Preface

This thesis is written as a closure for my study as a mechanical engineer at Gjøvik University College. It was carried out at CERN, where I spent six months as a technical student.

In connection with this I would like to thank all at Gjøvik University College, who have made it possible for me to come to CERN. Especially I would like to thank my supervisor, Are Strandlie. He encouraged me to take the challenge to go to CERN, and he also made it possible for me.

At CERN I would like to thank Jean-Philippe Tock, who has been my supervisor during my stay and also all the others in my group who gave me a warm reception. Among these I would like to give a special thanks to Cedric Garion for all the help and support he has given me during my stay.

I would also like to give a big thanks to Stephen March, who took the time to read through my entire report and give me feedback on my work.

CERN, September 2007

Cathrine Herberg

Contents

1 Introduction to the project

1.1 Organization of the report

The report was made during my stay at CERN. It has an organization according to the layout described by Gjøvik University College, but with individual adjustments.

Chapter 1	An introduction to the project, CERN and the student. This chapter also contains a terminology list for the report.
Chapter 2	Is the theory part of the project. It contains the most important parts of the theory read during the literature search.
Chapter 3	Is a short introduction to the equipment which I have used during this project.
Chapter 4	Describes the work of making the computer model and the work done at the CERN cryogenic laboratory.
Chapter 5	Shows the results of the computer model and the test made at the laboratory.
Chapter 6	Discussion of the results from the laboratory and the model I have made.
Chapter 7	The final conclusion and a short description of the further work.

1.2 CERN

CERN **(C**onseil **E**uropéen pour la **R**echerche **N**ucléaire), the European Organization for Nuclear Research, was founded in 1954. It is the biggest particle physics laboratory in the world, and is located astride the Franco-Swiss border near Geneva. It has become a prime example of international collaboration, with currently 20 member states. There are also many non-member states that are involved in different ways.

CERN is a laboratory where scientists unite to study the building blocks of matter and the forces that hold them together. It exists primarily to provide them with the necessary tools, such as accelerators, which accelerate particles to almost the speed of light, and detectors to make the particles visible. There are 6500 visiting scientists from all over the world that come to CERN for their research. This is half of the world's particle scientists. They represent 500 universities and over 80 nationalities.

CERN employs about 2600 people. These represent a wide range of skills such as physicists, engineers, technicians, craftsmen, administrators, secretaries, workmen and so on. The scientific and technical staff designs and builds the laboratory's machinery. They also help prepare, run, analyze and interpret the results, [1].

1.3 Definition of the project

The line N is a special superconducting line in the LHC, which is external to the cold mass. The line is connected to the cold mass every half cell, and due to this it will have the same operating pressure and temperature as the magnets. In the dispersion suppressor zones the cool down of the line N is slightly delayed with respect to the magnets, due to its geometrical design.

As this delay may affect the readiness of the accelerator for operating, it is desired that it is reduced to less than two hours. In a test called String 2 a full scale model of the LHC cell was built to validate the LHC systems in working condition, and to investigate the collective behavior under various conditions. During this test, there was installed a copper plug in line N. The result showed that the cool down time of the line was delayed by more than two hours.

After this test there has been designed a new copper heat exchanger that is used in the line N to make additional lambda fronts, and by this lower the cool down time of the line. The design of this heat exchanger has been chosen by mathematical models that were compared to the String 2. The finished heat exchanger has never been tested, but it is presumably that it will reduce the cool down time in line N to less than two hours.

The goal of this project is to follow up a test of the heat exchanger at the cryogenic laboratory at CERN. I will also try to make a computer model of the heat exchanger, which can be verified by the result of the test. The results from this computer model can later be used to calculate the cool down time of line N, and then see if the target for the cool down time is reached.

1.3.1 Scope

The first phase of the project will consist of a literature study. I will during this period read the necessary theory for me to understand the project. In the second phase I will start on the computer model. During this phase I need to acquire knowledge about the program I will be using. The test at the laboratory will start as soon as possible. Since this test will take a while to be completed I will follow it beside the other work.

1.3.2 Demarcation

The demarcation of this project is mainly set by the time of my stay at CERN. The time is short, and my background knowledge at subjects as helium is very low. This means that I will be using quite a lot of time reading different literature to be able to proceed in this project. I will in addition to this depend on help from others working here at CERN.

