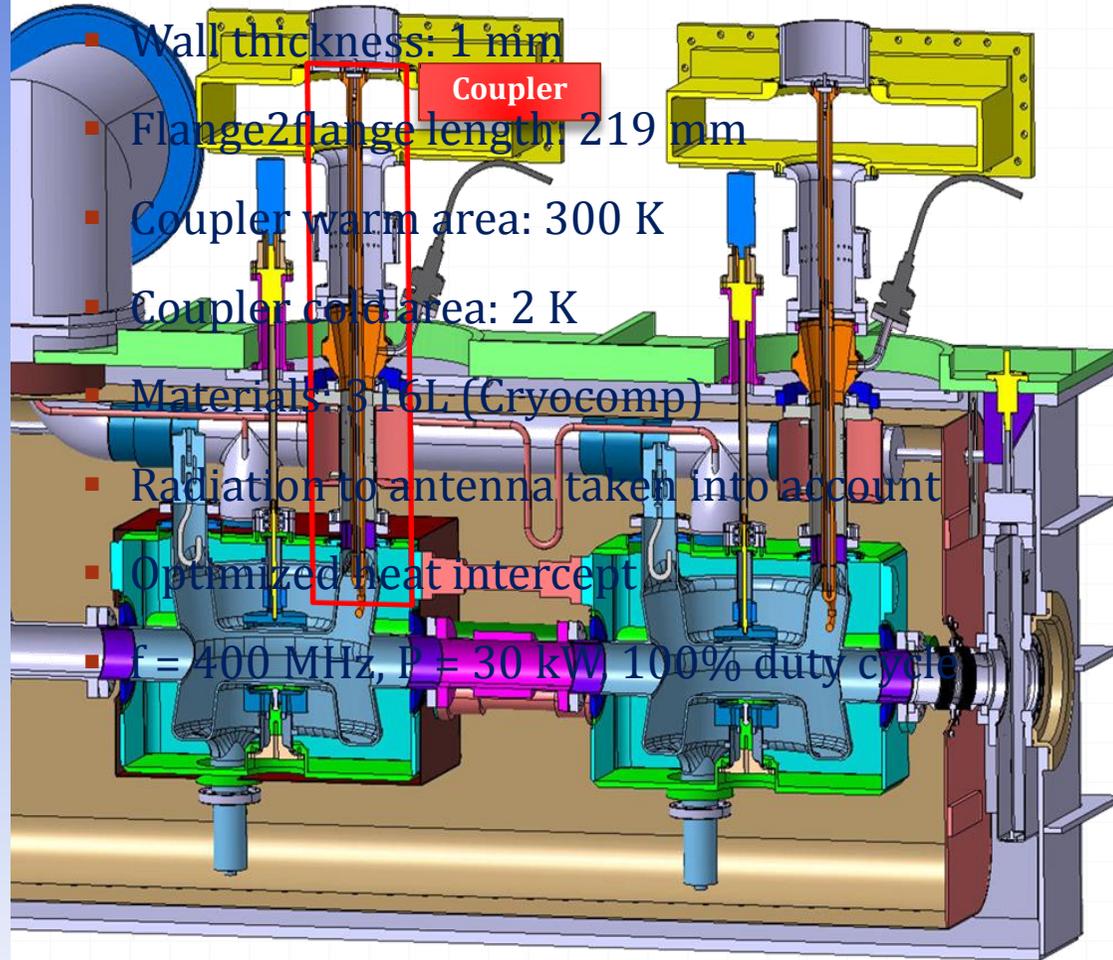
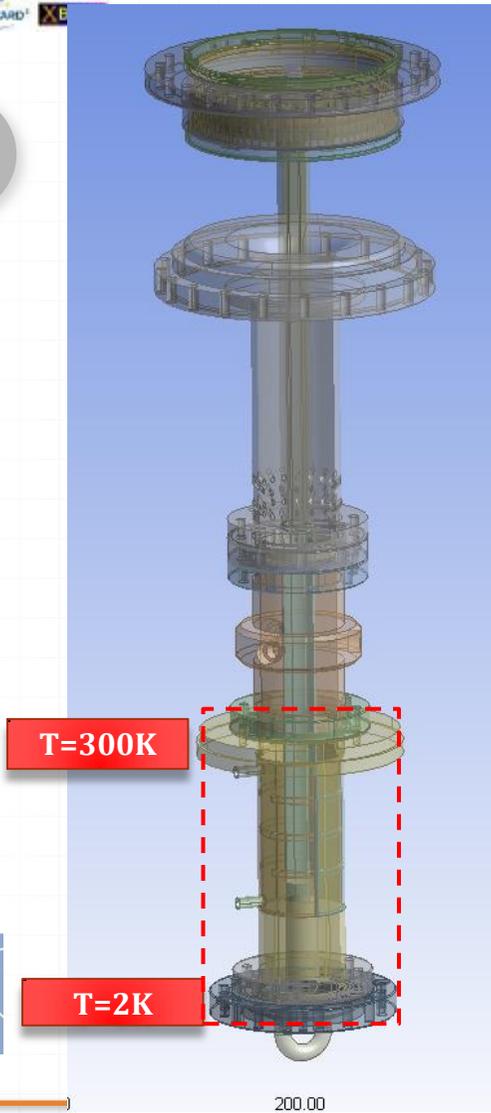
- $x_i$  = coordinate of i-node
- $dx$  = element length;  $A$  = conducting section
- $k$  = equivalent thermal conductivity of the section
- $R_{\text{wall}}$  = electrical resistivity of the inner face (copper)

### Thermal losses (W) with and without 80K heat intercept (Wall Thickness = 3 mm, L=340mm)

	RF off	RF on (P = 3 kW, f = 1000 MHz)
No cooling	12.8 W @2K	13 W @2K
Cooling with 1 Heat intercept (80K) $x/L=26\%$	<b>~2 W @2K</b> 45 W @80K	<b>~2 W @2K</b> 49 W @80K

# Crab cavity cryomodules: thermal calculations

## 3. BNL power coupler: Numerical (HFSS/ANSYS coupling)

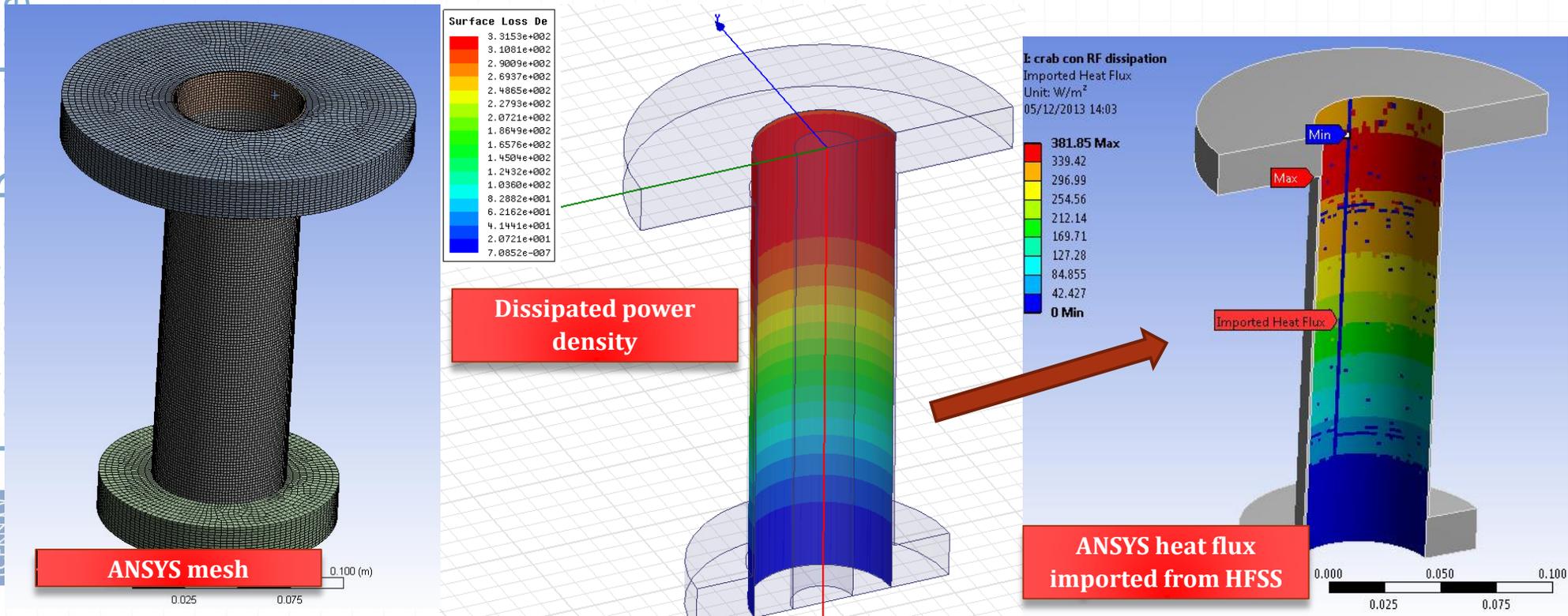


- Wall thickness: 1 mm
- Flange2flange length: 219 mm
- Coupler warm area: 300 K
- Coupler cold area: 2 K
- Materials: 316L (Cryocomp)
- Radiation to antenna taken into account
- Optimized heat intercept
- $f = 400 \text{ MHz}$ ,  $P = 30 \text{ kW}$  100% duty cycle

