MEMORANDUM

Date: February 8, 2012
To: MICE Coupling Coil Distribution
From: Alexi Radovinsky
Subject: Thermal FEA of Intermediate Cooling Station
Ref: MICECC -ARadovinsky-120208-01

Executive Summary

Results of the initial sizing of the Copper Current Leads for the MICE Coupling Coil were reported in [1]. They were based on the previous studies by Michael Green [2] and Li Wang [3], as well as specifications [4, 5] for the CRYOMECH Cryocoolers PT415. The present study concentrates on the FE thermal analyses of the intermediate cooling station [6] integrating 3 cryocoolers on 3 copper plates connected by 2 pairs of copper joint straps, and 2 copper blocks with prongs for terminals for the RT and HTS current leads. Perimeter of the array of copper plates is bolted to the intermediate radiation shield. The design of the intermediate cooling station is changed per recommendations by Alex Zhukovsky [8].

Thermal FEA was performed using TEMPO, a thermal package of the Vector Fields Opera program. A separate program using Mathematica was written to find a balance between the heat loads, the power vs. temperature performance characteristic of cryocoolers and the calculated temperature distribution in the copper plates. Here the performance of each cryocooler was taken in account individually, whereas in [1] the assumption was that all cryocoolers provide the same cooling power at the same temperature of the first stage.

The general conclusions are that for the current design
- Due to the abundance of the cooling power at the first stations of the cryocoolers their temperatures are close to 37 K and the cooling power is evenly shared between 29 W in the Central cryocooler and 32 W in the Side cryocoolers.
- With a 2-mil Kapton electrical insulator between the Copper Plate and the Copper Block the warmest point of the model, the Copper Current Lead terminal of the Copper Block, is just 2 K warmer than the first station of the cryocooler attached to the Side Copper Plate. Temperature drop across the electrical insulator is a fraction of 1 K.
- Power sharing between the Central and 2 Side Copper Plates is essential for redistributing cooling power of the cryocoolers. Without Copper Straps the Central cryocooler is loaded 3 times less than each of the Side cryocoolers and its working temperature is almost 6 K lower.

Design Changes

In the current baseline design [6] Copper Blocks carrying the transport current are bolted to the Copper Plates using rather complicated G10 insulating inserts. Copper Blocks are electrically insulated from the Copper Plates by a thick G10 insulating plate. Alex Zhukovsky recommended a different scheme [8], which is implemented in the FE model. The Copper Block has no holes in it. It is wrapped into Kapton and clamped to the Copper Plate by 2 SS plates, one below the Copper Block and one above the Copper Plate, tied together by 6 bolts, 3 in a row on each side of the Copper Block. SS plates are insulated from the Copper Block by Kapton and their connection bolts need no insulation from the Copper Plates. The distance between the holes and the edge of the Copper Plate is sufficient for the present bolted connection to the radiation shield. To make this possible the width of the Copper Blocks is reduced from 82 mm to 60 mm. The width of the terminal prongs is scaled in the same proportion, 60/82.

Model

These changes are introduced in the thermal FE model. Note that heat transfer through the SS clamping plates is negligible compared to the heat flow from the Copper Block to the Copper Plate through the Kapton insulation. Consequently, the SS clamping plates are not included in the FE model. The bottom and the top views of the Copper Plate Assembly are shown in Figs. 1.a and 1.b. Figure 1.c shows a better view of the parts in the model.