1.4 Work methods

This project will be done at CERN in Geneva, Switzerland. Here I will be a part of a group called MCS-IC, where MCS stands for magnets, cryostats and superconductors; and IC for interconnections. Most of the work will be done independently, but I am dependent on help from others in the group. Usually there will be a section meeting every Tuesday, where everybody can ask questions and tell how things are going with their work. In addition to this I will send a status report to my supervisor at Gjøvik University College every month.

I will also follow up the test in the cryogenic laboratory. Since I don’t have any experience on this field, the test will be done by the workers at the lab. My task will be to follow the test from the beginning to the end and to help if there are any problems that I can assist in.

1.5 The student’s background

This project is done by Cathrine Herberg. I am in my final year as bachelor Machine Engineer student at Gjøvik University College. My previous experience is:

2004-2007: **Bachelor Machine Engineer**
Gjøvik University College

2004: **Certificate of apprenticeship, Machine operator**
Mustad Longline

2000-2004: **Higher education entrance calcification and vocational training, Machine operator**
Raufoss secondary school

1.6 Terminology in the report

Busbar Main cable that carries the current for powering the magnets outside the magnet coil, [2].

Cernox™ Temperature sensors that can be used from 100 mK to 420 K with good sensitivity over the whole range. They have a low magneto-resistance, and are the best choice for applications with magnetic fields up to 30 T (for temperatures greater than 2 K). They are resistant to ionizing radiation, and are available in robust mounting packages and probes. Because of their versatility, they are used in a wide variety of cryogenic applications, such as particle accelerators, space satellites, MRI systems, cryogenic systems, and research science, [3].

Cryostat Cryostats are used to maintain and control low temperatures. It is a thermally insolated tub, where the pressure can be regulated by adjustable valves, [4].

Dipole A dipole magnet is a device with a magnetic north pole and a magnetic south pole. It can be used to make charged particles such as electrons move on a curved path. For example, dipole magnets are used in particle accelerators, [5].

Electron volt An unit of energy (eV) equal to the work requires to move one electron through a potential difference of 1 volt. The eV is a small unit of energy, so mega-electron volts (MeV) and giga-electron volts (GeV) are commonly encountered, [6].

FSI Fluid structure interaction (FSI) occurs when a fluid interacts with a solid structure, exerting pressure that may cause deformation in the structure and, thus, alter the flow of the fluid itself, [7].

Heat flux The heat flux is the amount of heat transferred across a surface of unit area in a unit time, [8].

Higgs boson Higgs boson is a hypothetical elementary particle (not proven in 2005), which according to electroweak theory is indirectly responsible for the mass of the elementary particle, [9].

Lambda front The boundary between He II and He I.

Quadrupole A quadrupole magnet is a device in which two magnetic north and two magnetic south poles that are arranged in alternation around an axis. In particle accelerators, magnets of this kind are used to focus/defocus the particle beam, [10]**.**

Superconductor A material which under a critical temperature can conduct electricity with no resistance. This occurs in some materials at cryogenic temperatures, [11].

Superfluid Superfluid is a state that occurs in some liquids at very low temperatures. In this state the superfluid has no friction and due to it high thermal conductivity it is almost a perfect heat conductor.

Synchrotron A synchrotron is a particular type of a cyclic accelerator. Here the particles are accelerated by a high-frequency field which is carefully synchronized with the particles movement. This makes the particle move forward. The particle is kept in its circular patch by the magnetic field which is increasing synchronous with the particles energy, [12].

Tesla Symbol T, SI unit for magnetic flux density. 1 tesla is equal to 1 weber/m^2 =104 gauss. The unit got its name from N. Tesla, [13].

2 Theory

2.1 Particle accelerators

In modern physics an accelerator is a common designation for machines which can accelerate electrical particles into a high velocity. Accelerators consist of two main parts, the ion source and the acceleration part. In the ion source it is released electrical charged particles. The particles can be electrons, protons, alpha particles or ions of heavy atoms. In the acceleration part these particles are affected by electrical forces and the velocity will increase. The energy the particle has archived at the end is a measurement for the size of the accelerator. This energy is measured in electron volt (eV).