# Crab cavity cryomodules: thermal calculations

## 3. BNL power coupler: Numerical (HFSS/ANSYS coupling)

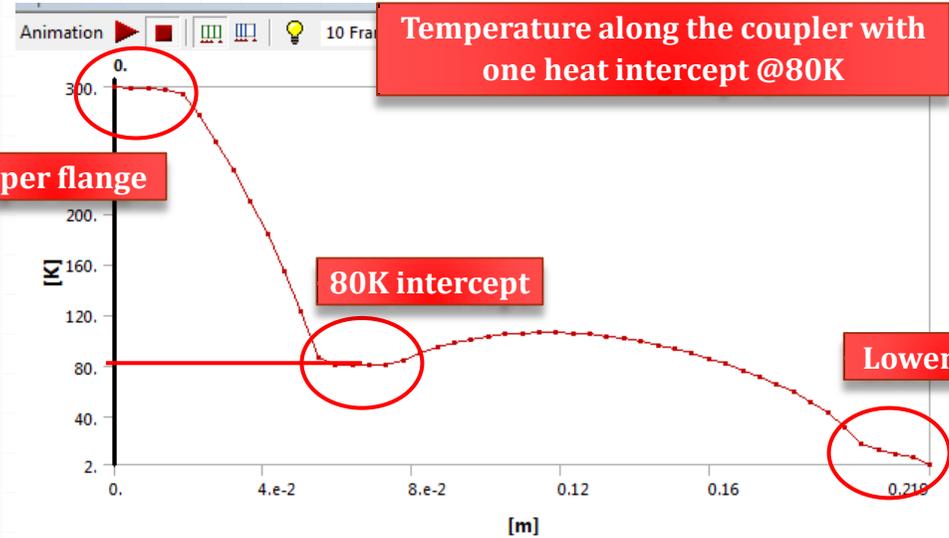
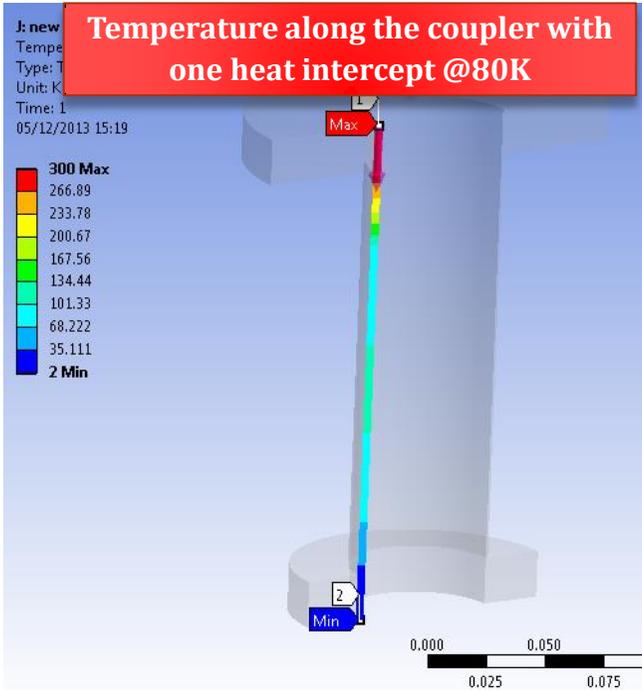
- a. Calculate the dissipated power with HFSS
- b. Prepare the ANSYS model (materials, mesh, boundaries, etc.)
- c. Import the surface loss density calculated with HFSS into ANSYS
- d. Launch the thermal calculation in ANSYS



# Crab cavity cryomodules: thermal calculations

## 3. BNL power coupler: Numerical (HFSS/ANSYS coupling) Results:

Temperature along the coupler with one heat intercept @80K



Temperature along the coupler with one heat intercept @80K

**Thermal losses (W) with and without 80K heat intercept  
(Wall Thickness = 1 mm, L=219mm)**

	RF off	RF on (P = 30 kW, f = 400 MHz)
No cooling	4.1 W @2K	6.3 W @2K
Cooling with 1 Heat intercept (80K) x/L=26%	<b>~1.3 W @2K</b> 14.4 W @80K	<b>~2.3 W @2K</b> 19.2 W @80K



# Outline

EN

Engineering Department

- Principles of cryostat insulation
- Crab Cavity cryomodules
  - Heat losses balance
  - Thermal calculations
- **Conclusions**





# Conclusions

EN

Engineering Department

- The highest contribute to the thermal losses to the cold mass is given by **conduction**
- The number of interconnections between the cold mass and the surrounding environments at higher temperature should be minimized
- The **material and geometry of such interconnections is being optimized from the thermal point of view**
- This operation is **particularly important for the SPS**, which has a limited thermal budget and the only active cooling will be via **one 80K nitrogen circuit**
- The total losses for each cryomodule have been estimated and a table is given, referred to the **worst case between the 3 cryomodules** (see K. Brodzinski's presentation)
- **Mechanical calculations ongoing to assess the feasibility of the proposed solutions!**





***Thank you for your attention!***



EN

Engineering Department





EN

Engineering Department

# *Backup slides*

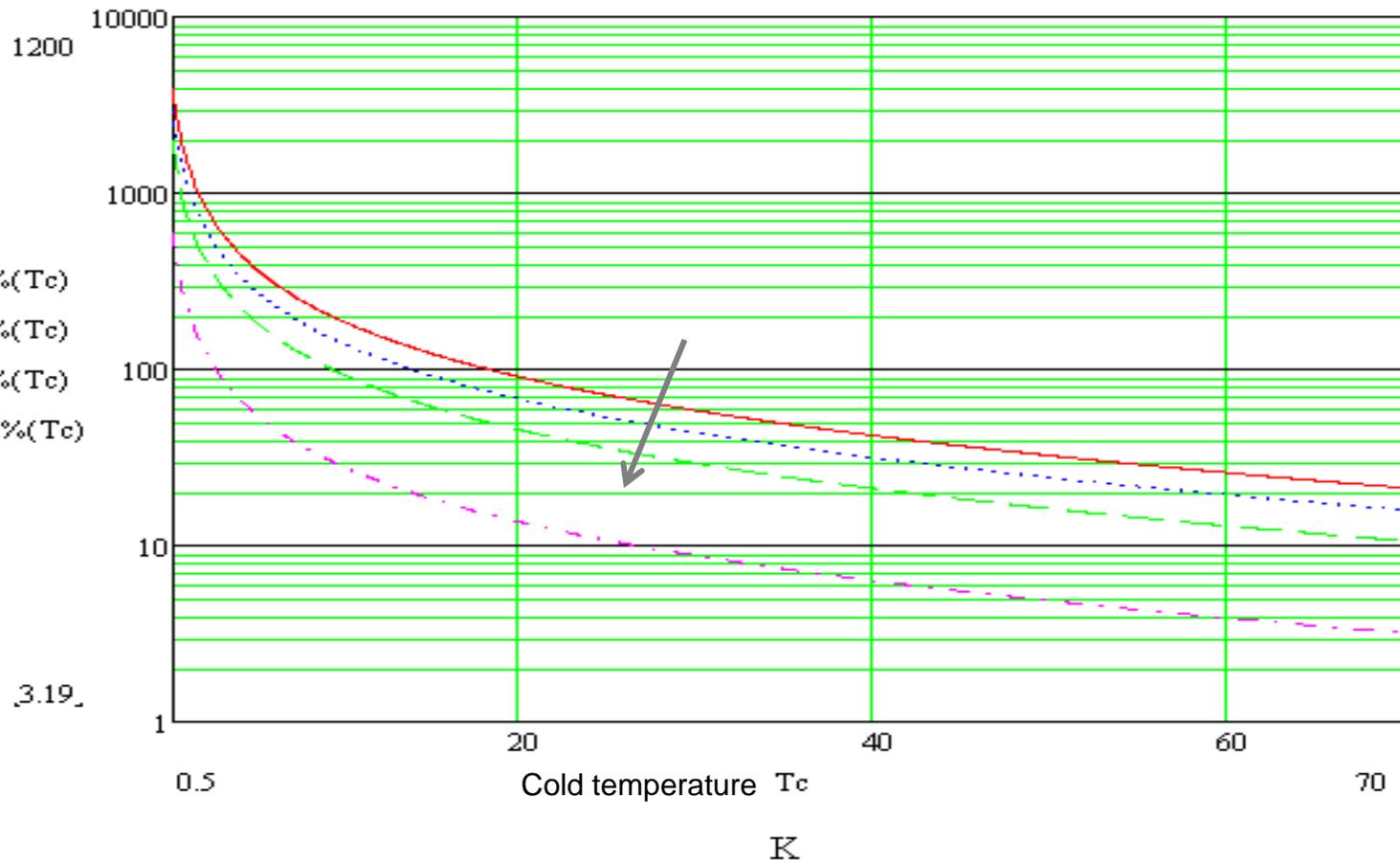




# COP of cryogenic refrigeration

State-of-the-art figures (LHC cryoplants):