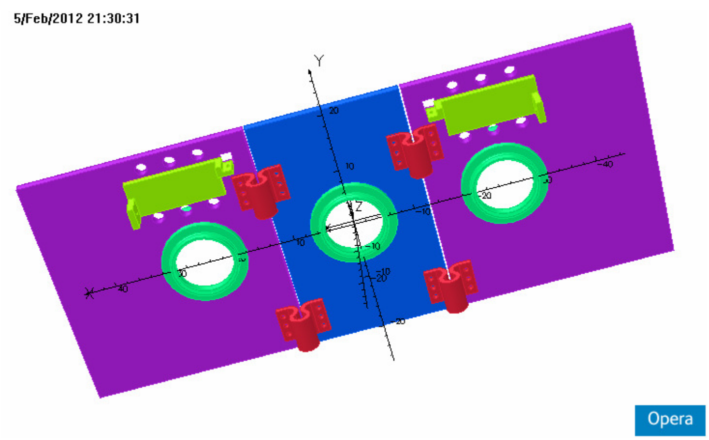


Fig. 1.a Model Bottom View

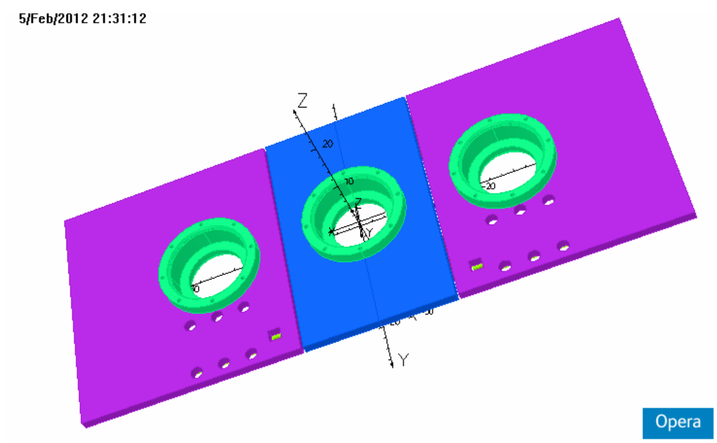


Fig. 1.b Model Top View

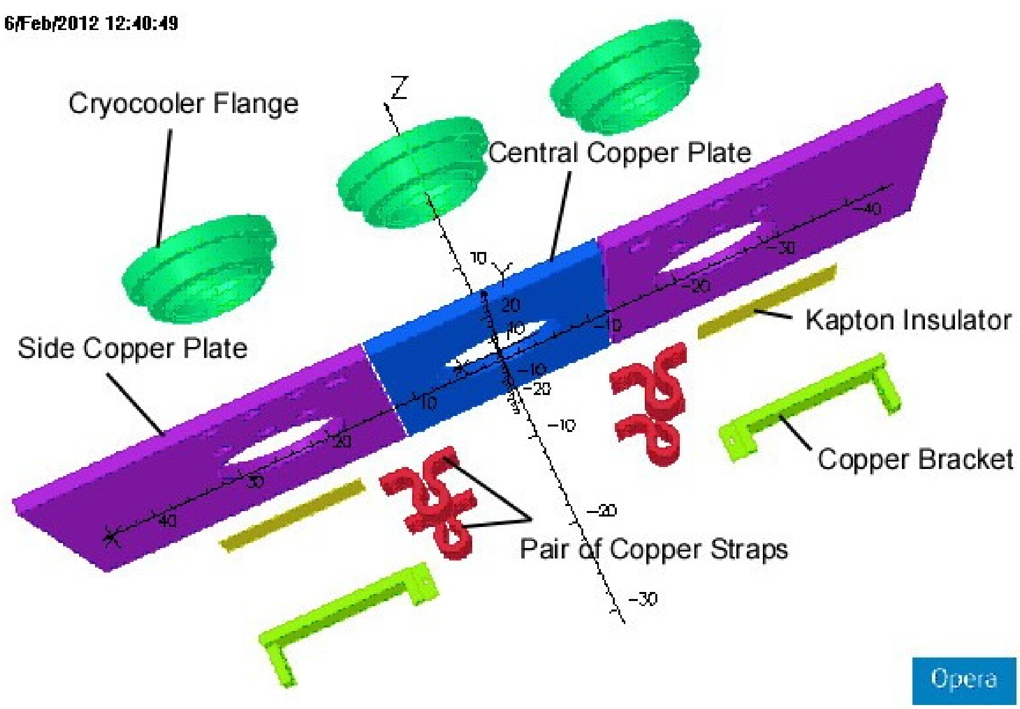


Fig. 1.c Parts Diagram

Note that the Central (c) Copper Plate shown in blue and two Side (s) Copper Plates shown in magenta are treated as separate parts. Below parameters related to these plates are marked by respective extensions, "_c" and "_s".

Figures 2.a through 4.c show surfaces highlighted in yellow where respective boundary conditions (BC) specified in the captions are applied. Boundary conditions Flux_cryo_c and Flux_cryo_s specify heat flux through the contact surface of the flange between the cryocooler and the Copper Plate. Boundary conditions Temp_cryo_c and Temp_cryo_s specify temperature at these interfaces. Boundary conditions Flux_shield_c and Flux_shield_c specify heat flux to the Copper Plates from the radiation shield. It is assumed to be distributed uniformly along the outer perimeter of the Copper Plate Assembly, so that Flux_shield_c = Flux_shield_s = Flux_shield. Finally, Flux_4k and Flux_300k specify heat flux through surfaces of the Copper Block providing contact with the cold, HTS, and warm, Copper, Current Leads respectively. Details of defining these boundary conditions are explained below.

