Fermi National Accelerator Laboratory

Technical Division

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Final report of the 9-weeks internship at Fermilab

Thermal analysis of the current leads for SSR1 cryomodules

July 31st – September 29th

E come quei che con lena affannata
uscito fuor del pelago a la riva
si volge a l'acqua perigliosa e guata,

così l'animo mio, ch'ancor fuggiva,
si volse a retro a rimirar lo passo
che non lasciò già mai persona viva.

CONTENTS

1 INTRODUCTION 4

2 CURRENT LEADS 4
  2.1 Design 4
  2.2 Problems and purposes 7

3 FINITE DIFFERENCES 7

4 FIRST MODEL 10
  4.1 Boundary conditions 10
  4.2 Thermal intercepts 10
  4.3 Results 11
  4.4 Uncertainties 12

5 IMPROVEMENTS 12
  5.1 Current values 12
  5.2 The ”helium guard” 14
  5.3 Copper block 14
  5.4 Size of wires 15
  5.5 Fins 15
  5.6 Copper selection 16

6 FINAL MODEL 18
  6.1 Assumptions 18
    6.1.1 Copper properties 19
    6.1.2 Natural air convection 19
    6.1.3 Fins 20
    6.1.4 Helium guard 20
  6.2 Results 21

7 COOLING DOWN 26

8 TEST SET-UP 26

9 CONCLUSION 29

1 INTRODUCTION

The Proton Improvement Plan-II (PIP-II) is a Fermilab's plan that has been developed to provide powerful and high intensity proton beam to the laboratory's experiments. In addition to its room temperature components, a key part of the PIP-II facility is a series of 25 cryomodules containing a total of 116 cavities that accelerate the beam to 800 MeV. Some of those cryomodule types contain Single Spoke Resonators (SSR) of two types (SSR1 and SSR2). There are two SSR1 cryomodules each with eight cavities and four focusing solenoids and seven SSR2 cryomodules each with seven cavities and three focusing solenoids.

The SSR1 cryomodule houses four superconducting magnet packages. Each of these packages consists of a solenoid coil and four coils which make horizontal and vertical correctors and a skew-quadrupole. Each magnet package is powered by a current lead assembly.

The purpose of this work is to suggest improvements for the current lead assembly, in order to ensure their proper operation.

I worked for 9 weeks at this project in Technical Division (July 31st - September 29th). All the thermal analyses in Chapters 4, 6 and 7 have been done by me, except the Ansys analysis for the contact resistance; Chapter 5 shows my suggestions in order to make the system more efficient; I also proposed a way to make some useful measurements in Chapter 8.

2 CURRENT LEADS

2.1 DESIGN

Figure 1 shows the longitudinal section of a lead. This image is not proportioned: each lead is more than 1.2 m long, and the diameters of the copper conductor are 2.558 mm for the 50 A wire and 3.264 mm for the 100 A wire. A lead is made by:

- a conductor, i.e. a cylindrical copper wire;
- a polyolefin jacket for insulation;
- epoxy
- a stainless-steel tube.

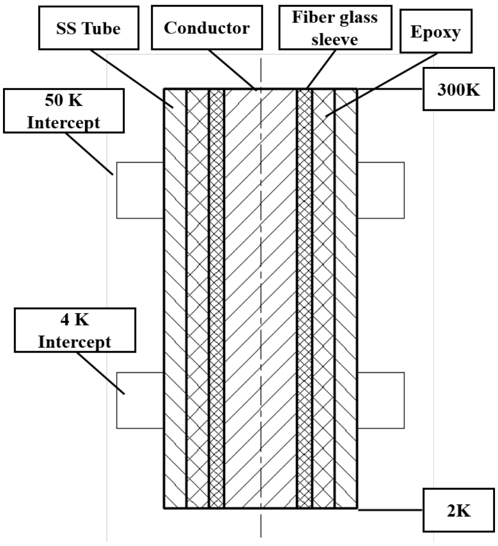


Figure 1: How a current lead is made.

Each cryomodule needs four current leads assembly, and each current leads assembly is made by eleven leads, nine of which with 100 A and two of which with 50 A. When I arrived at Fermilab, the current leads assembly design was the one shown in Figure 2. The stainless-steel tubes in which the conductor wire are contained are shown in gray. The tubes enter the cryomodule throughout the blue flange. All the parts above the blue flange are at room temperature and normal pressure environment. Conversely, all the parts we see in figure are located inside the vacuum vessel, therefore they are in a very low temperature and pressure environment.

The leads are brazed to two copper block, in orange. This two copper block are the *thermal intercept*, i.e. the apparatuses whose job is to cool down the leads. Each copper block is connected to an helium pipe:

- The first copper block is connected to an helium pipe. The helium flowing in this pipe is at 35-50 K. The connection between the copper block and the helium pipe is constituted by 5 thermal straps. In Figure 3 a thermal strap is shown. It is made of copper and its purpose is to transfer the heat between the copper block and the helium pipe.
- The second copper block is crossed by an helium pipe at 4 K. At the ends of the pipe there will be flanges in order to make connections with the helium distribution.

The second extremity of the leads is submerged in liquid helium at 2 K. The stainless-steel tube ends where the rectangular gray flange is. It means that the liquid helium is directly in contact with the insulator, in order to cool down efficiently the wires.

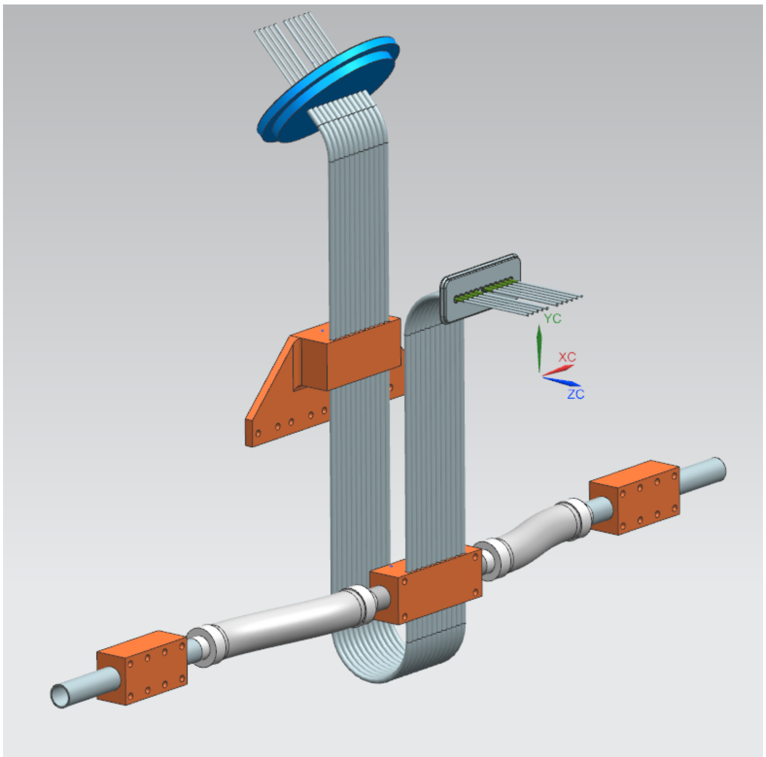


Figure 2: Design of the current leads assembly.