- COP @ 2 K → ~ 15% Carnot ( $990 W_{el}/W_{th}$ )\*
- COP @ 4.5 K → ~ 30% Carnot ( $210 W_{el}/W_{th}$ )\*
- COP @ 50 K → ~ 30% Carnot ( $16 W_{el}/W_{th}$ )



EN

Engineering Department

Coeff. Of Performance (COP), (W/W)

Carnot15%(Tc)  
Carnot20%(Tc)  
Carnot30%(Tc)  
Carnot100%(Tc)

3.19

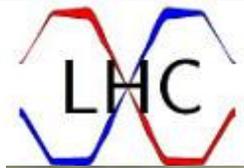
0.5

Cold temperature  $T_c$

K

60

70



# LHC Multi Layer Insulation (MLI)

## Features:

- 1 blanket (10 reflective layers) on cold masses (1.9 K)
- 2 blankets (15 reflective layers each) on Thermal Shields (50-65 K)
- Reflective layer: double aluminized polyester film
- Spacer: polyester net
- Stitched Velcro™ fasteners for rapid mounting and quality closing



Interleaved reflectors and spacers



Velcro™ fasteners



Blanket manufacturing



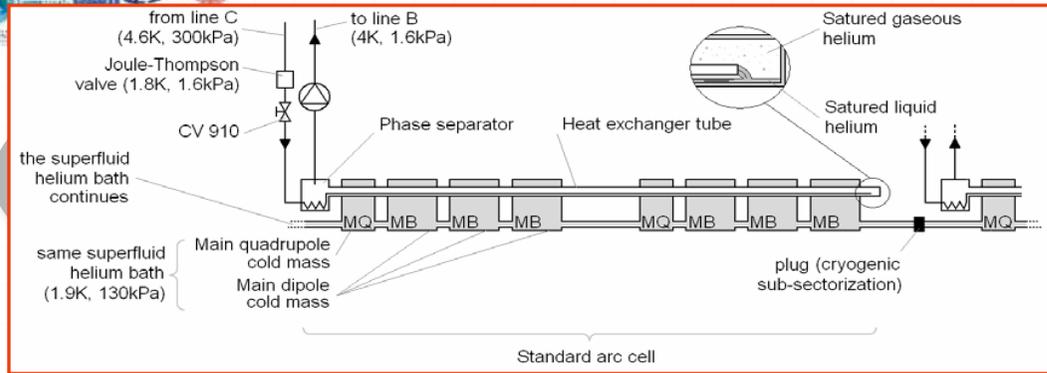
TTC Meeting

1 blanket on CM, 2 on thermal shield



# 10 MLI layers @ 2K (from LHeII calorimetric measurements in LHC)

## Static HL natural warm-up of cryogenic subsector after stop in cooling



Schematic cryogenic layout of a standard arc cell. A cryogenic subsector is defined as a unique common superfluid helium bath and includes two or three standard cells. A standard cell includes six dipoles and two quadrupoles and is cooled by a unique heat exchanger tube.

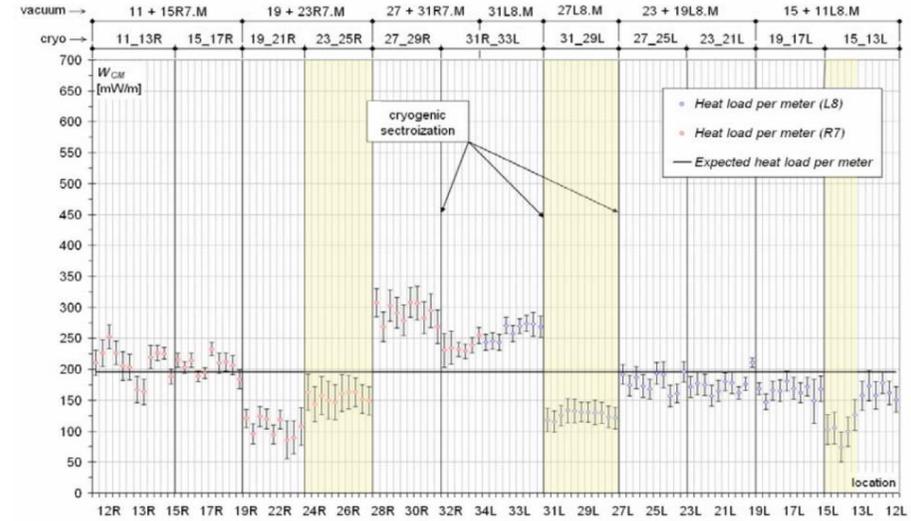
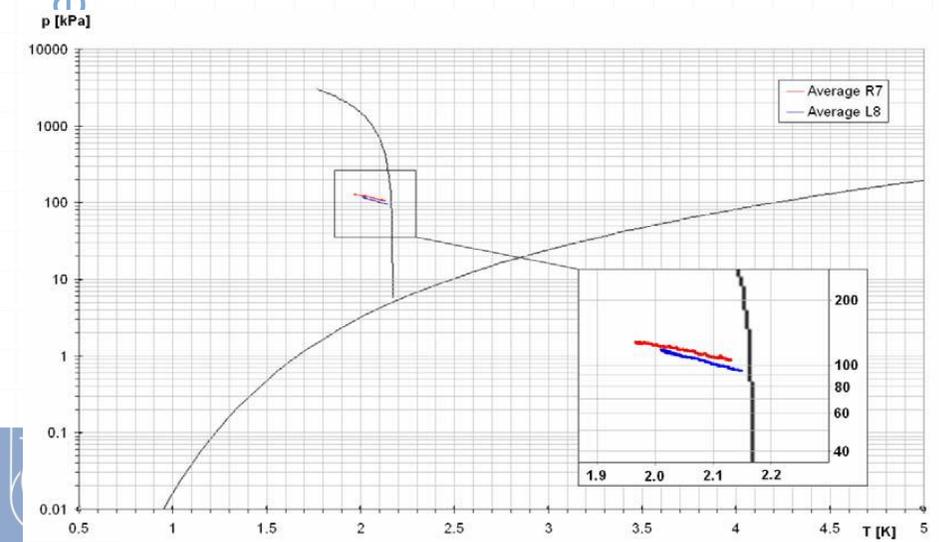


Figure 7 – Cold mass static heat loads in sector 7-8

$$W_{CM} = \frac{\Delta U_{CM}}{\Delta t \cdot L_{CM}}$$

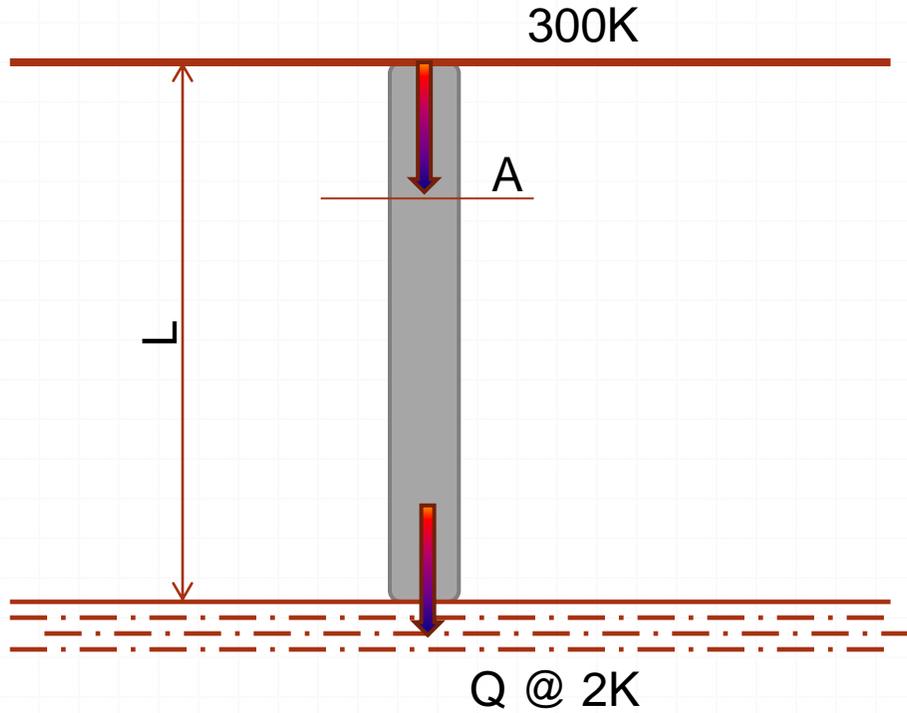


Average transformation in p-T helium phase diagram for the pressurized superfluid helium in the two halves of the sector.

- Average heat load to cold mass (10 MLI layers) ~ **0.2 W/m**
- Rescaled on cold mass surface: → ~ **0.1 W/m<sup>2</sup>**
- This is a conservative engineering figure:
  - Global figure, includes other sources of HL (conduction intercepts, radiation through thermal contractions plays, etc.)