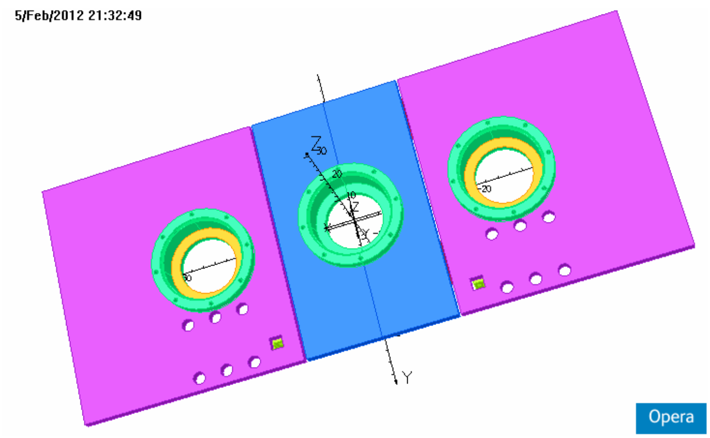


Fig. 2.a BCs Flux_cryo_s and Temp_cryo_s

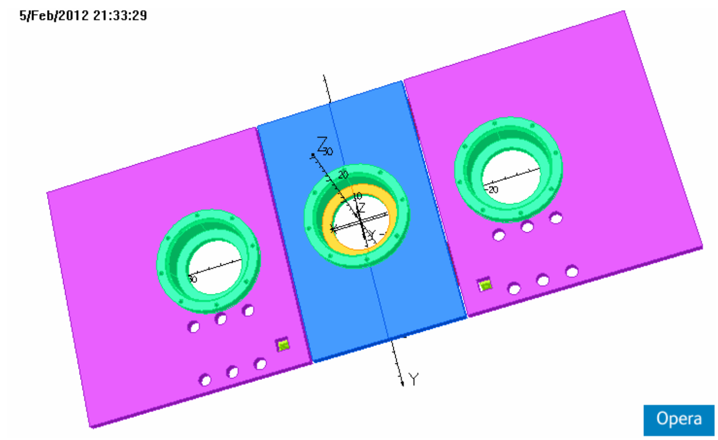


Fig. 2.b BCs Flux_cryo_c and Temp_cryo_c

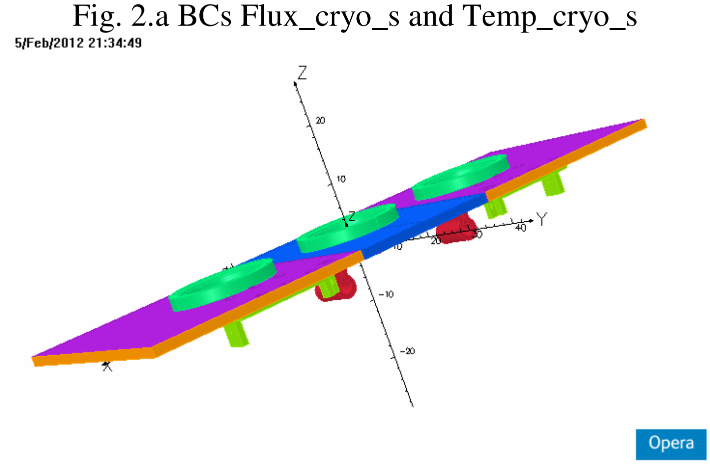


Fig. 3.a BC Flux_shield_s

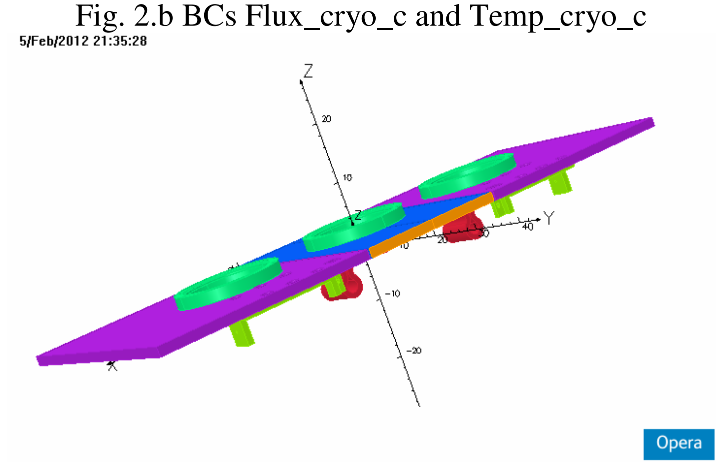


Fig. 3.b BC Flux_shield_c

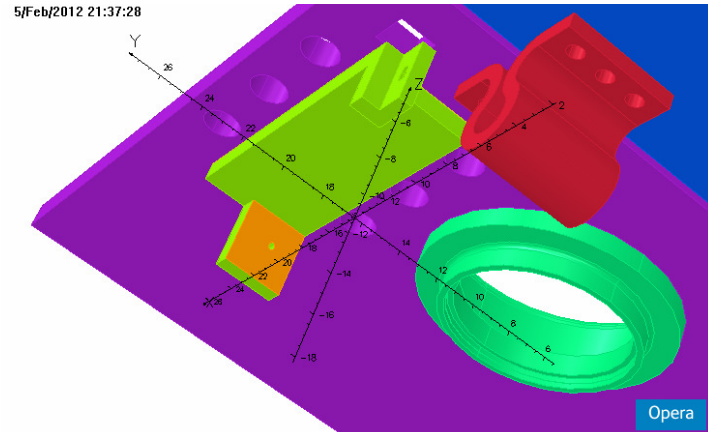


Fig. 4.a BC Flux_4k

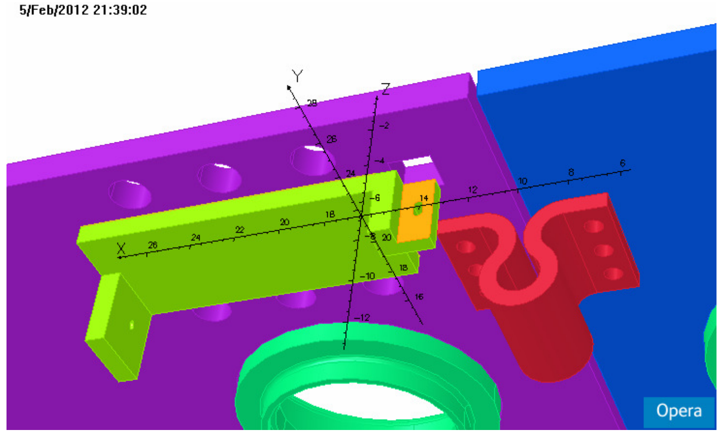


Fig 4.b BC Flux_300k

Thermal conductivity of all copper parts were defined as a function of temperature using the NIST data [7] for RRR=50.

In the model the thickness of the insulator between the Copper Plate and the Copper Block is 0.3 mm and its thermal conductivity is set to 0.886 W/m-K. This is equivalent to a 2-mil (0.0508 mm) layer of Kapton with thermal conductivity of 0.15 W/m-K [9], which is easily sufficient for a 1-kV voltage defined a design target in [10,11].

Joule heating from the transport current, Ic, in the Copper Block is neglected. For Ic=210 A Joule losses are of the order of 10^{-3} W. Electrical heating due to the contact resistance at the connections of the Current Leads to the Copper Block is also neglected.

Model A (MICECC-cu_plate-wa-2)

The peculiarity of defining BCs for this model is related to the fact that the performance of each of the cryocoolers is a function of the temperature of its first station. We can assume that due to the symmetry both Side cryocoolers are at the same temperature and provide the same cooling power. The Central cryocooler, connected to the Central Copper Plate having a smaller contact perimeter with the radiation shield and carrying no direct heat loads from the current leads provides less cooling power and has a lower working temperature. This results in a temperature drop between the higher temperature Side Copper Plates and the lower temperature Central Copper Plate. Consequently this causes a heat flow through 2 pairs of copper Joint Straps. Defining a self consistent set of the boundary conditions permitting a solution with temperature distribution and power balances compatible with the above requirements is a challenge.

Table 1.a shows a full set of these BCs used in Model A. Column (1) contains the name of the BC. Column (2) shows temperatures corresponding to respective BCs. These are temperatures of the first stations of the Central and Side Copper Plates. Columns (3) and (4) show the heating power transferred through and the area of the surface, on which this BC is specified. These surfaces are highlighted in yellow in the figures above. Column (5) contains the heat flux, which is the result of the division of the power by the area, through which it is transferred. Note that the Table is divided into 3 parts, related to Both Plates, the Central Plate and to one of 2 Side Plates and parts attached to them. Heat flux and the power are positive at interfaces with parts, which are at a higher temperature than the local temperature of the respective Copper Plate, and the other way around.

Table 1.a. Boundary Conditions, Model A

Boundary Conditions	(T)emp	(P)ower	(A)rea	(F)lux=P/A
	K	W	cm^2	W/cm^2
(1)	(2)	(3)	(4)	(5)
Both Plates				
Flux_shield		74.000	418.80	0.177
Central Plate				
Flux_shield_c		13.146	74.40	0.177
Flux_cryo_c		-29.110	67.10	-0.434
Temp_cryo_c	36.554			
- 2*P_straps		15.964		
Side Plate				
Flux_shield_s		30.427	172.20	0.177
Flux_cryo_s		-32.295	67.10	-0.481
Temp_cryo_s	37.267			
Flux_300k		10.000	4.76	2.101
Flux_4k		-0.150	13.30	-0.011
P_straps		-7.982		

Heat flux, Flux_shield_c = Flux_shield_s = Flux_shield, is calculated by dividing the total heat load at the first station from all sources, except for the Current Leads, by the area of the surface of the outer perimeter presumed to be in contact with the radiation shield. For the same reason as in [1] this power is set at 74 W as defined in [3] for a 100% contingency. Respective power loads on the Central and Side Copper Plates from the shield are P_shield_c=13.146 W and P_shield_s=30.427 W. From the results of the analyses [1] we know that power loads from the RT and HTS Current Leads can be set at P_300k = 10 W and P_4k = -0.15 W[1].

According to formula (A.1) in Addendum A heat capacities, P415_c and P415_s, of the cryocoolers attached to the Central and Side Plates as a function of the respective temperatures of their first stages, T415_c and T415_s, are defined by the formulae

(1) $P415\_c(T415\_c) = -1489.5512 + 112.47614 * T415\_c - 3.10904 * T415\_c^2 + 0.03844 * T415\_c^3 - 0.0001770150 * T415\_c^4$

$P415\_s(T415\_s) = -1489.5512 + 112.47614 * T415\_s - 3.10904 * T415\_s^2 + 0.03844 * T415\_s^3 - 0.0001770150 * T415\_s^4$

Power balances for the Central and the Side Copper Plate subassemblies can be expressed analytically as

(2) $- P415\_c(T415\_c) + P\_shield\_c + 2*P\_straps = 0$

$- P415\_s(T415\_s) + P\_shield\_s + P\_300k + P\_4k - P\_straps = 0$

Here all components are either constant values or functions of T415_c and T415_s. The only undefined function is P_straps. This is the power shared between the Copper Plates through a pair of Copper Straps shown in Fig.