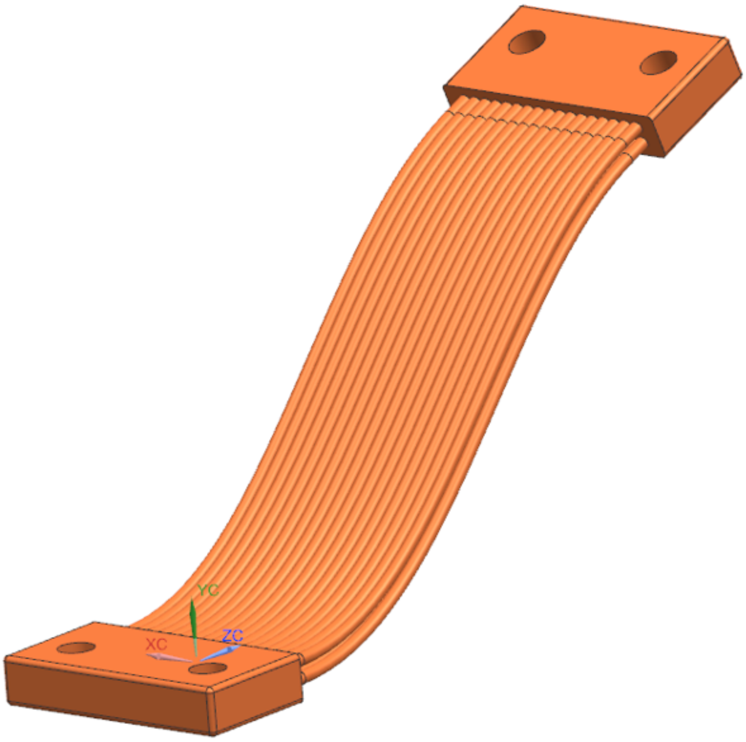


Figure 3: Thermal strap.

2.2 PROBLEMS AND PURPOSES

The cryomodule needs to be at very low temperature. Many efforts has been made in order to minimize the heat transfer between the room temperature and the 2 K stage.

The current leads being bolted to the vacuum vessel on one side and connected to the 2 K stage on the other side, a lot of heat will be transferred to the 2 K stage. The amount of heat transferred to this stage is due to:

- *heat conduction* from room temperature to the liquid helium inside the cryomodule;

  $$\dot{Q} = -kS\frac{dT}{dx} \tag{1}$$

  where k is the conductivity, S is the section of the wire and $\dot{Q}$ is the power transferred through this section;

- *heat generation* by Joule effect.

  $$P = IR^2 \tag{2}$$

  where P is the power generated, I the current and R the resistance.

To decrease the heat generated by Joule effect, the cross section of the copper wires can be increased and a high quality copper can be used. Unfortunately, these two changes would increase the heat transferred by conduction. Therefore an optimization needs to be found.

For this optimization, the goals are:

1. to avoid an hot-spot along the wires (say, the temperature of the copper should be below 70°C);
2. to keep the amount of heat flowing into liquid helium very low.

In order to reach the target, thermal intercepts can be used. Nevertheless, since the electrical insulator (polyolefin) is also a good thermal insulator, the thermal resistance between the intercepts and the copper wires is too high. In addition, the brazing between the copper block and the stainless-steel tube is a delicate operation.

3 FINITE DIFFERENCES

The purpose of this model is to calculate the temperature profile and the heat exchanges of each lead during the steady-state conditions

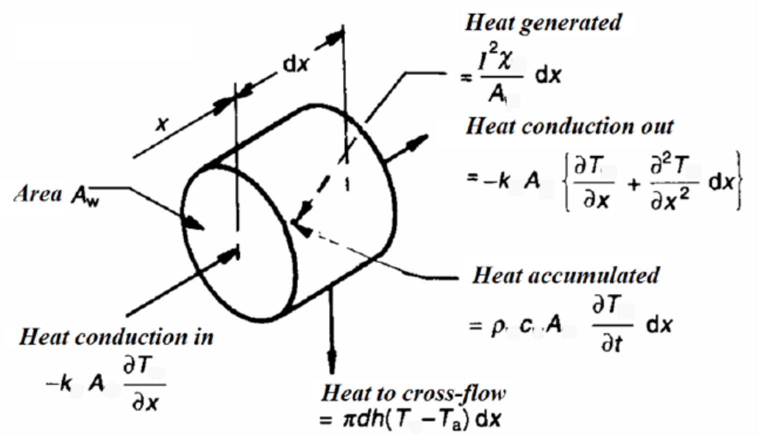


Figure 4: Aggiustare.

(i.e. maximum current), by using the finite-difference method. Finite-difference methods (FDM) are numerical methods for solving differential equations by approximating them with difference equations, in which finite differences approximate the derivatives.

Let χ be the electrical resistivity and k the thermal conductivity. Figure 4 shows the heat balance in an little element of wire of length dx and section A. Please note that A is the cross section of the copper wire only, not of the whole lead.

First of all, in each element of wire heat generation by Joule effect is present. The electrical resistance of the element is $\frac{\chi}{A}dx$, and the heat generated is

$$dJ_i = I^2 \frac{\chi}{A} dx \tag{3}$$

Across both the sections there is heat conduction. The heat transfer across each section is $-kA\frac{\partial T}{\partial x}$, where the minus sign means that the heat flows in the opposite direction of the increasing derivative. N.B.: in this work only the conductivity of the copper is considered in order to calculate the heat conduction along the wire (thermal conductivity of insulation, epoxy and stainless-steel is supposed to be zero).

This work just deals with steady-state conditions, therefore $\frac{\partial(\cdot)}{\partial t} = 0$, i.e. every value does not change over time.

The heat transfer between the wire and the outside is very complicated. In general, the amount of heat flowing across the lateral surface of the cylindrical wire depends on the difference in temperature between the wire and the outside. Later this discussion will be undertaken.

Let L be the entire length of each wire and N the number of elements in which this L is divided. Let us number each of the N elements of the wire by the subscript $i = 1, 2, \ldots, N$. Therefore, T_i is the temperature of the center of the i-th element. In Finite Difference Methods, dx is not an infinitesimal, but rather it is substituted by $\Delta x = \frac{L}{N}$. With this new meaning, Equation 3 becomes (also dQ is not an infinitesimal anymore);

$$J_i = I^2 \frac{\chi_i}{A} \Delta x \quad i = 1, 2, \dots, N \tag{4}$$

The derivative of the temperature with respect to x, calculated in the section between the $(i-1)$-th element and the i-th element, can be approximated by:

$$\left.\frac{\partial T}{\partial x}\right|_{(i-1)|(i)} = \frac{T_i - T_{i-1}}{\Delta x} \quad i = 1, 2, \dots, N \tag{5}$$

In order to approximate the heat conduction across the surface, the thermal conductivity of the $(i-1)$-th element is considered:

$$Q_{(i-1)|(i)} = -k_{i-1}\, A\, \frac{T_i - T_{i-1}}{\Delta x} \quad i = 1, 2, \dots, N \tag{6}$$

Let Q_i be the heat transfer between the i-th element and the outside, across the lateral surface. It depends on what kind of cooling system is used for that element (air convection, helium convection, thermal intercept, etc.). In general, this amount of heat is a function of the temperature T_i multiplied for the difference between T_i and a fixed temperature $\hat{T}$ (for example, $\hat{T}$ could be the temperature of the helium in the second thermal intercept), that is:

$$Q_i = f(T_i) \cdot (T_i - \hat{T}) \quad i = 1, 2, \dots, N \tag{7}$$

Of course, $T_i - \hat{T}$ could also be negative, and, given that $f(T_i) > 0$, Q_i would be negative too. Later in this document all the calculations about these cooling systems are explained, i.e. all the calculations needed to find the function $f(T_i)$.

Finally, in order to get the steady-state conditions, a balance equation can be written for each element of wire:

$$J_i = Q_{(i)|(i+1)} - Q_{(i-1)|(i)} + Q_i \quad i = 1, 2, \dots, N \tag{8}$$

In total, there are $4N$ unknown variables, i.e. J_i, $Q_{(i-1)|(i)}$, Q_i, T_i, for $i = 1, 2, \dots, N$. There also are $4N$ equations: Eq. 4, Eq. 6, Eq. 7, Eq. 8, that is re-written here for greater clarity.

$$\begin{cases} J_i = I^2 \frac{\chi_i}{A} \Delta x, & i = 1, 2, \dots, N \\ Q_{(i-1)|(i)} = -k_{i-1}\, A\, \frac{T_i - T_{i-1}}{\Delta x} & i = 1, 2, \dots, N \\ Q_i = f(T_i) \cdot (T_i - \hat{T}) & i = 1, 2, \dots, N \\ J_i = Q_{(i)|(i+1)} - Q_{(i-1)|(i)} + Q_i & i = 1, 2, \dots, N \end{cases}$$

To solve this problem, Matlab has been used.