# Ways of intercepting solid-conduction heat in-leaks

A) Pure conduction, no heat intercepts

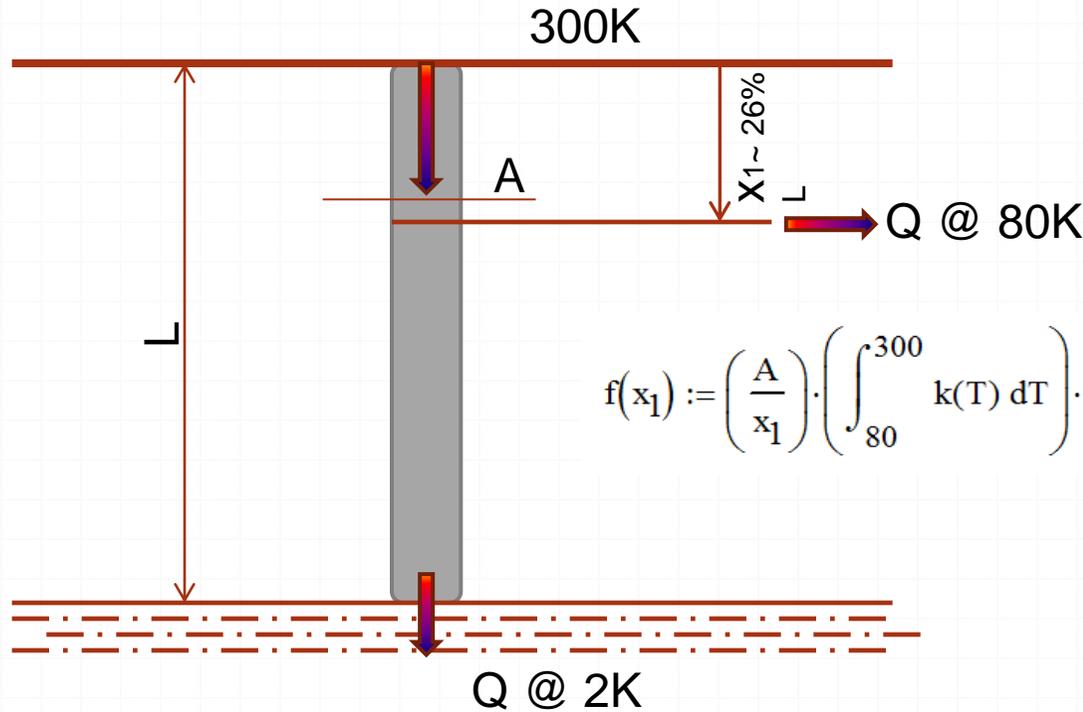


$$Q_{2K} := \frac{A}{L} \cdot \int_{T_c}^{T_w} k(T) dT$$

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
<b>A) No intercept</b>	<b>11.629</b>	<b>11512.71</b>								<b>11,513</b>

# Ways of intercepting solid-conduction heat in-leaks

B) Perfect heat intercept @ 80 K, in optimized position (w.r.t total power)



Minimizing using cost factors:  
 $C_1 = 16 \text{ w/w}$   
 $C_3 = 990 \text{ w/w}$

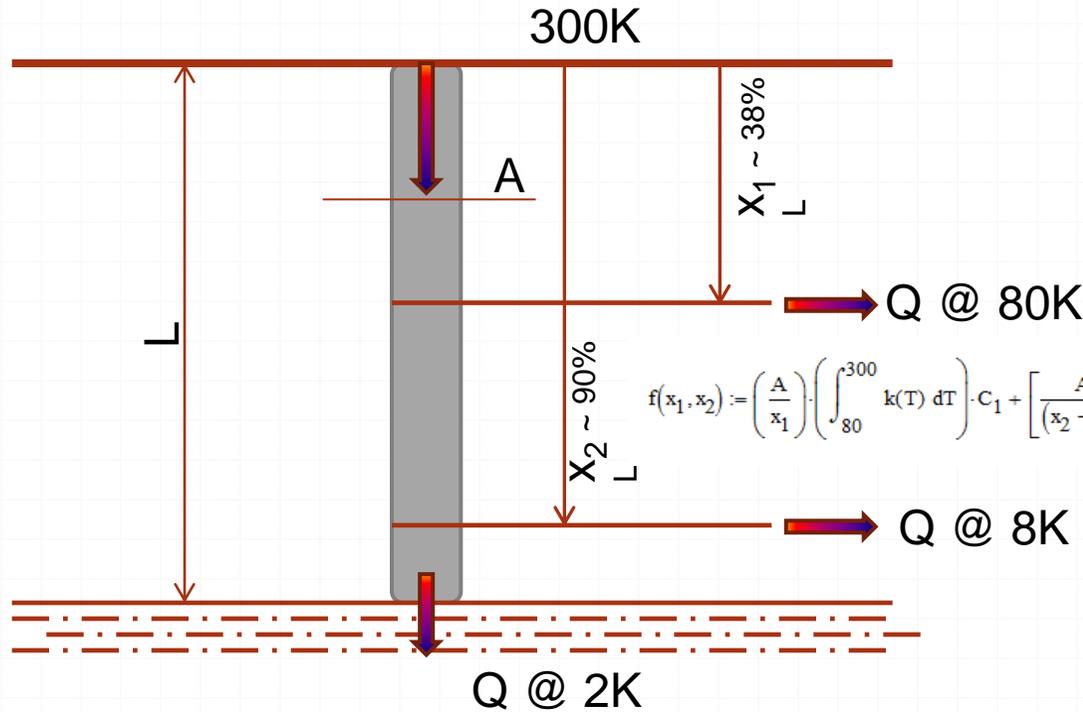
$$f(x_1) := \left( \frac{A}{x_1} \right) \cdot \left( \int_{80}^{300} k(T) dT \right) \cdot C_1 + \left[ \frac{A}{(L - x_1)} \right] \cdot \left( \int_2^{80} k(T) dT \right) \cdot C_3$$

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
<b>B) 1 optimised and perfect intercept @ 80K</b>	<b>1.816</b>	<b>1797.84</b>			<b>39.513</b>	<b>632.208</b>				<b>2,430</b>



# Ways of intercepting solid-conduction heat in-leaks

C) Perfect heat intercepts @ 80 K & 8 K in optimized position (w.r.t total power)



Minimizing using cost factors:  
 $C_1 = 16 \text{ w/w}$   
 $C_2 = 210 \text{ w/w}$   
 $C_3 = 990 \text{ w/w}$

$$f(x_1, x_2) := \left(\frac{A}{x_1}\right) \cdot \left(\int_{80}^{300} k(T) dT\right) \cdot C_1 + \left[\frac{A}{(x_2 - x_1)}\right] \cdot \left(\int_8^{80} k(T) dT\right) \cdot C_2 + \left[\frac{A}{(L - x_2)}\right] \cdot \left(\int_2^8 k(T) dT\right) \cdot C_3$$

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
B) 1 optimised and perfect intercept @ 80K	1.816	1797.84			39.513	632.208				2,430
C) 2 optimised and perfect intercepts @ 80K & 8K	0.129	127.71	2.64	580.8	26.816	429.056				1,138

EN

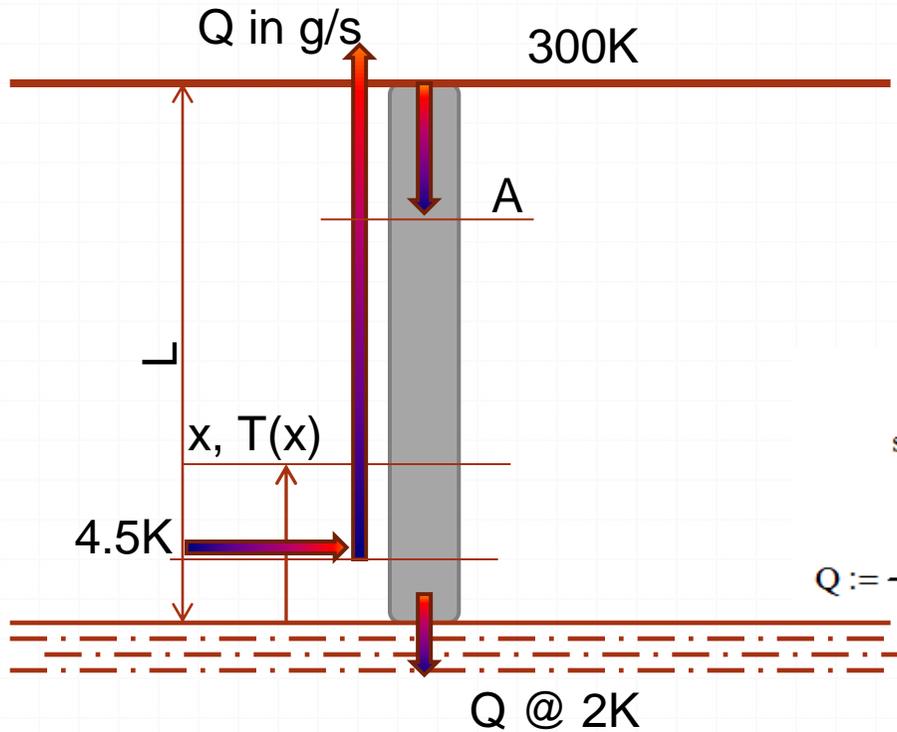
Engineering Department





# Ways of intercepting solid-conduction heat in-leaks

D) Self-sustained He vapour cooling, 4.5 K-300 K



**Assuming:**

- $T_{\text{vapour}} = T_{\text{support}}$   
(perfect heat exchange)
- $Q_{4.5K} = L_v \cdot \frac{dm}{dt}$   
(vapour generated only by residual heat conduction to 4.5 K bath)