[1] P_4k is relatively small and its choice has a very small impact on the results of these analyses.

5.a. From simulations of several subsidiary models it was concluded that it would be valid to make the following assumptions:

- Temperature drop across the copper plate between the first station of the cryocooler and the points of attachment of the Straps is small compared to the minimum temperature drops between the Central and the Side Copper Plates;
- Heating power through the Straps is proportional to the temperature drop between the points of contact with the Copper Plates at the ends of the Straps.
-

Consequently we can assume that

(3) P_straps = dPdT*(T415_s - T415_c),

where dPdT is a coefficient, which was calculated using a subsidiary Model S (MICECC-cu_plate-wa-1). Figures 5.a and 5.b show that for dT= T415_s - T415_c =5 K the power integral through the pair of Straps is P_straps=56 W. The coefficient in (2) is

(4) dPdT= P_straps/(T415_s - T415_c) = 56 W / 5 K = 11.2 W/K.

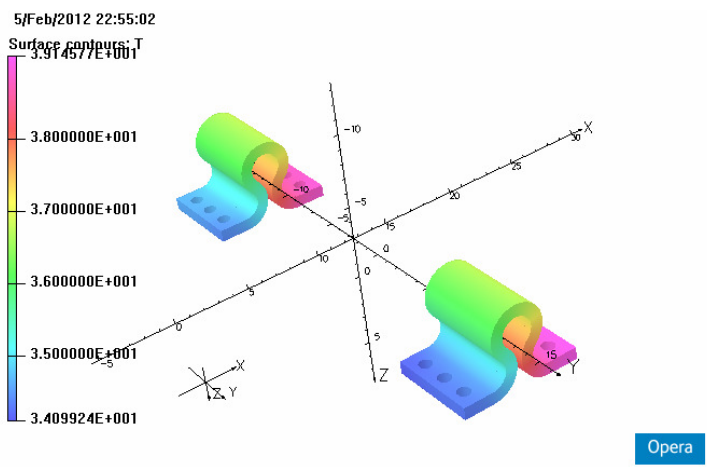


Fig. 5.a Temperature drop along Straps dT=5 K. Model S

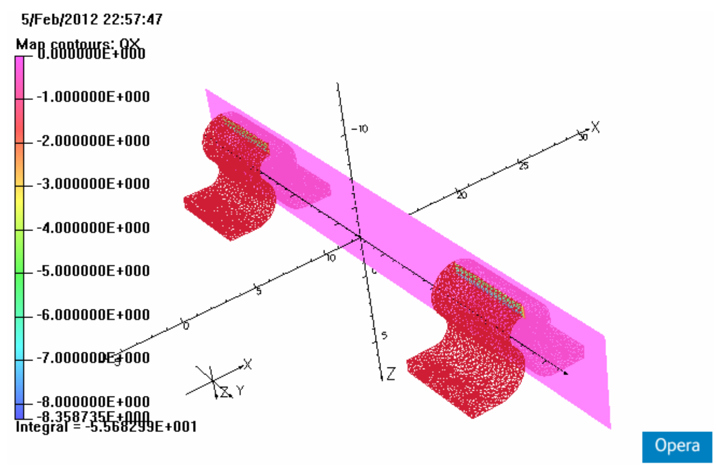


Fig. 5.b Power through 2 Straps P_straps=56 W. Model S

Solving nonlinear system of equations (1), (2), (3) and (4) using Mathematica we can calculate a combination of values of the temperature and cooling power of cryocoolers, (T415_c, P415_c) and (T415_s, P415_s), which is expected to provide a power balance between the plates subassemblies with the account of heat transfer through the straps.

For the baseline Model A these values were calculated. In Table 1.a they are highlighted by blue font.

The expected power depositions to the Central and Side Copper Plates through the Straps are shown in Table 1.a in red. They are calculated from respective balances (2). They are not specified in the model. Instead they can be used for verifying the quality of the solution by the degree of its convergence to a proper power balance with account of the cryocooler performance vs. temperature diagram.

In this particular case the calculated power transferred through a pair of Straps is 7.377 W, which is close to the expected |P_straps| = 7.982 W in Table 1.a.

Model B (MICECC-cu_plate-wo-clips-1)

Model B was created and analyzed to assess the value of having Straps connecting the Copper Plates.

This model is the same as above with the following exceptions. First, there are no Straps connecting the Copper Plates. Second, boundary conditions in the part specifying the cryocooler first station temperature and cooling power are calculated using the same equations (1)-(2), only in this case P_straps=dPdT=0 and these equations are solved independently. Full set of boundary conditions for this model is shown in Table 1.b.

Note that in this case the Central cryocooler delivers 3 times less power than each of the Side cryocoolers. It's temperature is almost 6 K lower.

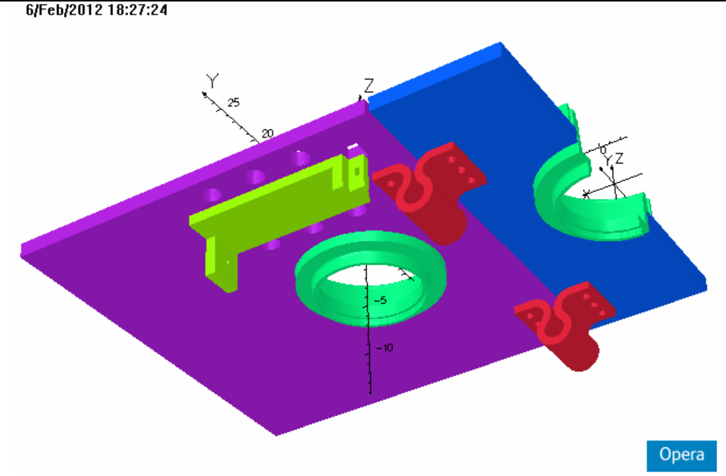
Table 1.b. Boundary Conditions, Model B

Boundary Conditions	(T)emp	(P)ower	(A)rea	(F)lux=P/A
	K	W	cm^2	W/cm^2
(1)	(2)	(3)	(4)	(5)
Both Plates				
Flux_shield		74.000	418.80	0.177
Central Plate				
Flux_shield_c		13.146	74.40	0.177
Flux_cryo_c		-13.146	67.10	-0.434
Temp_cryo_c	33.739			
- 2*P_straps		0.000		
Side Plate				
Flux_shield_s		30.427	172.20	0.177
Flux_cryo_s		-40.277	67.10	-0.481
Temp_cryo_s	39.427			
Flux_300k		10.000	4.76	2.101
Flux_4k		-0.150	13.30	-0.011
P_straps		0.000		