4 FIRST MODEL

This model has been done using the very first design of the current leads assembly. Let x be the curvilinear coordinate of a lead, in a way that (referring to Figure 2):

- at $x = 0$ m the lead enters the cryomodule;
- at $x = 0.258$ m starts the first thermal intercept;
- at $x = 0.3088$ m ends the first thermal intercept;
- at $x = 0.75$ m starts the second thermal intercept;
- at $x = 0.8008$ m ends the second thermal intercept;
- at $x = L = 1.1498$ m the lead is submerged in liquid helium

4.1 BOUNDARY CONDITIONS

For this first model the boundary conditions are as follows:

- at $x = 0$ m, $T = 300$ K;
- at $x = L$, $T = 2$ K.

This is a Dirichlet problem. These boundary conditions mean that in $x = 0$ and $x = L$ any amount of heat could be possible in order to hold the temperatures at 300 K and 2 K.

At 2 K the helium is superfluid and, for this reason, it has some properties that could be helpful or troubling: it has zero viscosity but infinite thermal conductivity. So, the heat exchange between the copper wire and the liquid helium at $x = L$ is very high, actually. We can consider the second boundary condition a good hypothesis.

Unfortunately, the first boundary condition is not representative of the physical problem. Later in this work this subject will be examined.

4.2 THERMAL INTERCEPTS

From $x = 0.258$ m to $x = 0.3088$ m and from $x = 0.75$ m to $x = 0.8008$ m, the leads are brazed to two copper blocks that represents the thermal intercepts. Of course the thermal resistance between the copper wire and each copper block includes the following thermal resistances:

- the insulator;
- epoxy;
- stainless-steel tube;
- the brazing.

Of course, the total thermal resistance is temperature-dependent: the lower the temperature, the higher the thermal resistance. In this work this temperature-dependence is considered to be linear. Moreover, the thermal resistance depends on how long is the contact between the lead and the copper block. For this reason, the following data is attributed to the thermal resistance per unit length ($KW^{-1}m^{-1}$).

So, the thermal resistance per unit length as a function of temperature is expressed by:

$$R_{th}(T) = a \cdot T_m + b, \qquad 2\ K < T < 110\ K \tag{9}$$

where T_m is the mean temperature between the local temperature of the copper wire and the temperature of the helium of that intercept. Coefficients a, b are settled as follows:

- for the 100 A wire, $a = -0.01247\ W^{-1}m^{-1}$ and $b = 1.877\ KW^{-1}m^{-1}$;
- for the 50 A wire, $a = -0.0176\ W^{-1}m^{-1}$ and $b = 2.649\ KW^{-1}m^{-1}$;

In addition to the thermal resistance calculated with Equation 9, in the first thermal intercept there is also the thermal resistance of the thermal straps (shown in Figure 3). It is calculated by using the thermal conductivity of RRR=100 copper (RRR will be explained later in this work) at room temperature (that is the worst case, but it is not so different from the thermal conductivity at the actual temperature), and the total section of all the ropes of the straps.

4.3 RESULTS

Figure 5 shows the temperature profile along the copper wire; Table 1 shows the amount of heat extracted by each thermal intercept and by superfluid helium at the second extremity. The total amount of heat is calculated by considering nine 50 A wires and two 100 A wires.

Clearly, what we care the most is the amount of heat flowing into liquid helium. In total, 4.19 W are flowing to the 2 K stage. It is

	First t.i.	Second t.i.	Liquid helium
50 A wire	2.46	0.70	0.19
100 A wire	8.06	4.25	1.24
TOTAL	38.26	14.8	4.19

Table 1: Power extracted by the thermal intercepts and the liquid helium. All the values are expressed in *watt* (W).

an huge value, and this is caused by the 100 A wires, mainly. Moreover, the 100 A temperature profile reveals a big hot-spot between the thermal intercepts: here the temperature almost reaches the room temperature. For this reason, the temperature of the copper wire in proximity to the second thermal intercept is around 100 K. This situation is unacceptable.

4.4 UNCERTAINTIES

The first calculation confirmed that the original design of the current leads did not meet the requirements. First the temperature is too high inside the cryomodule and the heat on the 2 K stage is too important.

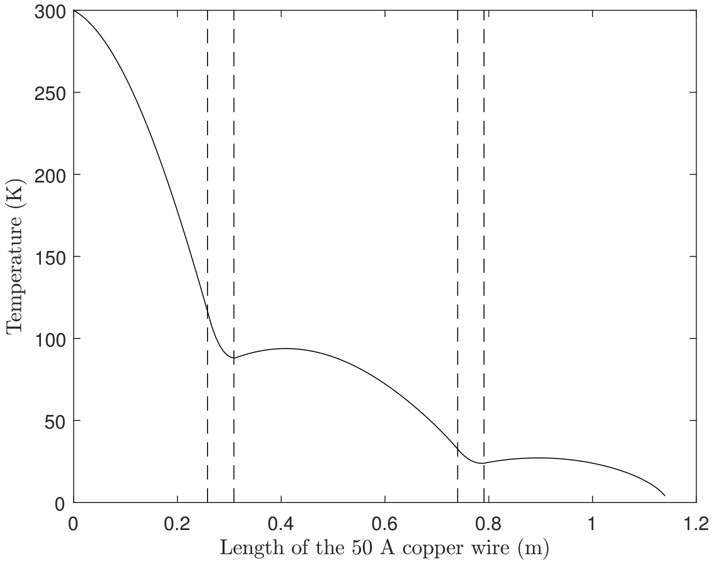
In the following chapter, I will present the design changes which were necessary in order to meet the requirements. Moreover I will improve the model by taking in consideration the convection between the vacuum vessel and the current leads. In this way we can check if the boundary condition used for the first model is correct.

5 IMPROVEMENTS

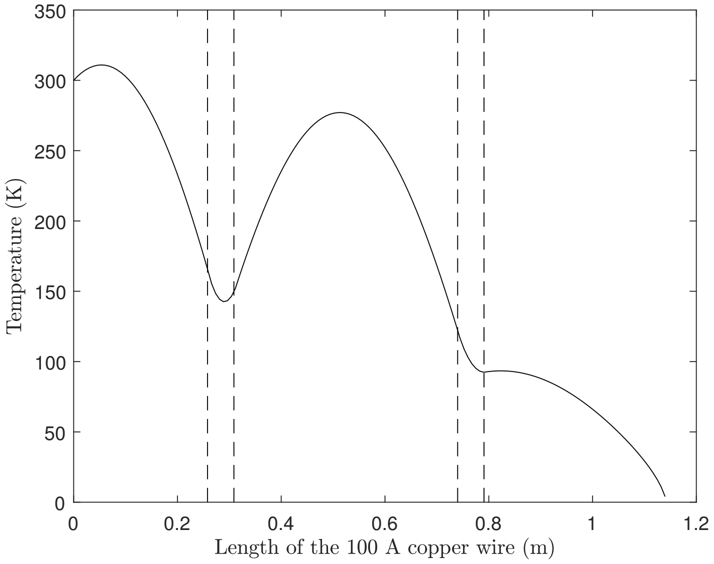
5.1 CURRENT VALUES

A good news came from the Magnet System Department. The current of the solenoid will never go above 85 A. For the corrector magnets, powered by the nine smaller leads, the current should always be below 40 K. Nevertheless, since the correctors can go to 50 A without problems, the worst case has been considered:

- nine leads with 50 A;
- two leads with 85 A;



(a)



(b)

Figure 5: Temperature profile along the copper wires. Vertical lines stand for the extremities of the thermal intercepts.