$$Q := \frac{k(T)}{\text{length} - L_f} \cdot \left[ 1 + (T - T_{\text{bath}}) \cdot \frac{cp(T)}{L_{he}} \right]$$

attenuation factor

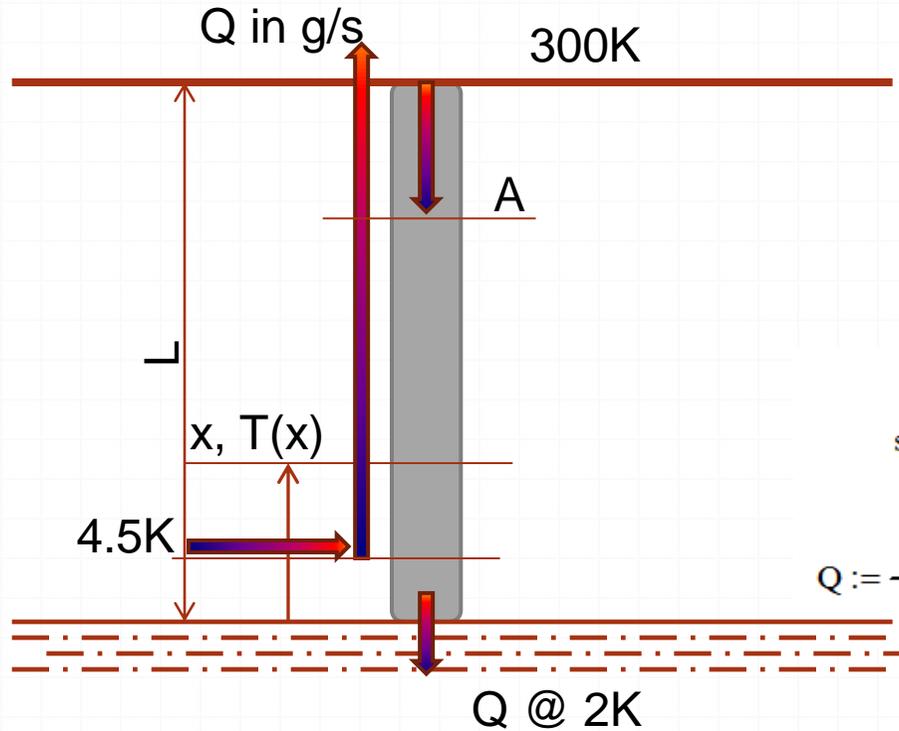
Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
B) 1 optimised and perfect intercept @ 80K	1.816	1797.84			39.513	632.208				2,430
C) 2 optimised and perfect intercepts @ 80K & 8K	0.129	127.71	2.64	580.8	26.816	429.056				1,138
D) 4.5K self-sustained vapour cooling	0.031	30.69					0.019	1.9	407	438

**Conclusion:** Vapour cooling on st. steel supports, if optimally exploited, can provide more than a factor 2 electrical power saving w.r.t. standard heat intercept techniques



# Ways of intercepting solid-conduction heat in-leaks

D) Self-sustained He vapour cooling, 4.5 K-300 K



**Assuming:**

- $T_{\text{vapour}} = T_{\text{support}}$   
(perfect heat exchange)
- $Q_{4.5K} = L_v * dm/dt$   
(vapour generated only by residual heat conduction to 4.5 K bath)

$$Q := \frac{k(T)}{\text{length} - L_f} \cdot \left[ 1 + (T - T_{\text{bath}}) \cdot \frac{cp(T)}{L_{\text{he}}} \right]$$

attenuation factor

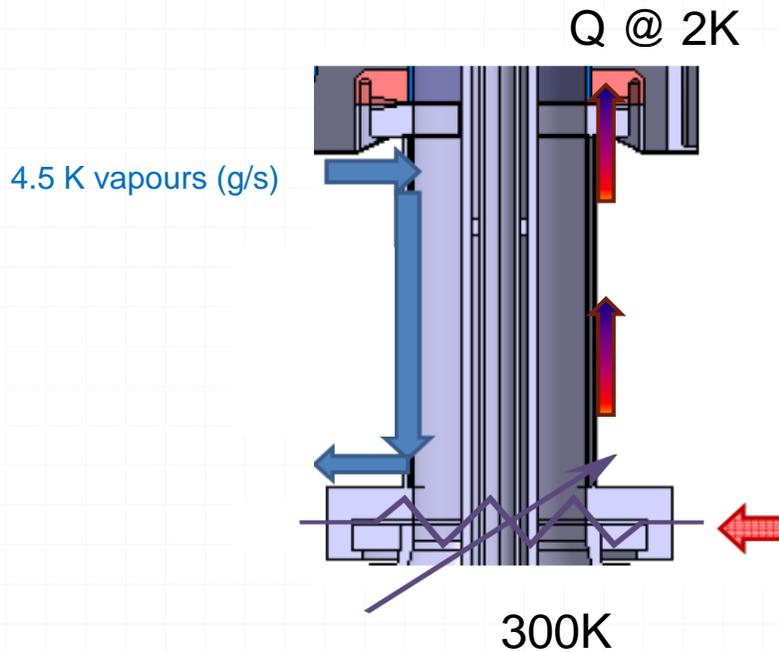
the gas cooling is a non-isothermal phenomenon (values of row "D"). to compare it to the other powers you need to consider an equivalent isothermal power at 4.5K: 100 W at 4.5K for 1 g/s helium gas. This value takes into account (i) the thermodynamic transformations required to re-liquefy the warm gas and (ii) the refrigerator efficiency with respect to Carnot. See for more details <http://cds.cern.ch/record/808372/files/p295.pdf>

**Conclusion:** Vapour cooling on st.steel supports, if optimally exploited, can provide **more than a factor 2 electrical power saving** w.r.t. standard heat intercepts techniques



# Ways of intercepting solid-conduction heat in-leaks

E) Real case, He vapour cooling, 4.5 K-300K



## Assuming:

- $T_{\text{vapour}} \neq T_{\text{support}}$  (real convection)
- $dm/dt$  set to 0.04 g/s
- Cu conduction (internal wall)
- Radiation heat load
- Electrical power to keep 300K (or > dew point): 60 W

## Analysis of thermal performance:

- Semi-analytical model, 3 layers, 1D meshing
- Work done by R.Bonomi, CERN TE-MS

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
B) 1 optimised and perfect intercept @ 80K	1.816	1797.84			39.513	632.208				2,430
C) 2 optimised and perfect intercepts @ 80K & 8K	0.129	127.71	2.64	580.8	26.816	429.056				1,138
D) 4.5K self-sustained vapour cooling	0.031	30.69					0.019	1.9	407	438
E) Real case, He vapour cooling, 4.5K-300K	0.1	99					0.04	4	880	1,039

Now the power gain appears marginal w.r.t. case C), which is an ideal simplified case.

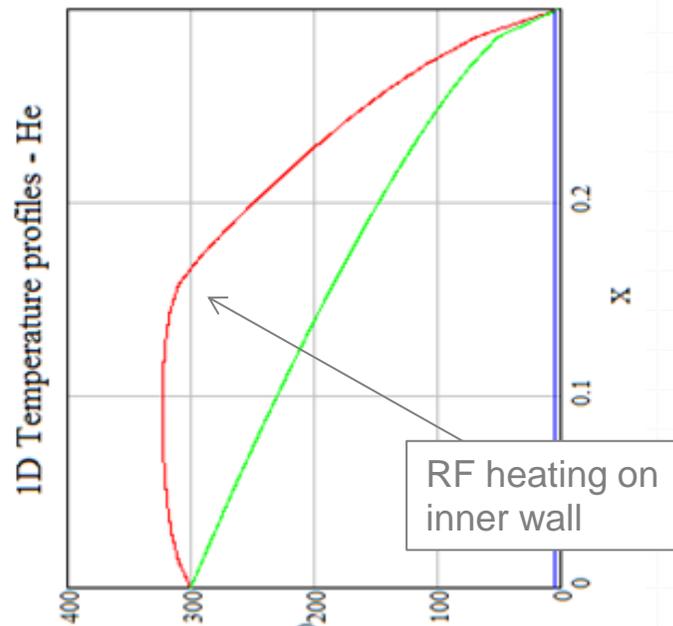
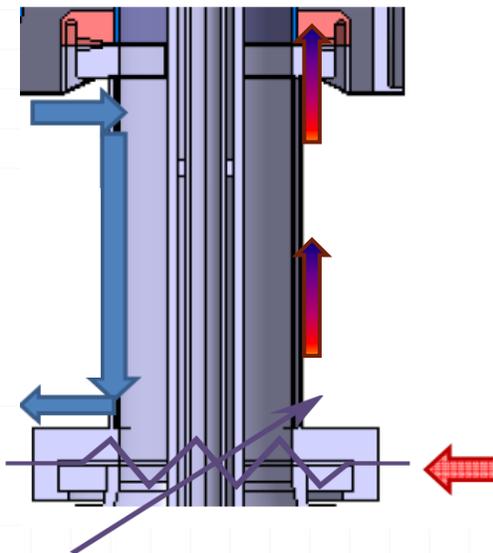
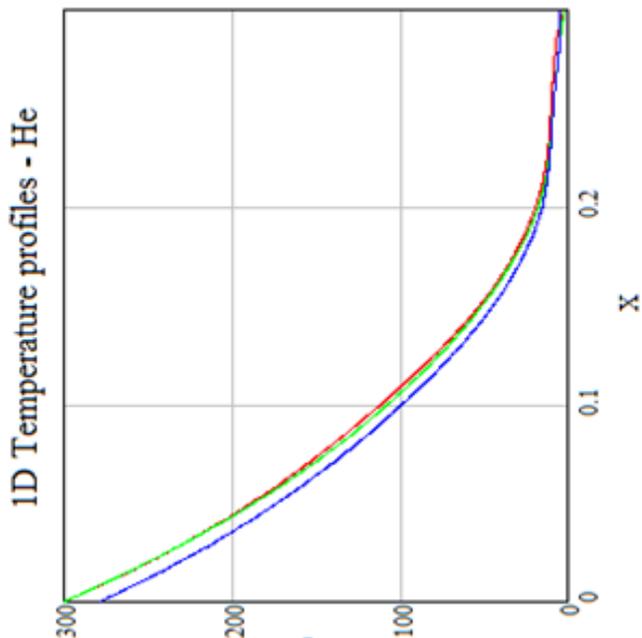