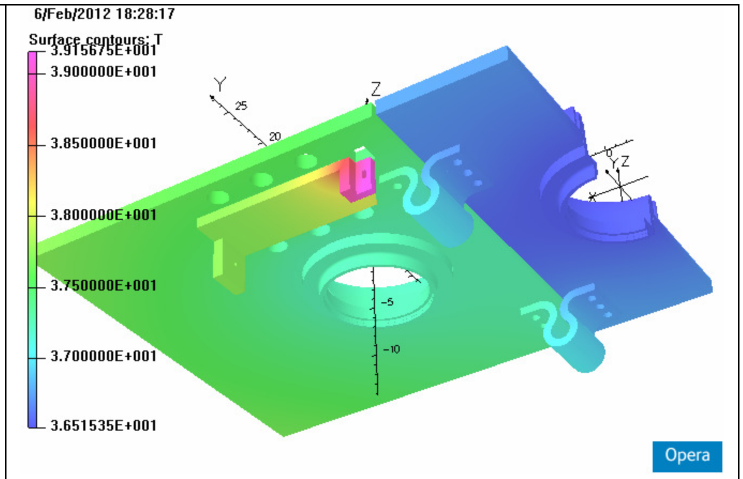
Analyses

Graphic results of the FE analyses of Models A and B specified in Tables 1.a and 1.b are shown in Tables 2.a and 2.b respectively.

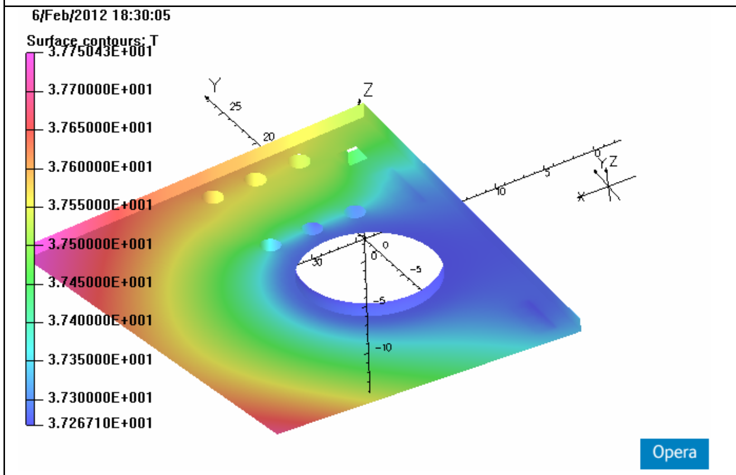
Table 2.a. Analyses Results, Model A



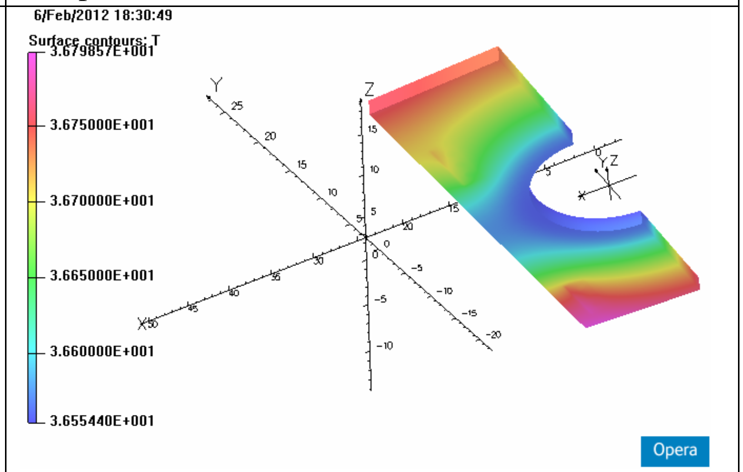
Model Bottom View



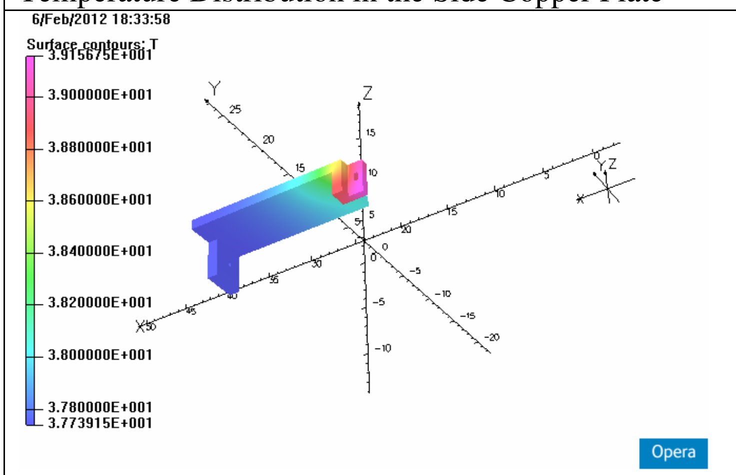
Temperature Distribution in the Model



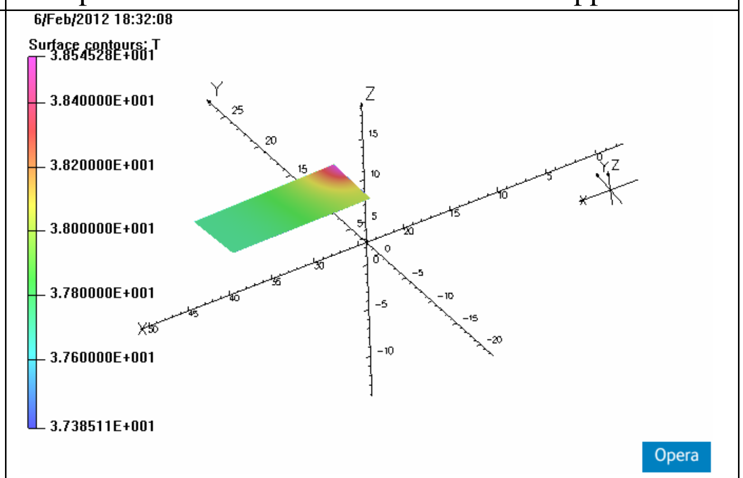
Temperature Distribution in the Side Copper Plate