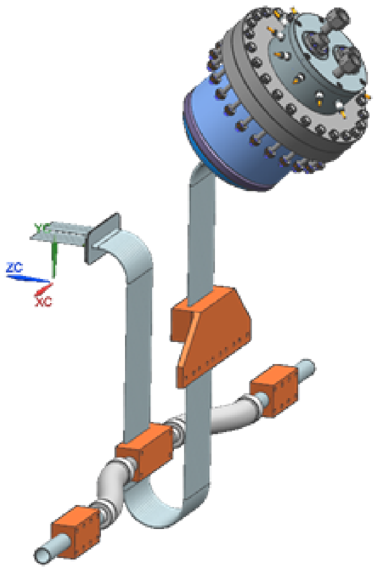


Figure 6: Helium guard and leads. The entire helium guard will be outside the vacuum vessel. Conversely, the leads pass through the helium guard and then they go inside.

5.2 THE "HELIUM GUARD"

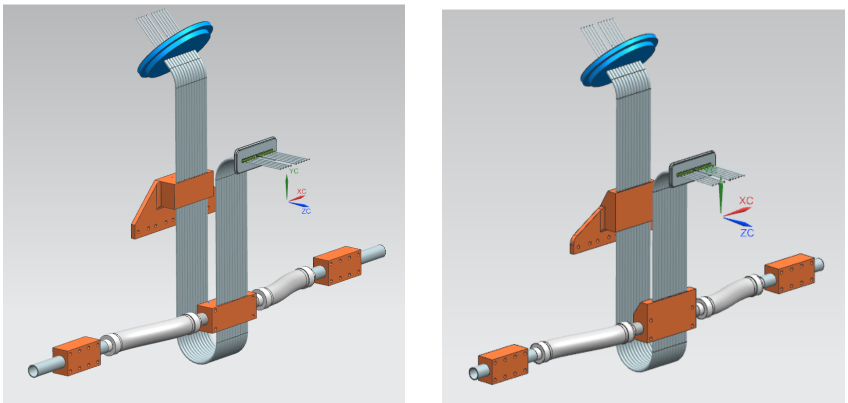
As already mentioned, the second extremity of leads is submerged in superfluid helium at 2 K. Given that superfluids have zero viscosity, the epoxy covering is needed in order to avoid leakage along the leads. Nevertheless, leaks are possible if the covering in epoxy is not perfect.

In order to prevent a leak, the "helium guard" solution has been implemented. Figure 6 shows the helium guard and its connection with the leads. It is a cylindrical closed volume (diameter 250 mm, height 250 mm) directly connected to the blue flange of Figure 2, that contains helium under pressure (4 bar max). In this way, even if there will be a leak along the wire, the 2 K helium bat will not be spoiled by air.

Of course, there will be natural convection between helium and wires, and also between air and the outside of the helium guard. Steady-state temperature of helium will obviously be higher than room temperature. For this reason, natural convection in helium guard is less efficient than natural convection of air.

5.3 COPPER BLOCK

Figure 5 shows that thermal intercepts will extract power and will decrease the temperature, but it is not enough. As already mentioned, thermal intercept are not very efficient because of insulation that make the thermal resistance too high.



(a)

(b)

Figure 7: Comparison between old design (a) and new design (b). The length of the copper blocks (in orange) brazed to the leads is increased from 50.8 mm to 80.8 mm.

In order to decrease the thermal resistance and to make the cooling system more efficient, the length of the copper blocks can be increased. Therefore the thermal intercept will be more efficient.

Both the copper blocks of thermal intercepts are made 30 mm longer than before. Figure 7 shows how the design changed.

5.4 SIZE OF WIRES

According to the first model, the first boundary condition was 300 K, but is it possible to hold that temperature at the entrance?

Considering a constant cross section of the wire inside and outside the cryomodule, I performed simple (note that for the 85 A lead, a diameter of 3.26 mm has been considered) calculations in order to estimate the temperature of a wire. In steady-state the wire temperature reaches 80°C, much higher than the boundary conditions considered in the first model.

In order to reduce the heat generated by Joule effect, the diameter of the 85 A wires can be increased to 5.189 mm when the wire is outside the stainless-steel tube. By decreasing the diameter, the heat generated by Joule-effect will be less important and the natural convection will be more efficient.

The diameter of the 50 A wires will remain 2.558 mm everywhere.

5.5 FINS

Nevertheless increasing the diameter of the 85 A wires is not enough. Fins are needed in order to extend the contact surface between air

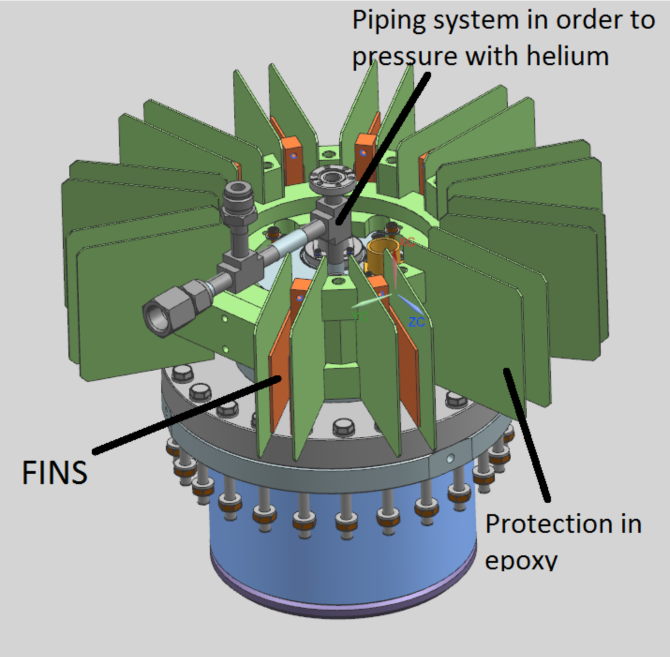


Figure 8: Helium guard and fins.

and wires. Two fins per wire are positioned just outside the helium guard. In this way, the wires pass through the fins, then they enter inside the helium guard, and then they enter inside the vacuum vessel throughout the blue flange.

Figure 8 shows the helium guard in blue with a gray flange needed to separate helium from air. From the top of the guard, a pipe will provide helium at the pressure wanted.

Effect of the fins will be examined later in this work.

5.6 COPPER SELECTION

Electrical resistance of each element of wire of length dx depends on two factors:

- section area, A;
- electrical resistivity, χ.

For the first model, regular copper has been used, but there are different kinds of copper with lesser resistivity. *Residual Resistivity Ratio* (RRR) is a parameter usually defined as the ratio of the resistivity of a material at room temperature and at 0 K:

$$\text{RRR} = \frac{\chi_{300\text{K}}}{\chi_{0\text{K}}} \tag{10}$$

Of course, 0 K can never be reached in practice so some estimation is usually made.

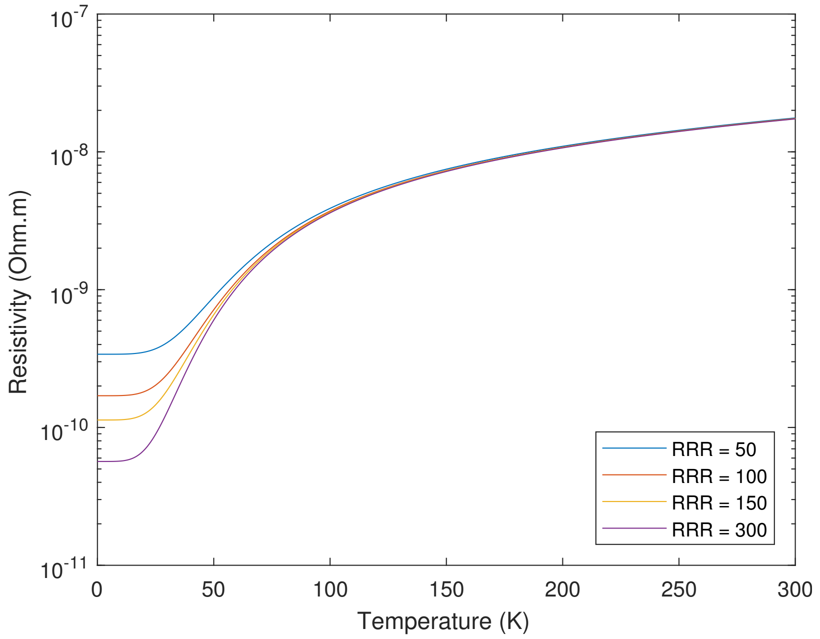


Figure 9: Resistivity of several kinds of copper (temperature-dependence).