# Ways of intercepting solid-conduction heat in-leaks

F) Real case, He vapour cooling, 4.5K-300K, RF power on

**RF power on**

G) Real case, No He vapour cooling, RF power on



**When RF is on, a distributed vapour cooling is essential to contain distributed RF heating (local heat intercepting can hardly provide efficient cooling)**

Case	Q @ 2K [W]	Wel [W]	Q @ 8K [W]	Wel [W]	Q @ 80K [W]	Wel [W]	vapours rate g/s	Q equiv. @ 4.5K [W] (1g/s=100W)	Wel [W]	Total Wel [W]
A) No intercept	11.629	11512.71								11,513
B) 1 optimised and perfect intercept @ 80K	1.816	1797.84			39.513	632.208				2,430
C) 2 optimised and perfect intercepts @ 80K & 8K	0.129	127.71	2.64	580.8	26.816	429.056				1,138
D) 4.5K self-sustained vapour cooling	0.031	30.69					0.019	1.9	407	438
E) Real case, He vapour cooling, 4.5K-300K	0.1	99					0.04	4	880	1,039
<b>F) Real case, He vapour cooling, 4.5K-300K, RF power on</b>	<b>0.5</b>	<b>495</b>					<b>0.04</b>	<b>4</b>	<b>880</b>	<b>1,435</b>
<b>G) Real case, No He vapour cooling, RF power on</b>	<b>22</b>	<b>21780</b>					<b>0</b>	<b>0</b>	<b>0</b>	<b>21,780</b>

# Crab cavity cryomodules: thermal calculations

## 2. ODU high-order mode coupler: Semi-analytical

- Contributions considered: conduction + dissipated power (when RF is on)

$$Q_{\text{condI}}(T_a, T_b) := - \int_{T_a}^{T_b} \frac{k(T) \cdot A}{dx} dT$$

$$P_{\text{rf}}(T_{\text{wallI}}, i) := \frac{1}{2} \int_{x_i - \frac{dx}{2}}^{x_i + \frac{dx}{2}} I_{\text{eq}}(X)^2 \cdot R_{\text{wall}}(T_{\text{wallI}}) dX$$

$$I(x) := I_0 \cdot 2 \cdot \sin\left(\frac{\omega}{c} \cdot x\right)$$

$$I_0 := \left(2 \cdot \frac{P_p}{Z_0}\right)^{0.5} = 10.954 \text{ A}$$

$$c = 2.998 \times 10^8 \frac{\text{m}}{\text{s}}$$

$$f := 1000 \cdot 10^6 \text{ Hz}$$

$$\omega := 2 \cdot \pi \cdot f$$

$$I_1(x) := I_0$$

$$I_2(x) := I_g(1.1 \cdot \text{period}, 0, 0, x)$$

$$I_3(x) := I_g(1.0 \cdot \text{period}, 1, 0, x)$$

$$I_4(x) := I_g(1.25 \cdot \text{period}, 1, \pi, x)$$

$$I_5(x) := I_0 \cdot 2 \cdot \sin\left(\frac{\omega}{c} \cdot x\right)$$

$$Q_{\text{condI}}(T_{w1}, T_{w2}) + P_{\text{rf}}(T_{w2}, 2) + Q_{\text{rad}}(T_{w2}, 2) = Q_{\text{condI}}(T_{w2}, T_{w3}) + Q_{\text{convI}}(T_{w2}, T_{g2}, \text{hgas}, 2)$$

$$Q_{\text{convI}}(T_{w2}, T_{g2}, \text{hgas}, 2) + Q_{\text{convE}}(T_{wE2}, T_{g2}, \text{hgas}, 2) = -Q_{\text{gas}}(T_{g1}, T_{g2})$$

$$Q_{\text{condE}}(T_{wE1}, T_{wE2}) = Q_{\text{condE}}(T_{wE2}, T_{wE3}) + Q_{\text{convE}}(T_{wE2}, T_{g2}, \text{hgas}, 2)$$

### Travelling Wave envelope

R = 0, phase = 0 deg => SW to build TW envelope

R = 1, phase = 0 deg => **full reflection, no beam**, open circuit at cold end

R = 1, phase = 180 deg => **full reflection, beam loading**

i tempi corretti sono stati ottenuti con un file di prova in modo da avere il max envelope (andrebbero fatti meglio, usando formula di Rolf che descrive l'envelope)

# Crab cavity cryomodules: thermal calculations

## 2. ODU high-order mode coupler: Semi-analytical

- Contributions considered: conduction + dissipated power (when RF is on)

$$Q_{cond}(T_a, T_b) := - \int_{T_a}^{T_b} \frac{k(T) \cdot A}{dx} dT$$

$$Prf(T_{wall}, i) := \frac{1}{2} \int_{x_i - \frac{dx}{2}}^{x_i + \frac{dx}{2}} I_{eq}(X)^2 \cdot R_{wall}(T_{wall}) dX$$

$$I(x) := I_0 \cdot 2 \cdot \sin\left(\frac{\omega}{c} \cdot x\right)$$

- $x_i$  = coordinate of i-node
- $dx$  = element length;  $A$  = conducting section
- $R_{wall}$  = resistance of tube wall as a function of temperature

$$I_1(x) := I_0$$

$$I_2(x) := I_g(1.1 \cdot \text{period}, 0, 0, x)$$

$$I_3(x) := I_g(1.0 \cdot \text{period}, 1, 0, x)$$

$$I_4(x) := I_g(1.25 \cdot \text{period}, 1, \pi, x)$$

$$I_5(x) := I_0 \cdot 2 \cdot \sin\left(\frac{\omega}{c} \cdot x\right)$$

### Travelling Wave envelope

$R = 0$ , phase = 0 deg => SW to build TW envelope

$R = 1$ , phase = 0 deg => **full reflection, no beam**, open circuit at cold end

$R = 1$ , phase = 180 deg => **full reflection, beam loading**

i tempi corretti sono stati ottenuti con un file di prova in modo da avere il max envelope (andrebbero fatti meglio, usando formula di Rolf che descrive l'envelope)

$$I_0 := \left(2 \cdot \frac{P_p}{Z_0}\right)^{0.5} = 10.954 A$$

$$c = 2.998 \times 10^8 \frac{m}{s}$$

$$f := 1000 \cdot 10^6 \text{ Hz}$$

$$\omega := 2 \cdot \pi \cdot f$$

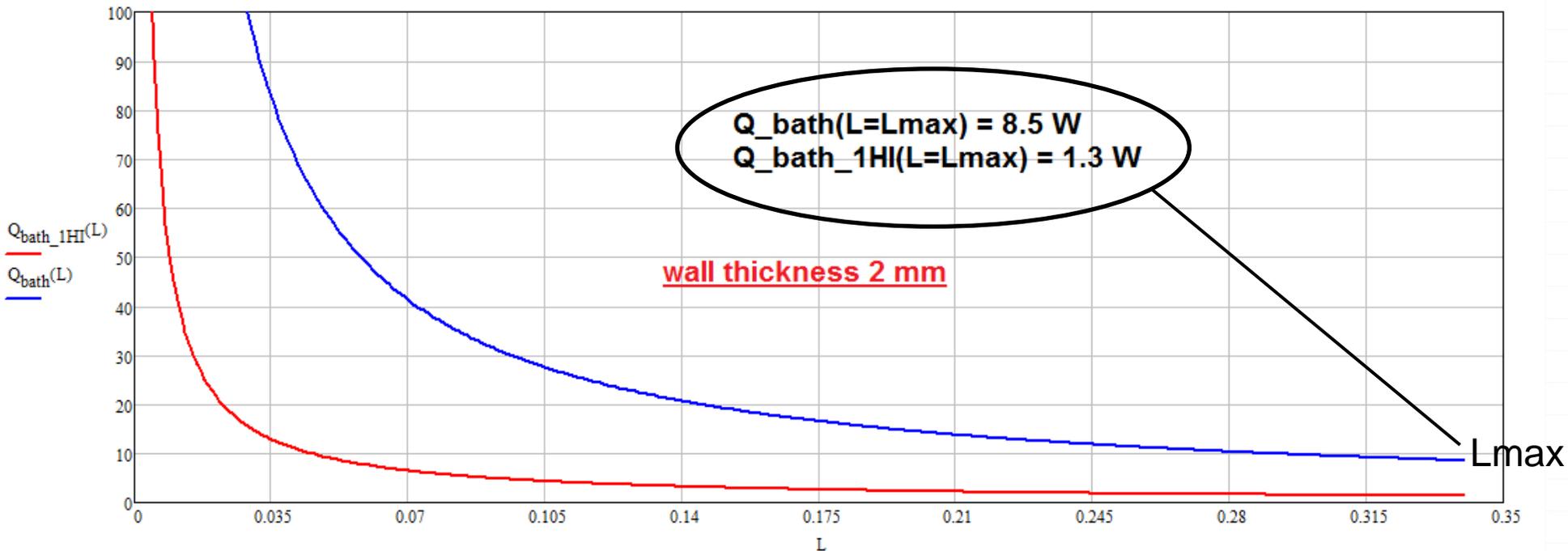


# Thermal analysis of HOM coupler

**Results for RF power OFF:** results without RF power, for a wall thickness of 2 mm: thermal load to the bath with and without heat interceptor for different lengths of the tube not covered by He bath.