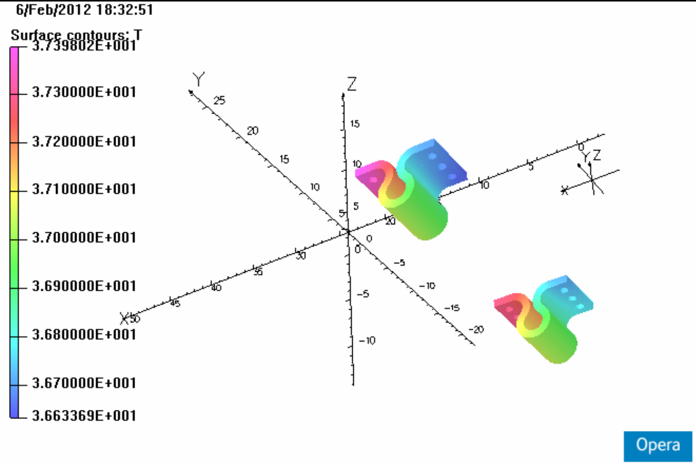
Temperature Distribution in the Central Copper Plate



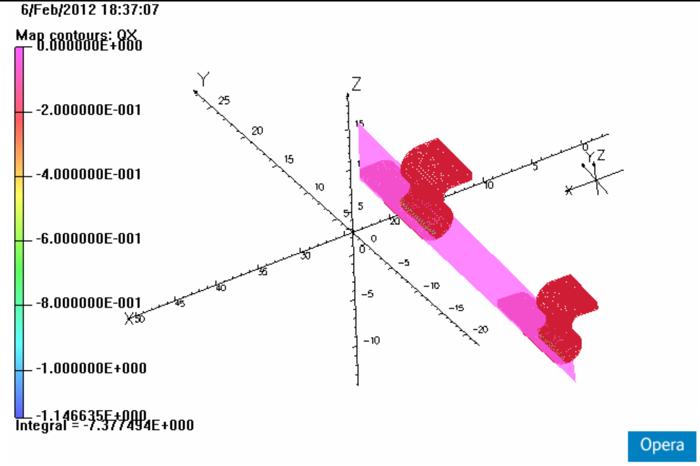
Temperature Distribution in the Copper Block