Regluar copper is RRR$\simeq$ 10. To calculate the resistivity for an intermediate temperature T this formula is used:

$$\chi(T) = 10^{-8}\left[\frac{1.7}{RRR} + \left(\frac{2.325\cdot10^{9}}{T^{5}} + \frac{9.571\cdot10^{5}}{T^{3}} + \frac{1.327\cdot10^{2}}{T}\right)^{-1}\right] \tag{11}$$

Figure 9 shows how resistivity depends on temperature, for several kinds of copper quality. This plots are based on Equation 11.

It is clear that the higher the RRR, the lower the resistivity, so it would be better to use an high RRR copper. Unfortunately, the higher RRR, the higher the conductivity. Figure 10 shows how conductivity depends on temperature, for several kinds of copper quality. It means that we cannot use an arbitrarily high RRR: indeed, if RRR is too high, the amount of heat flowing into liquid helium by conduction becomes too much. As a consequence, low RRR means a lot of heat generation by Joule effect, and high RRR means a lot of heat transferred by conduction.

Anyway, regular copper was not the best choice.

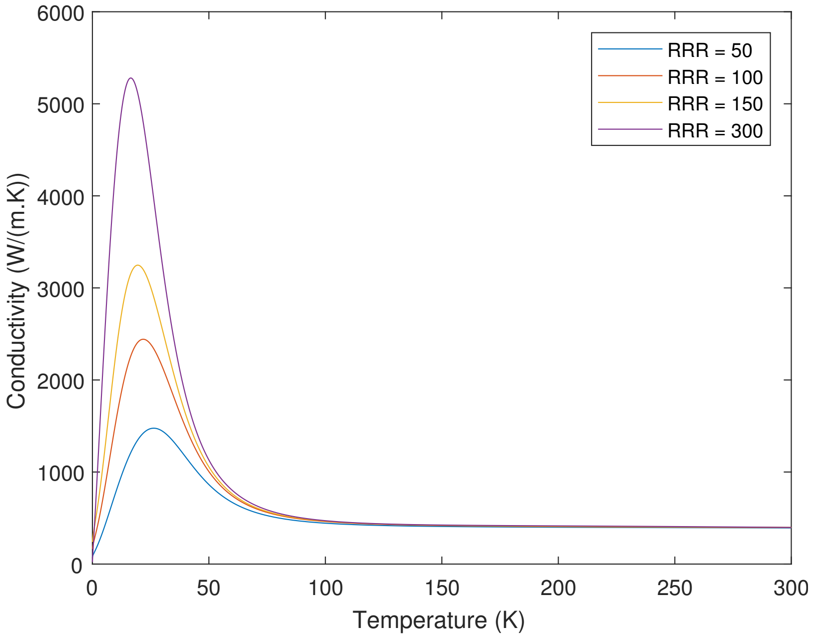


Figure 10: Conductivity of several kinds of copper (temperature-dependence).

6 FINAL MODEL

6.1 ASSUMPTIONS

In this section, every assumption done with MATLAB will be discussed. As already mentioned in the first model, let x be the curvilinear coordinate of a lead. In this model, the parts of the leads placed outside the cryomodule are also considered. Nevertheless, $x = 0$ remains the point in which the leads enter the cryomodule. It means that x can be negative:

- from $x = -1.2$ m and $x = -0.3$ m the lead is submerged in air at room temperature. This segment is needed in order to be sure that the leads in air reach the steady-state conditions, and that the steady-state does not depend on the boundary condition.
- from $x = -0.3$ m to $x = -0.28$ m the lead is soldered to the fins;
- from $x = -0.28$ m to $x = 0$ m the lead are inside the helium guard, and here is the helium natural convection;
- at $x = 0$ m the lead enters the cryomodule;
- at $x = 0.258$ m starts the first thermal intercept;

- at $x = 0.3088$ m ends the first thermal intercept;
- at $x = 0.75$ m starts the second thermal intercept;
- at $x = 0.8008$ m ends the second thermal intercept;
- at $x = L = 1.1498$ m the lead is submerged in liquid helium

6.1.1 Copper properties

Equation 11 is used in order to calculate the resistivity of copper, and a similar formula is used for conductivity. Unfortunately, these formulas are strongly non-linear, and as a consequence the algorithm becomes less stable.

Moreover Matlab does not allow to use polynomial approximation with a degree higher than 2, the only way is to linearize the formulas. For example, the function from Equation 11 is evaluated for m discrete temperatures and discrete RRR, say, $T^{(1)}, T^{(2)}, \dots, T^{(j)}, \dots, T^{(m)}$. Let us fix the RRR value. If the value of the resistivity at $T^\star$ is wanted, where $T^j < T^\star < T^{j+1}$, it can be estimated by tracing a line between $\chi(T^{(j)})$ and $\chi(T^{(j+1)})$. This trick makes stable the algorithm, and it can be used for any non-linear property.

6.1.2 Natural air convection

In order to estimate the heat due to natural air convection on the wire, a long cylindrical copper wire with the new diameters (see Section 5.4) is considered. Each wire has a polyolefin jacket (insulator) 0.5 mm thick. For every possible temperature of an element (dx long) of wire, the algorithm calculates:

- $T_{w,i}$, the temperature of the ”wall”, i.e. the temperature of the outer surface of the insulator of the i-th element;
- h_i, the heat transfer coefficient between the lead and the air.

In order to calculate the heat transfer coefficient, the wire has been considered infinite. Formulas are got from [2].Although this formulas are valid only for isothermal cylinder, they are applied for each element of wire, so each element of wire has a different heat transfer coefficient.

The heat extracted by air from each element is calculated by:

$$Q_i = h_i \cdot \pi \cdot dx \cdot \Delta T_i \tag{12}$$

where $\Delta T_i = T_{w,i} - T_\infty$.

6.1.3 Fins

Once the length and the width of each fin are fixed, the heat exchange between fins and air can be calculated by using the inclined plate approximation. Each fin has a different inclination compared to the horizontal, from 0^o to 45^o. Given that the 45^o inclination implies a smaller heat transfer coefficient, all the fins are conservatively considered with this inclination.

Each wire has four flat surfaces exposed to air, two for each fin. For each possible ΔT between the fins and the air, the heat transfer coefficient is calculated. Given that the heat transfer does not change a lot for $1K < \Delta T < 50K$, a mean heat transfer coefficient has been evaluated and used for every ΔT. Each fin is considered isothermal and its temperature is equal to the temperature of the wire to which they are soldered. All the heat exchanged by the air is extracted to the elements of wire that coincide to the solder.

6.1.4 Helium guard

Inside the helium guard there is heat exchange between the eleven wires and the helium and also between the helium guard and the air. Given that the temperature of the wire is higher than the room temperature (because of Joule effect), the steady-state temperature of the helium is higher than the room temperature, too.