Engineering Department

Thermal load to the bath for different chimney lengths not immersed into He bath, with and without 1 optimized heat interceptor (W)

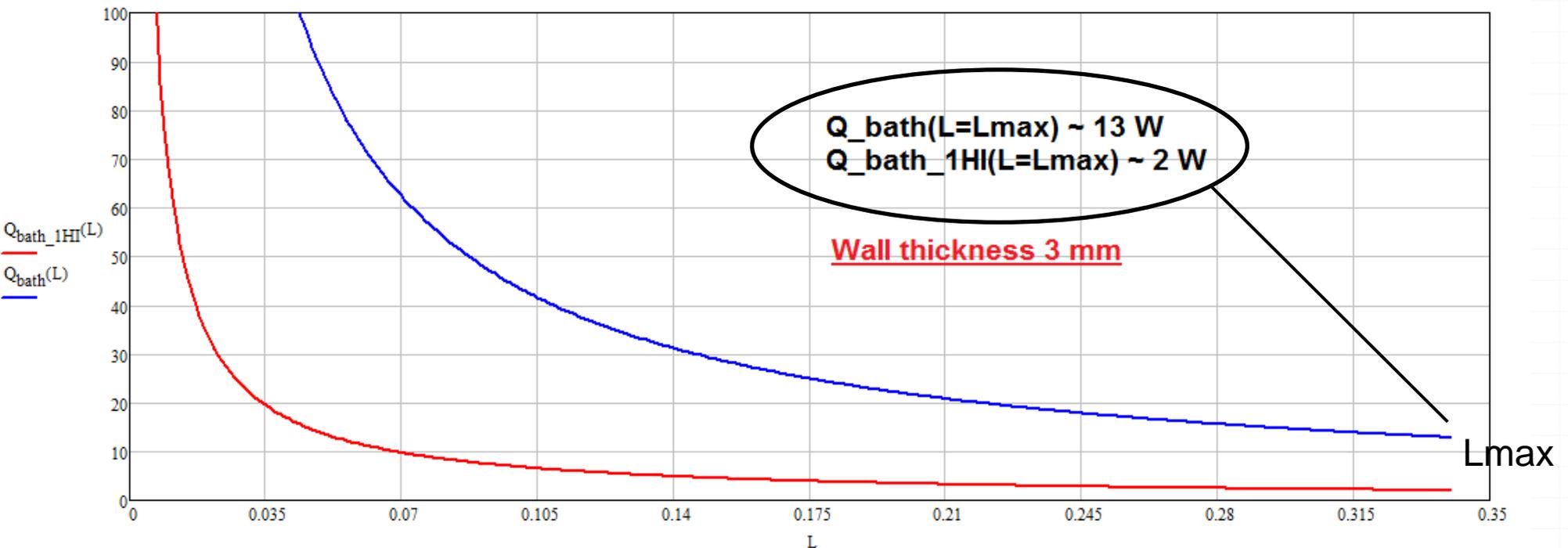




# Thermal analysis of HOM coupler

**Results for RF power OFF:** results without RF power, for a wall thickness of 3 mm: thermal load to the bath with and without heat interceptor for different lengths of the tube not covered by He bath.

Thermal load to the bath for different chimney lengths not immersed into He bath, with and without 1 optimized heat interceptor (W)

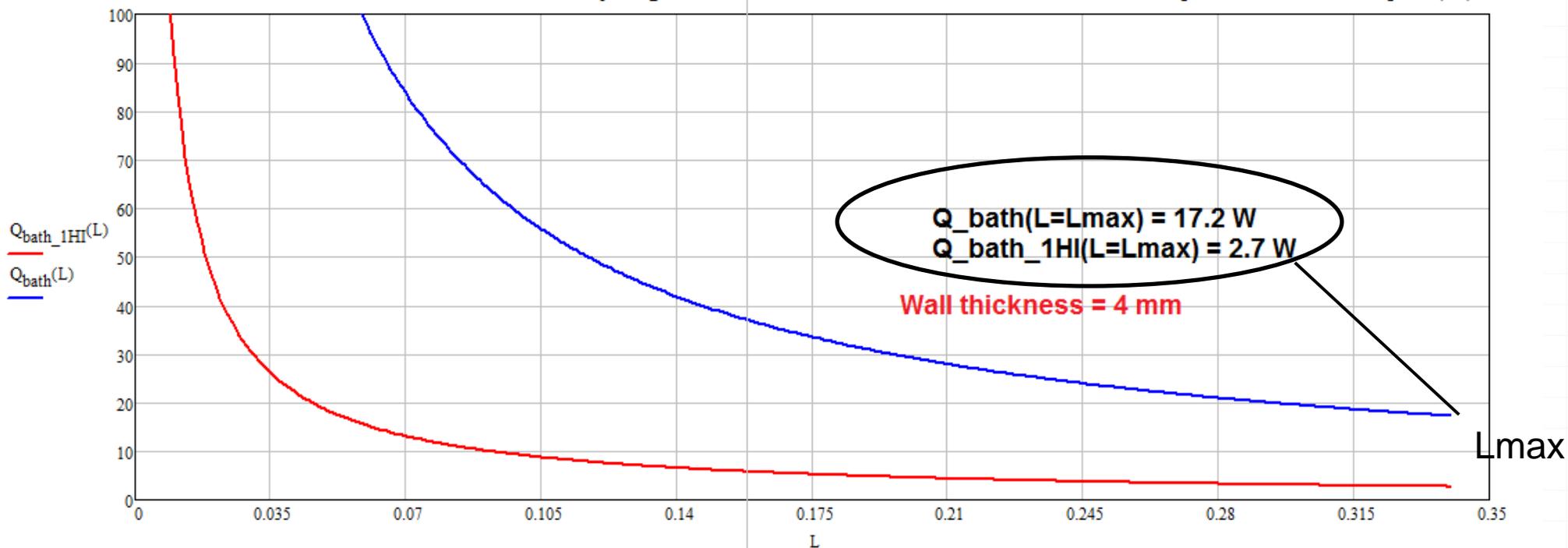




# Thermal analysis of HOM coupler

**Results for RF power OFF:** results without RF power, for a wall thickness of 4 mm: thermal load to the bath with and without heat interceptor for different lengths of the tube not covered by He bath.

Thermal load to the bath for different chimney lengths not immersed into He bath, with and without 1 optimized heat interceptor (W)





# Thermal analysis of HOM coupler

Result summary, for different wall thickness and  $L=L_{max}$

Values of  $Q_{bath}$  (W); Wall Thickness = 2 mm,  $L=L_{max}=340\text{mm}$

	No RF	RF ( $P_p = 3 \text{ kW}$ , $f = 1000 \text{ MHz}$ )
No cooling	8.5 W	8.7 W
1 Heat interceptor (80K)	1.3 W ( $x=88 \text{ mm}$ , $x/L=26\%$ )	1.4 W ( $x = 88 \text{ mm}$ )

Values of  $Q_{bath}$  (W); Wall Thickness = 3 mm,  $L=L_{max}=340\text{mm}$

	No RF	RF ( $P_p = 3 \text{ kW}$ , $f = 1000 \text{ MHz}$ )
No cooling	12.8 W	13 W
1 Heat interceptor (80K)	2 W ( $x=88 \text{ mm}$ , $x/L=26\%$ )	2 W ( $x = 88 \text{ mm}$ )

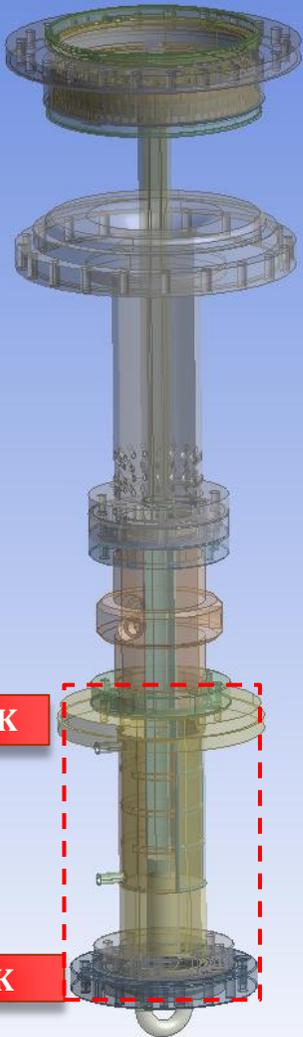
Values of  $Q_{bath}$  (W); Wall Thickness = 4 mm,  $L=L_{max}=340\text{mm}$