Temperature Distribution in the Kapton Insulator

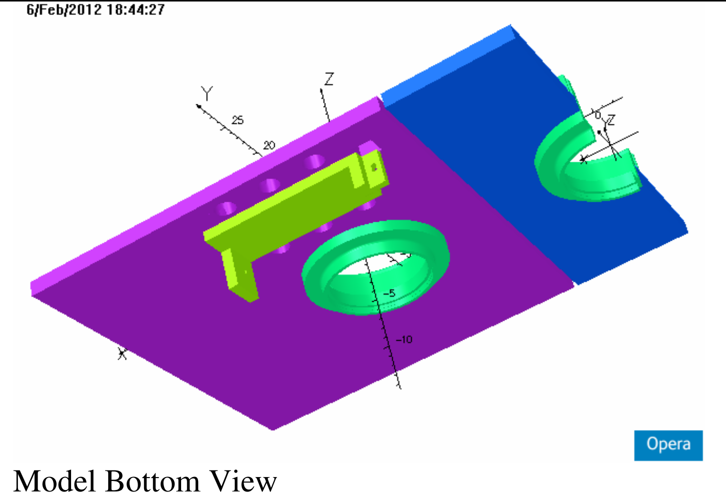


Temperature Distribution in the Copper Straps

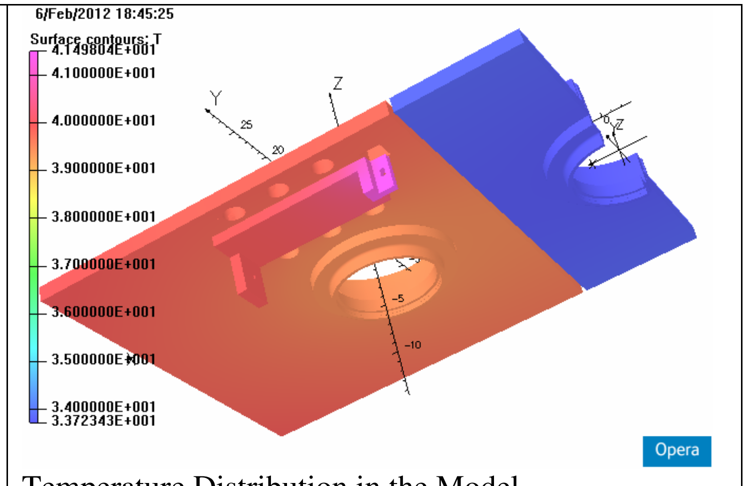


Power through a pair of Copper Straps

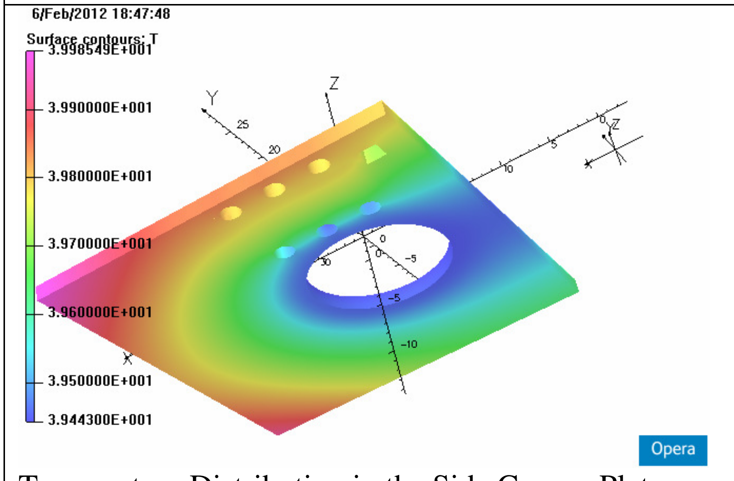
Table 1.b. Analyses Results, Model B



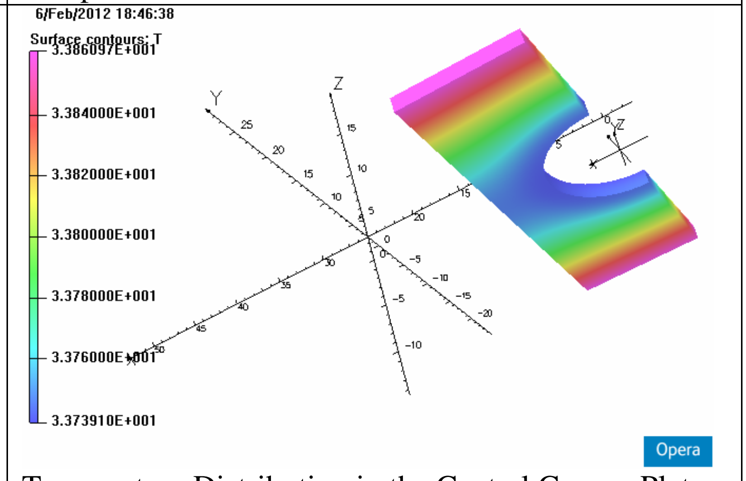
Model Bottom View



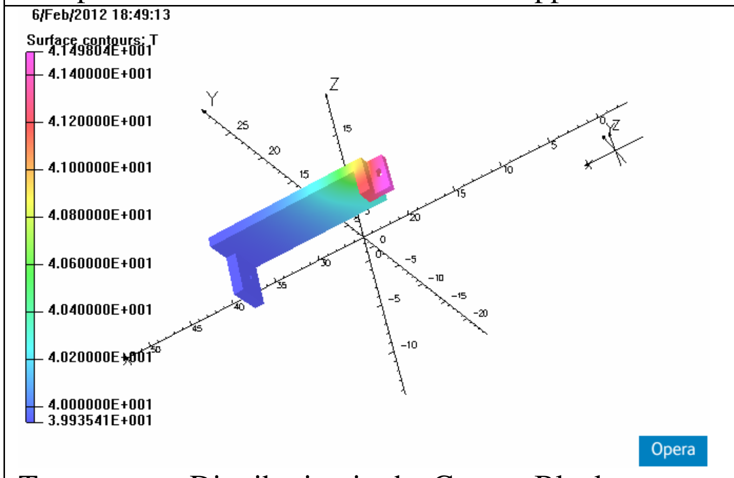
Temperature Distribution in the Model



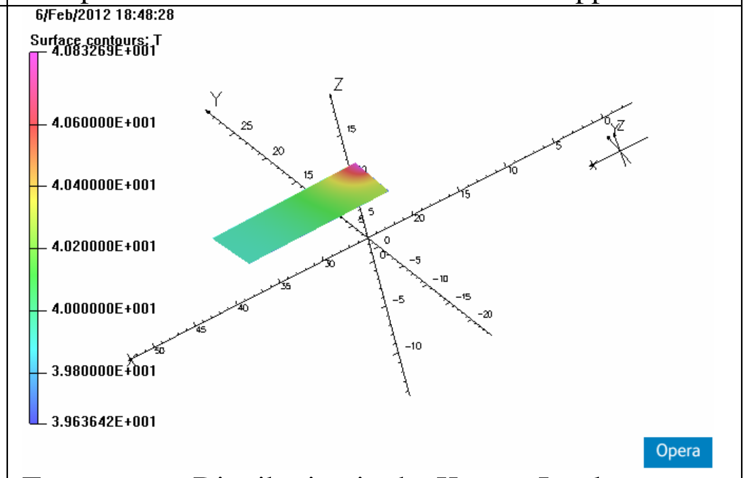
Temperature Distribution in the Side Copper Plate



Temperature Distribution in the Central Copper Plate



Temperature Distribution in the Copper Block



Temperature Distribution in the Kapton Insulator

Conclusions and Comments

The following conclusions can be made from analyzing results shown in Tables 2.a and 2.b

1. Results of thermal analyses of Model A representing the baseline design of the Intermediate Cooling Station showed that this design is acceptable. Due to the abundance of the cooling power at the first stations of the cryocoolers their temperatures are close to 37 K and the cooling power is evenly shared between 29 W in the Central cryocooler and 32 W in the Side cryocoolers.

2. 1.5-cm thick Copper Plates provide sufficient thermal conductivity to limit temperature drops between the cryocooler and any point of the Copper Plate to less than 1 K.

3. With a 2-mil Kapton insulator between the Copper Plate and the Copper Block the warmest point of the model, the Copper Current Lead terminal of the Copper Block, is just 2 K warmer than the first station of the cryocooler attached to the Side Copper Plate. Temperature drop across the insulator is a fraction of 1 K.

4. Power sharing between the Central and 2 Side Copper Plates is essential for redistributing cooling power of the cryocoolers. Without Copper Straps the Central cryocooler is loaded 3 times less[2] than each of the Side cryocoolers and its working temperature is almost 6 K lower.

5. The purpose of Copper Straps is to allow independent flotation of the Copper Plates to avoid overstressing the structure of the cryocolers between the RT and the first station flanges due to its different thermal contraction. Structural analyses can show if the flexibility of the Straps made of solid copper as shown in the solid model [6] is sufficient for this purpose. One of the alternatives, free of these potential drawbacks can be using flexible thermal links [12] like those shown in Fig. 6. The spec for choosing these links is that thermal resistance of a connection between any of the Side Plates to the Central Plate at the 40-K temperature has to be no less than dPdT=11.2 W/K as defined in this study.

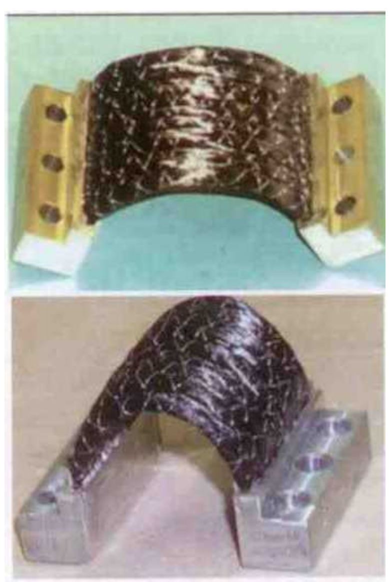


Fig. 6. Examples of thermal links [12].

[2] The model didn't include the radiation shield. In the current design [6] the radiation shield has slots aligned with the slots between the Central and the Side Copper Plates. The effect of the radiation shield on the temperature and power distribution between the Copper Plates is expected to be negligibly small.

6. The distance between the top of the Copper Plates and the inside of the RT Cryostat is about 23 cm. The length of the Copper Current Leads specified in [1] is 30 cm. This allows for some slack in the Copper Current Leads. The Lorentz force on the Leads is about 0.2 T * 210 A * 0.3 m = 12 N. This force, though small can bend thin, about 4-mm diameter, Copper Leads. The previous design showed Copper Current Leads bent the way shown in Fig.7. This is a good arrangement as long as the direction of the current in both the Leads and the Coil is as shown in this diagram. This way the direction of the force is such that the Leads bend outwards and need no special restraints.