Let us suppose that we know the helium temperature inside the helium guard. The heat exchange between each wire and the helium by convection can be calculated in a similar way to the natural air convection already described, but the formulas needed are those with inclined wires (45^o from horizontal). Furthermore, a pressure of 3 bar is considered inside the helium guard, but the heat transfer does not change meaningfully with the pressure. Moreover, the heat exchange between air and helium guard depends on:

- the heat transfer coefficient between helium and the inner wall of the helium guard. This coefficient is calculated by approximating the helium guard with a parallelepiped cavity: the heat transfer coefficient is supposed to be $4.2\frac{W}{m^2K}$;
- the thermal resistance through the wall of the guard. This thermal resistance is supposed to be zero, because the wall is wide and thin;
- the heat transfer coefficient between air and the outer wall of the guard. It can be calculated by using formulas for "a small ratio body inside a fluid".

So, if we knew the temperature of the helium, the problem would be solved. The physical temperature of the helium (steady-state) is the temperature at which the heat transferred between helium and wires is equal to the heat transferred between air and helium.

In order to calculate the temperature of helium inside the helium guard, the *regula falsi* algorithm is implemented. In this way, the temperature of the helium can be known with a precision of 0.5 K within 8 iterations.

6.2 RESULTS

In this section several plots are disclosed. These plots represent the temperature profiles of the copper wires. For each of these plots, the x-axis represents the length of the copper wire, like described at the beginning of Chapter 6.1. There are two vertical dotted lines that represent where the wires enter and exit the helium guard. To the left of the helium guard, the wires are submerged in air. Conversely, at $x = 0$, the wires enter the vacuum vessel and, at the right extremity of the x-axis, the wires are submerged in liquid helium.

Each Figure has two plots: the first one describes the 50 A wires, and the second one the 85 A wires. For each Figure, all the parameters are fixed, except one in order to show what happens if that parameter changes. Moreover, a table shows the amount of heat extracted by:

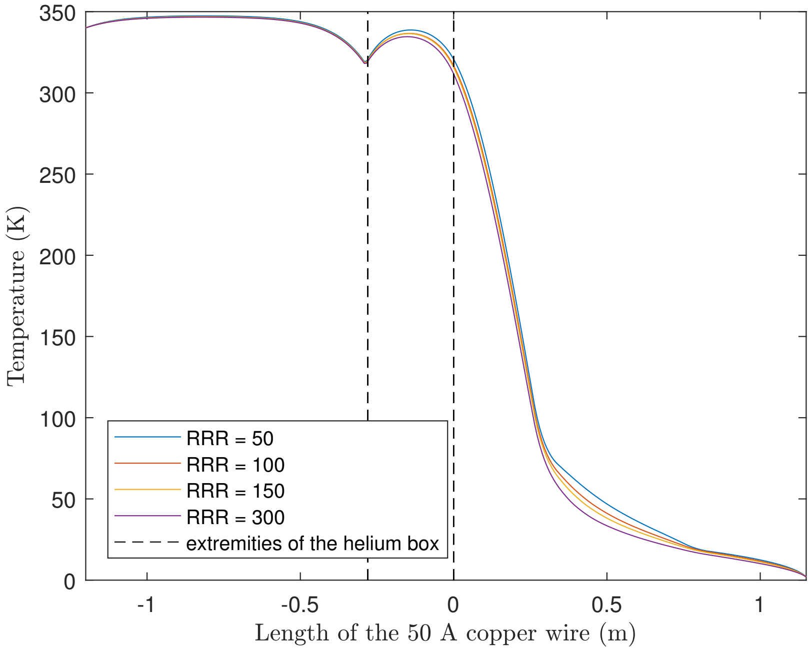
- the fins (natural convection),
- helium inside the helium guard,
- the first thermal intercept,
- the second thermal intercept,
- liquid helium.

Figure 11 shows what happens if the quality of copper changes. As we can see, the higher the RRR, the lower the temperature everywhere. This is caused by the lower electrical resistivity, mainly. This is not necessarily a good result: indeed, although the temperature is lower, the amount of heat flowing into liquid helium is higher, because of the higher conductivity. Table 2 shows the power extracted by each cooling system. As we can see, a RRR from 50 to 150 is still efficient for the wires, the heat at 2 K being acceptable. Conversely, for RRR=300, 10 W will flow into liquid helium.

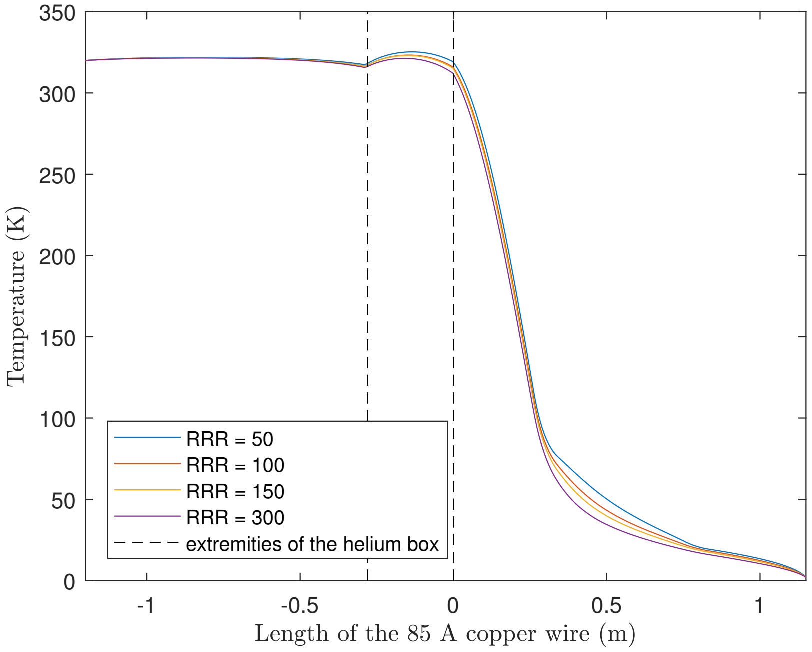
As it will be discussed later, we have a big uncertainty related to the value of the thermal resistance of the thermal intercepts. For this value some estimations have been done, and has been presented in Section 4.2. But what happens if this estimate is not accurate? Figure 12 shows what happens if the contact resistance is multiplied by a factor: 1, 1.5, 2, 3. Obviously, the higher this factor, the higher

RRR	fins	helium guard	1^{st} t.i.	2^{nd} t.i.	liquid helium
50	14.44	12.3	21.16	6.06	2.84
100	14.05	21.16	21.13	5.75	4.73
150	14.05	11.04	19.38	5.46	6.30
300	13.66	10.40	15.59	4.88	9.99

Table 2: Heat extracted (W) by each cooling system, for different values of RRR.



(a)



(b)