	No RF	RF ( $P_p = 3 \text{ kW}$ , $f = 1000 \text{ MHz}$ )
No cooling	17.2 W	17.4 W
1 Heat interceptor (80K)	2.7 W ( $x=88 \text{ mm}$ , $x/L=26\%$ )	2.7 W ( $x = 88 \text{ mm}$ )

No sensible effect of the RF losses with the inputs considered

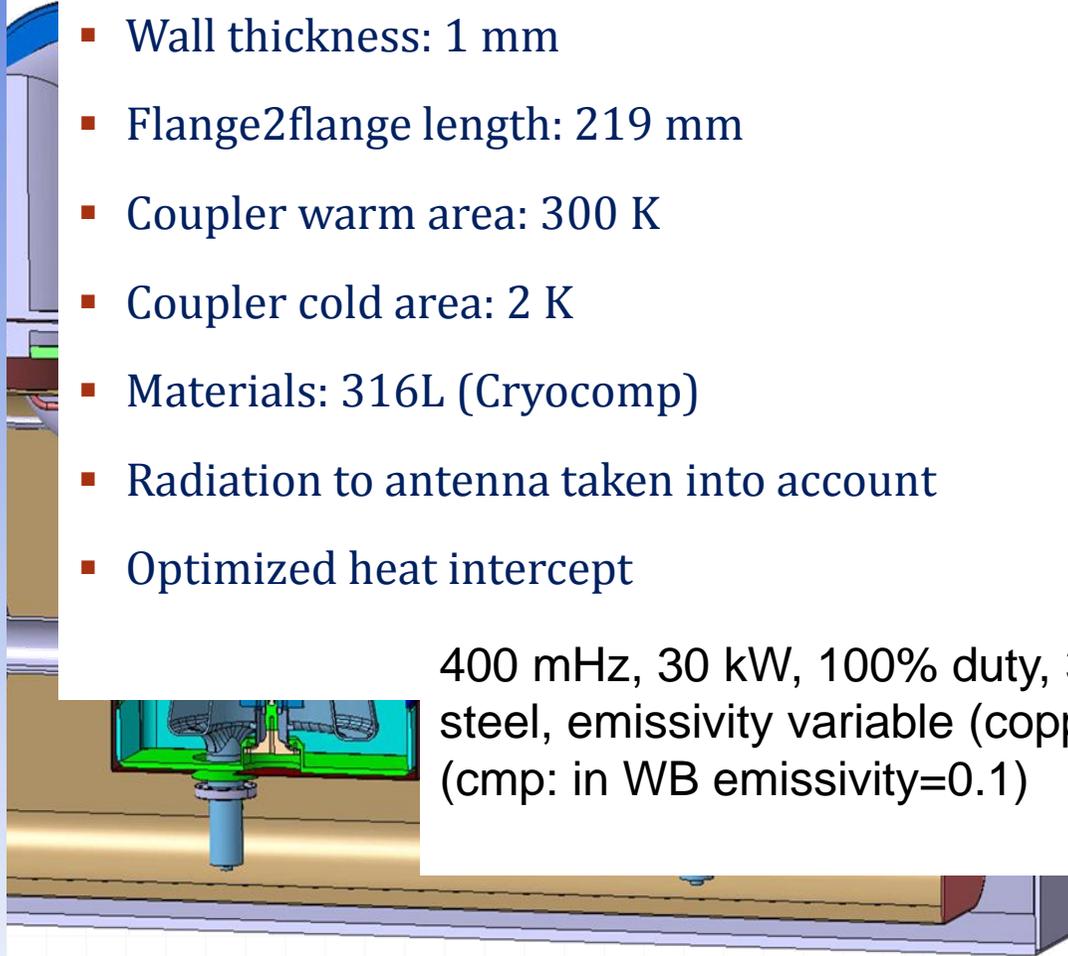
# Crab cavity cryomodules: thermal calculations

## 3. BNL power coupler: Numerical (HFSS/ANSYS coupling)



- Wall thickness: 1 mm
- Flange2flange length: 219 mm
- Coupler warm area: 300 K
- Coupler cold area: 2 K
- Materials: 316L (Cryocomp)
- Radiation to antenna taken into account
- Optimized heat intercept

400 mHz, 30 kW, 100% duty, 300-2K, 1mm steel, emissivity variable (copper) 0.02-0.1 (cmp: in WB emissivity=0.1)



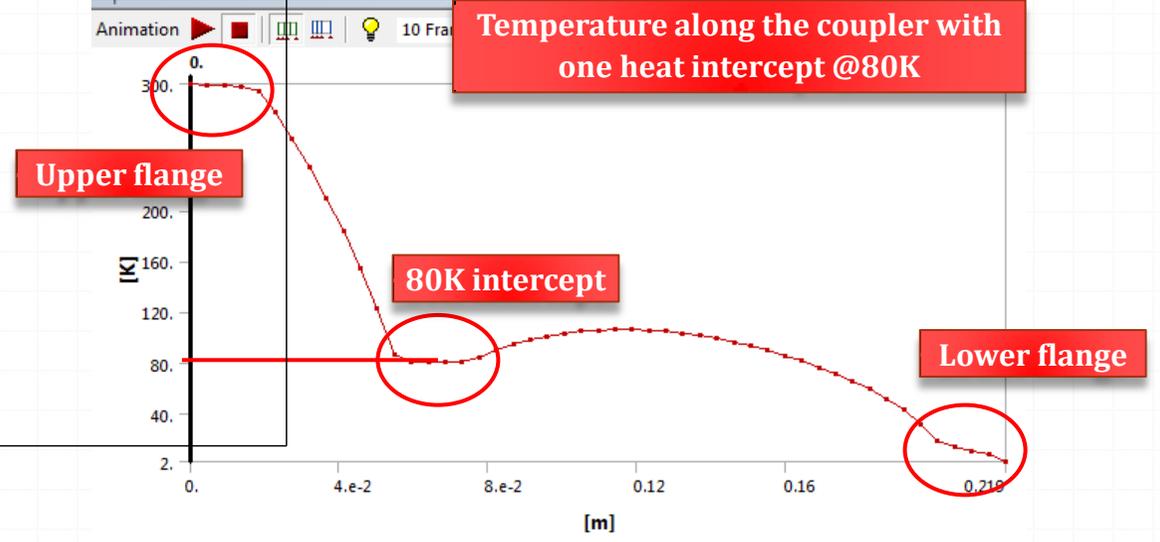
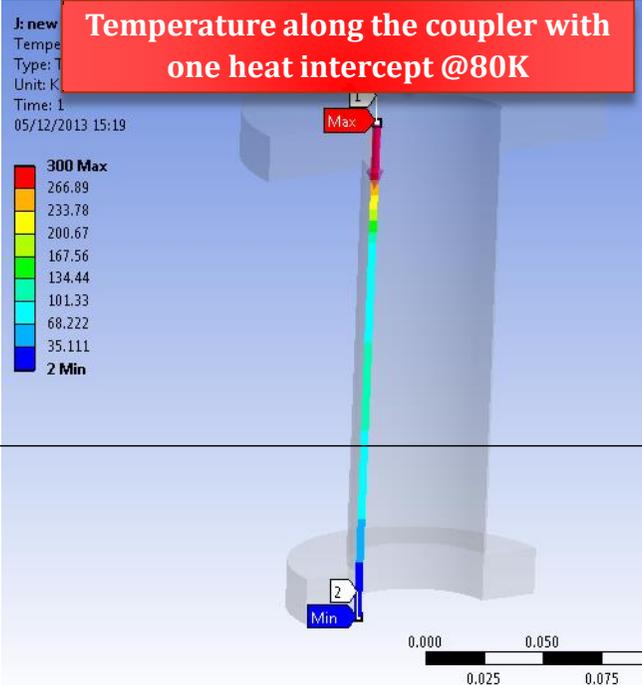
219 mm long (flange to flange)  
 62 mm inner diameter  
 wall emissivity = 0.1  
 antenna radiation at 300 K ("to ambient")

# Crab cavity cryomodule: thermal calculations

## 3. BNL power coupler: Numerical (HFSS/ANSYS coupling) Results:



Engineering Department



	[W]	NO INTERCEPT	80 K INTERCEPT
NO RF	Q 2 K	-4.119	-1.272
	Q 300 K	+2.833	+14.088
	Q 80 K	-	-14.472
	Q rad	+1.301	+1.696
	error	< 1 mW	78 mW only at intercept location
30 kW input RF POWER	Q 2 K	-6.308	-2.342
	Q 300 K	-2.604	+11.786
	Q 80 K	-	-19.166
	Q rad	+0.890	+1.684
	error	10 mW	95 mW only at intercept location
RF dissipated [W]		~ 2	~ 1

1 mm steel wall, no copper  
 219 mm long (flange to flange)  
 62 mm inner diameter  
 wall emissivity = 0.1  
 antenna radiation at 300 K ("to ambient")