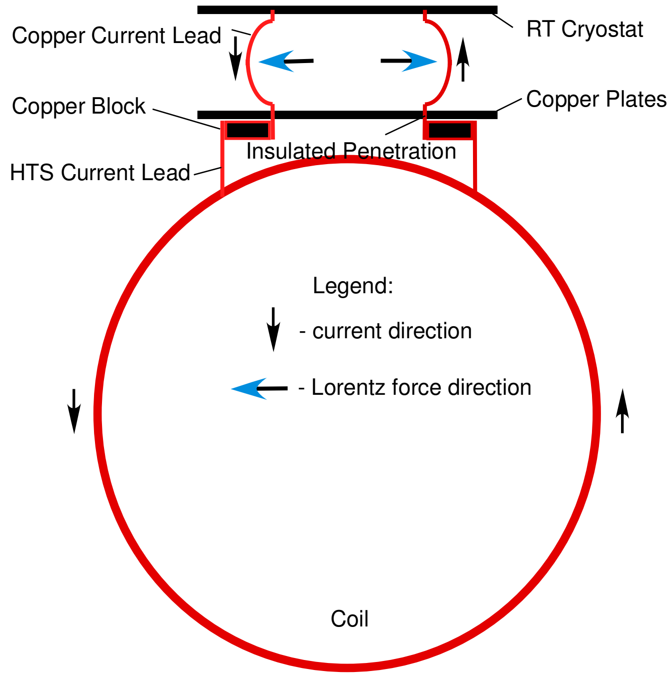


Fig. 7. Current and Lorentz Force Directions

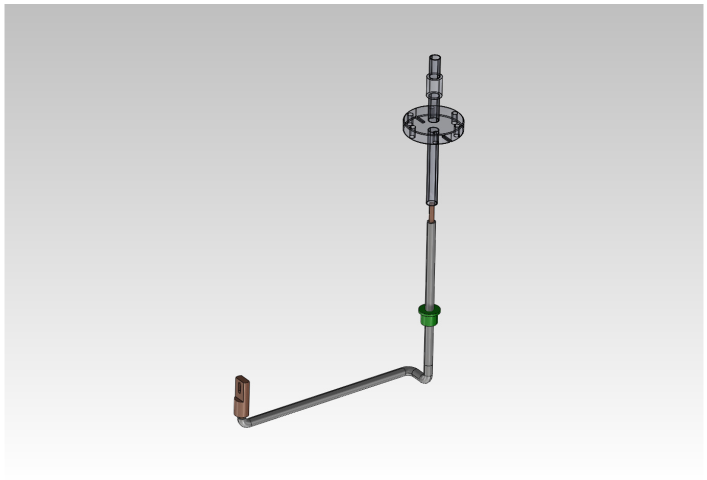


Fig. 8 Present design [6] of the Copper Current Lead.

7. The penetration of the Copper Current Lead through the Copper Plate (see Fig. 7) has to be electrically insulated by an electrical insulation insert. Due to the proximity of its location to the cold end of the Copper Current Lead the temperature drop between the Lead and the Copper Plate is practically zero, so that this insulator has a very small effect on the intended temperature distribution in the Copper Current Leads. This is a big improvement compared with the present design [6] with a G10 insulating spacer (shown in green in Fig. 8) in the middle of the Copper Current Lead. At this point the temperature of the Current Lead is more that 200 K [1] and the temperature drop to the 40-K Copper Plate is more than 150 K. Heat leak through this insulator is significant and it is not taken in account by the design of the Copper Current Leads.

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ADDENDUM A

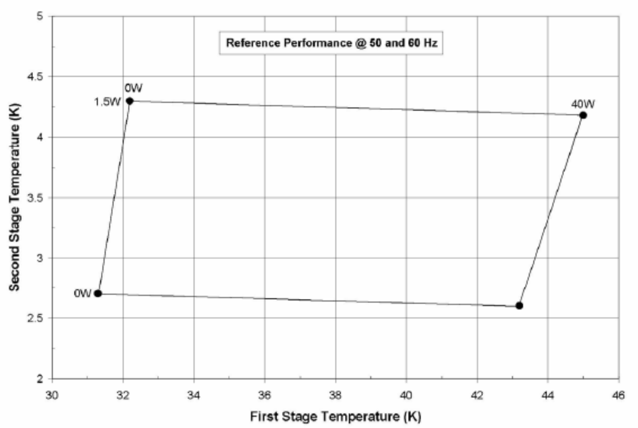

Fig. A.1.a PT415 Cryorefrigerator Capacity Curve. Certified Performance: 1.5W@4.2K with 40W@45K (Specification by Cryomech [4].)

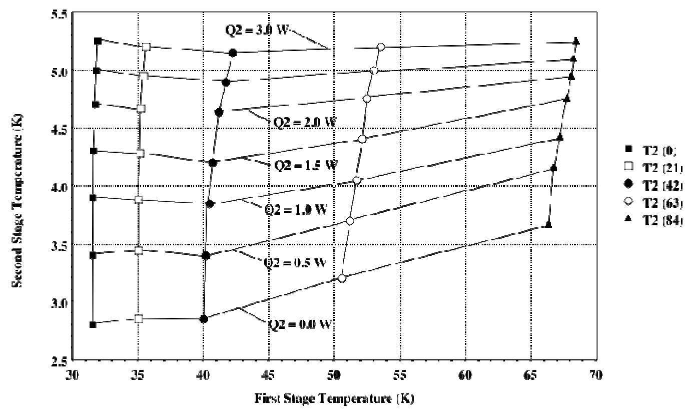

Fig. A.1.b Operating temperature diagram for the first-stage temperature T1 and the second-stage temperature T2 of a PT415 pulse tube cooler as a function of the first-stage heat load Q1 and the second stage heat load Q2. (Data taken by Florida State University [5].)

Relation between the capacity, P415, of the first stage of the cryocooler and the temperature of this stage T, [32K<T<70K]. For the second stage held at 4.2 K.

(A.1) $$P415(T) = -1489.5512 + 112.47614*T - 3.10904*T^{2} + 0.03844*T^{3} - 0.0001770150*T^{4}$$

Figure A.3 shows P415 as a function the temperature of the first stage of the cryocooler.

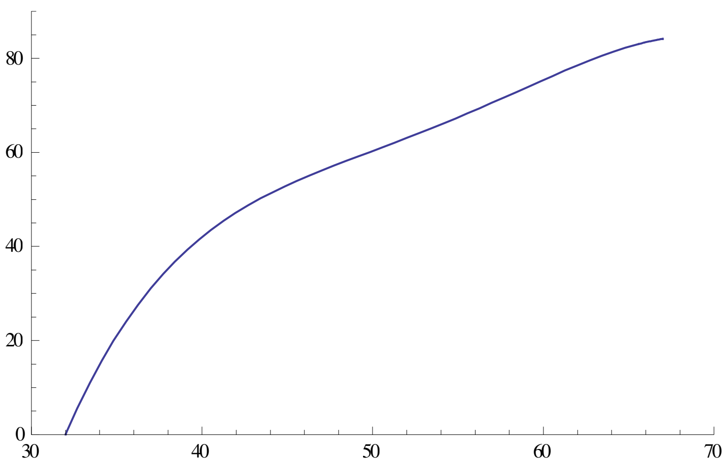

Fig. A.2 PT415 first stage capacity, P415 [W], vs. temperature, T [K], for the second stage at 4.2 K.