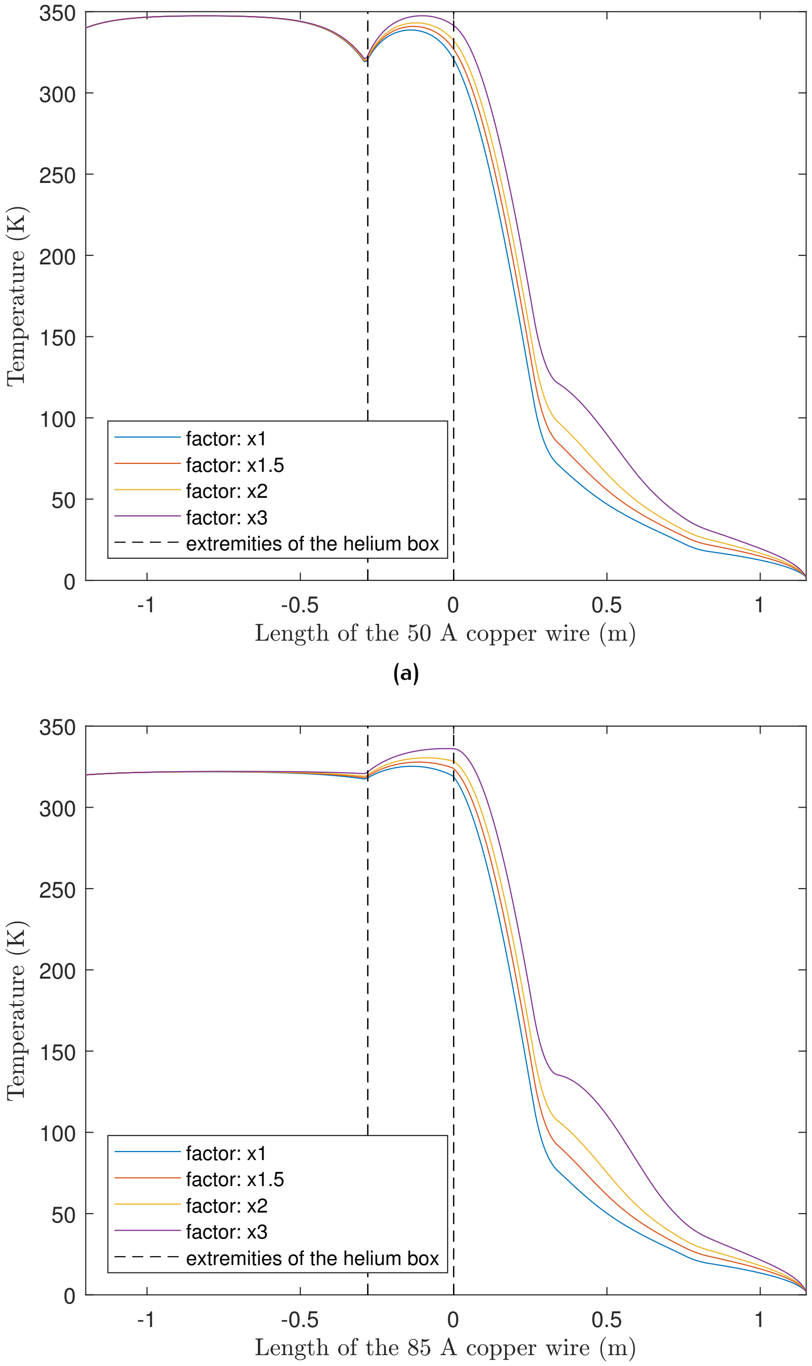
Figure 11: Temperature profiles of the 50 A wires (a) and 85 A wires (b), for different values of RRR.

the temperature profile, especially close to the first thermal intercept. Indeed, for a factor=3 the temperature at the first thermal intercept could be higher than 100 K. Moreover, the power flowing into the liquid helium increases too, but for factor=3 it is anyway below 7 W (see Table 3). For these plots, RRR=50 has been considered.

For the previous plots, fins are supposed to be 50x50 mm (length x width). Figure 13 shows what happens if a width of 0, 25, 50 or 75 mm is considered (of course, 0 mm means no fins). This plots show that if there are not fins, the temperature at the entrance of the helium guard could be higher than 350 K, and so the temperature of the helium inside the helium guard could be too high.

factor	fins	helium guard	1^{st} t.i.	2^{nd} t.i.	liquid helium
1	14.44	12.31	24.16	6.06	2.84
1.5	14.79	13.71	24.93	5.75	5.98
2	15.12	14.82	25.91	5.72	4.96
3	15.78	16.50	28.43	4.18	6.73

Table 3: Heat extracted (W) by each cooling system, for different values of the thermal intercept contact resistance.



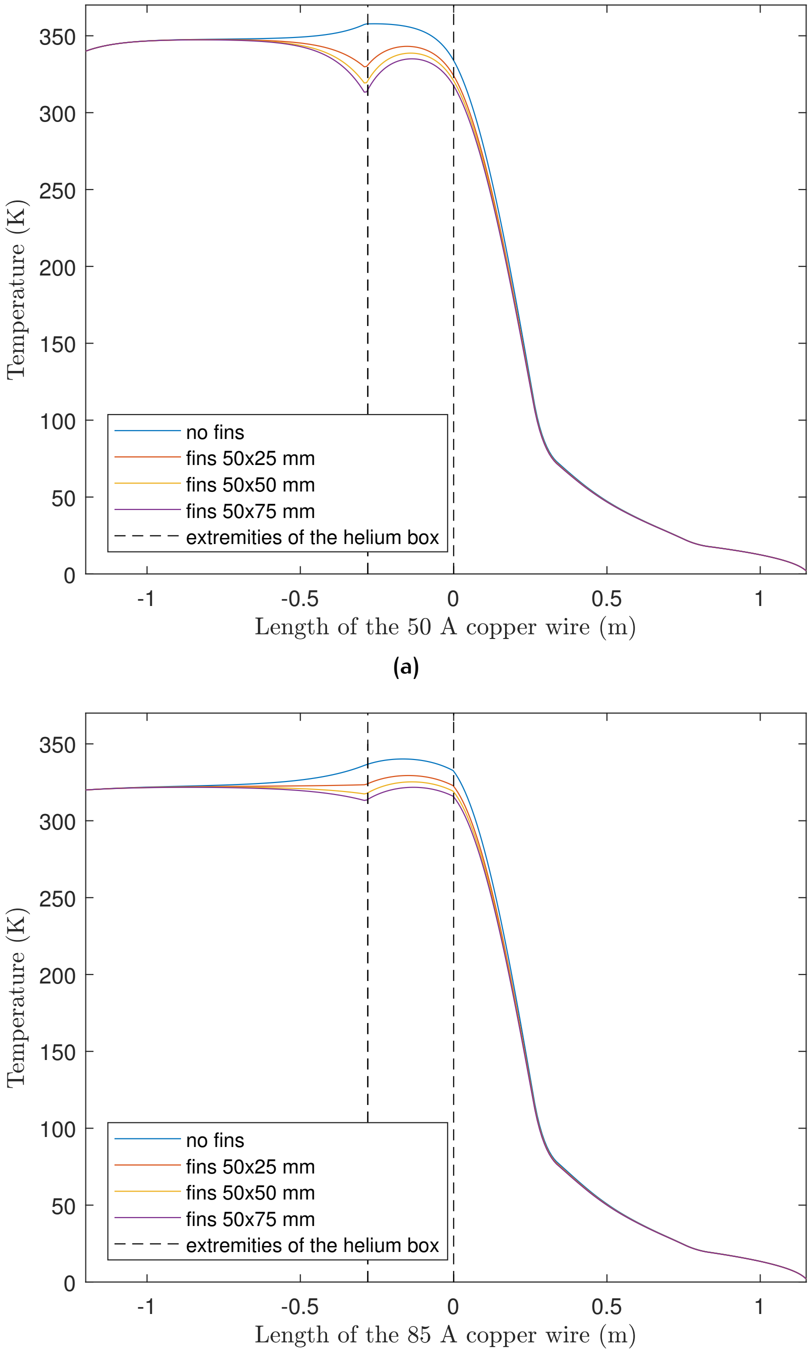
(a)

(b)

Figure 12: Temperature profiles of the 50 A wires (a) and 85 A wires (b), for different values of the thermal intercept contact resistance.

width fins	fins	helium guard	1^{st} t.i.	2^{nd} t.i.	liquid helium
0.0	0.00	20.29	25.53	6.11	2.87
25	10.13	14.75	24.51	6.08	2.84
50	14.44	12.31	24.16	6.06	2.84
75	16.57	11.27	23.82	6.05	2.84

Table 4: Heat extracted (W) by each cooling system, for different values of the width of each fin (mm).



(a)

(b)

Figure 13: Temperature profiles of the 50 A wires (a) and 85 A wires (b), for different values of the width of each fin.

7 COOLING DOWN

During the cool down of the cryomodule the magnets are not powered. This means that no current flows inside the leads. As a consequence, there is no Joule effect and all the temperature profiles shown before are lower. Nevertheless, the temperature could be too cold and condensation or ice could appear on the outer surface of the cryomodule.

Figure 14 shows the temperature profile calculated. The following list is about the amount of heat extracted from each cooling system:

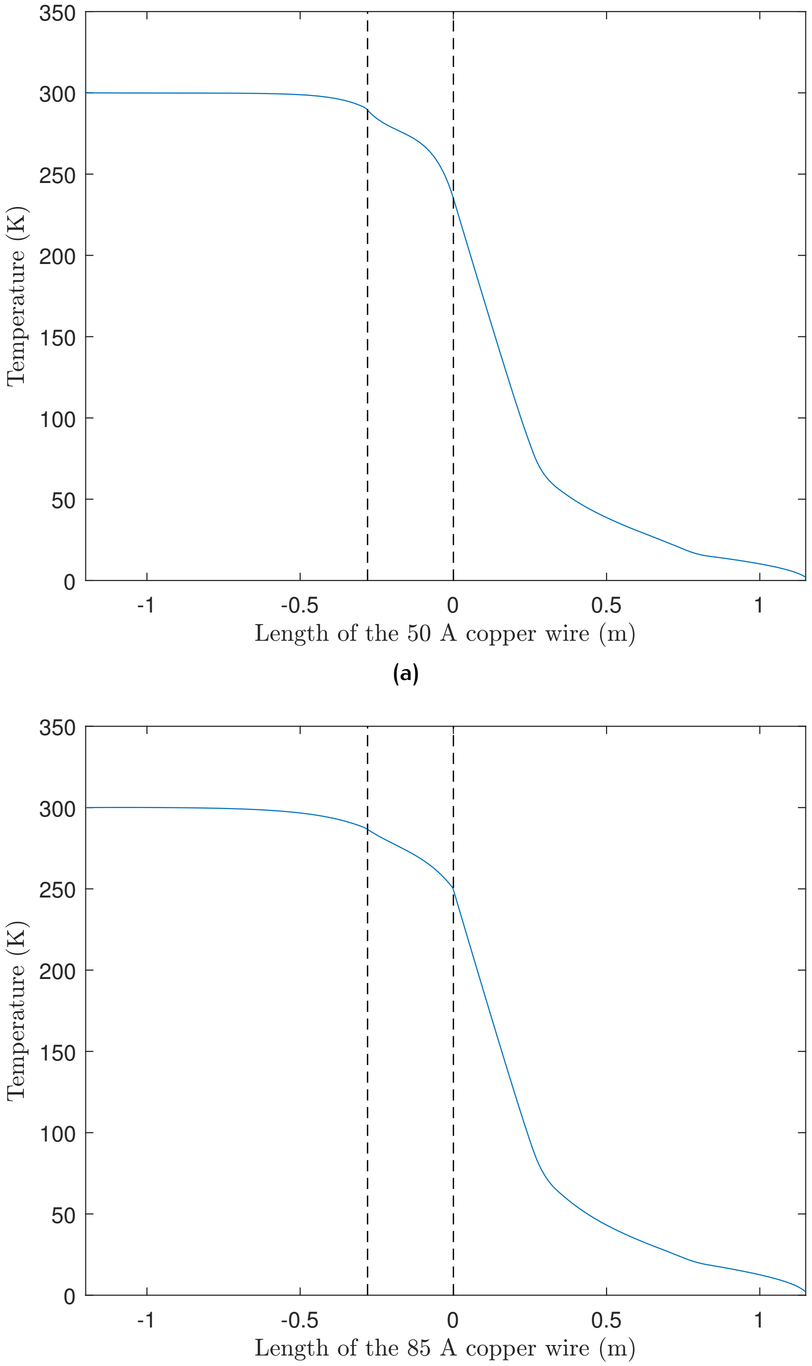
- heat extracted by fins: -3.28 W;
- heat extracted by the helium inside the guard: -10.22 W;
- heat extracted by the first thermal intercept: 9.27 W;
- heat extracted by the second thermal intercept: 4.67 W;
- heat extracted by liquid helium: 1.97 W.

As we can see, at the entrance of the cryomodule, the wires are at -23°C. For this reason, the use of an electrical heater to increase this temperature and to avoid condensation has been suggested. This electrical heater can be applied on the inner surface of the helium guard and it should be at least 15 W powerful.

8 TEST SET-UP

An unresolved uncertainty is on the thermal resistance between the wires and the copper block (thermal intercept). In this chapter a way to measure it is proposed, by using the facilities that Fermilab currently owns. In particular, this test should be done in STC.

Before putting the assembly inside the cryostat, an electrical heater is applied to the copper block related to the first thermal intercept. Then, the entire current leads assembly is put in STC, totally insulated from room temperature. The second thermal intercept is connected, through ConFlat flanges, to the helium distribution at 4 K or the nitrogen distribution at 77 K. The electrical heater is turned on, in order to have on the first thermal intercept a warmer temperature,



(a)

(b)

Figure 14: Temperature profiles of the 50 A wires (a) and 85 A wires (b), for zero current.

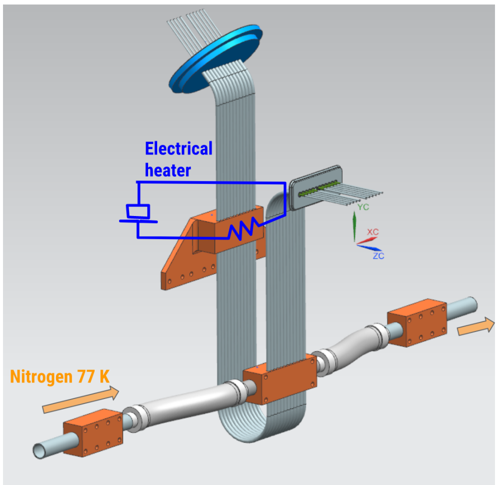


Figure 15: Test set-up in STC.

for example, 8 K or 81 K in case we use nitrogen. We can control this temperature with accuracy and we can measure the heat generated by the heater. Figure 15 shows this set-up.

Once the steady-state condition has been reached, this four temperatures can be measured:

1. temperature of the first copper block (T_1);
2. temperature of the copper wires in proximity to the first copper block (T_2);
3. temperature of the copper wires in proximity to the second copper block (T_3);
4. temperature of the the second copper block (T_4);

Then, these temperature differences can be calculated: ΔT_{1-2}, ΔT_{2-3}, ΔT_{3-4}. We know the power Q_{heater} generated by the heater, so each thermal resistance between two point i and j can be calculated by using the following equation:

$$R_{i-j} = \frac{\Delta T_{i-j}}{Q_{heater}} \tag{13}$$

Of course, R_{1-2} and R_{3-4} represent the thermal resistance between the copper wire and the copper block, i.e. the purpose of this test.

Furthermore, the temperatures T_2 and T_3 can be measured for each one of the eleven copper wires. In this way, if one of the eleven brazed joint went wrong, a different T_2 or T_3 will be measured.

How can we measure T_2 and T_3 without making holes in the stainless-steel tube? For example, if we want to measure T_2, we can measure the temperature of the first extremity of the copper wires, instead. Indeed, there is no heat flowing between point 2 and the first extremity, so this two temperatures can be considered equal. The same analysis can be done for point 3 and the second extremity.

A quick estimate about the time needed to wait for the steady-state shows that 1-2 days are needed in the case of nitrogen and at least one week for the helium case. This estimation has been made by considering the thermal resistance we predicted with Ansys and the thermal capacity of the copper and the insulator.

9 CONCLUSION

From the first model to the last design of the current leads assembly, a lot of analysis have been performed in order to warrant the proper operation. The design of the thermal intercept have been improved to lower the temperature profile, and decrease the heat on the 2K stage. An optimum RRR has been found between 50 and 150. Parametric studies have been done in order to evaluate the risk due to some parameters which are difficult to evaluate. A test setup have been suggested in order to qualify the leads after the manufacturing.

With these improvements, the temperature profile and the heat at 2K match the requirements. The current leads' design is now completed, and ready for procurement.

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