There are two different types of accelerators, the linear and the circular. The names come from the shape of the particle path. In a linear accelerator the path is straight and in a cyclic accelerator the path is circular.

Even though the particle accelerator has been developed for research within nuclear physics and elementary particle physic they are today used in many other fields as well. Minor accelerators for electrons, protons, and alpha particles are used in structure inspection of solid materials. Electron accelerators and large proton accelerators are used for radiation treatment in medicine. In addition to this, accelerators are used to produce radioactive nuclides for examinations and treatment of patients, as well as industry and technical, chemical and biological research, [14].

2.1.1 LHC – The Large Hadron Collider

CERN is now (2007) building the world's largest and most powerful particle accelerator. It is called the Large Hadron Collider (LHC). Large because it is installed in a tunnel which is about 27 km in circumference, and buried between 50-150 m below ground. Hadron is because of the accelerating hadrons[1], and collider because it's colliding particles from two particle beams, traveling in different directions. The tunnel is located between the Jura mountain range in France and Lake Geneva in Switzerland. This tunnel was already built in the 1980s for the previous big accelerator, the Large Electron-Positron collider (LEP) which was dismantled in 2000, [15].

[1] Hadrons are particles composed of quarks, such as protons and neutrons. On the other hand, leptons are particles that are not made of quarks, such as electrons and muons.

Fig. 2.1.The LHC seen from above

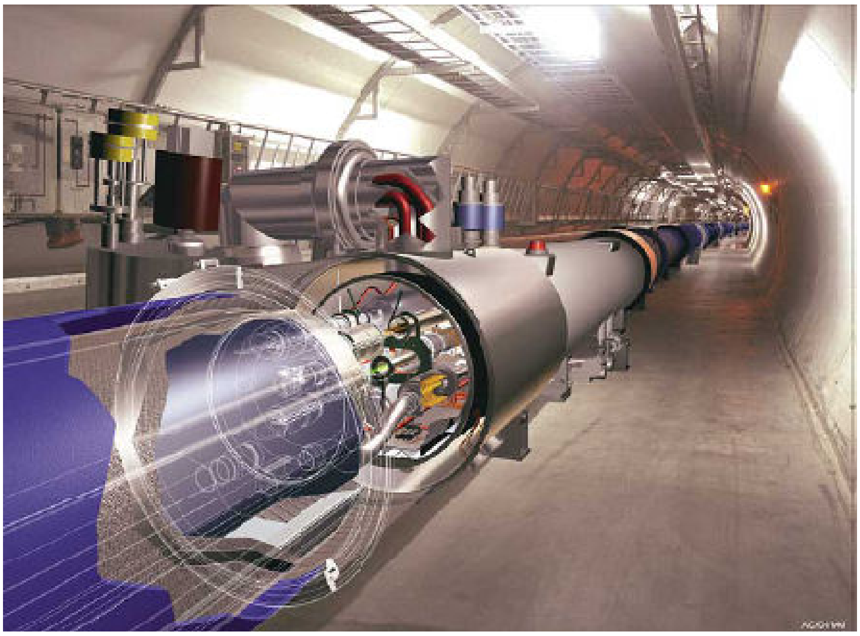

Fig.2.2. Model of inside the tunnel

The accelerator complex at CERN is a succession of machines with increasingly higher energies. Each machine injects the beam into the next one, which brings the beam to an even higher energy, [16]. The last element in the chain is the LHC, where the particles will travel trough a vacuum comparable to outer space. Here the beam will make millions of circuits. On each circuit the beam will receive an additional impulse from an electric field contained in accelerating cavities, until they reach the energy[2] of 7 TeV. To control the beams at such high energies, the LHC uses 1800 superconducting magnet systems to guide the beams around the ring. These magnets are built from superconducting materials with a coil of niobium-titanium. Operating at 1.9 K the magnets can conduct electricity without resistance and create much stronger magnetic fields than ordinary electromagnets. The superconducting magnets operate with a magnetic field at about 8 T (tesla), while ordinary “warm” magnets only can achieve a maximum field of about 2 T. Without the superconducting magnets it wouldn’t have been possible to accelerate particles to as high energies as 7 TeV.

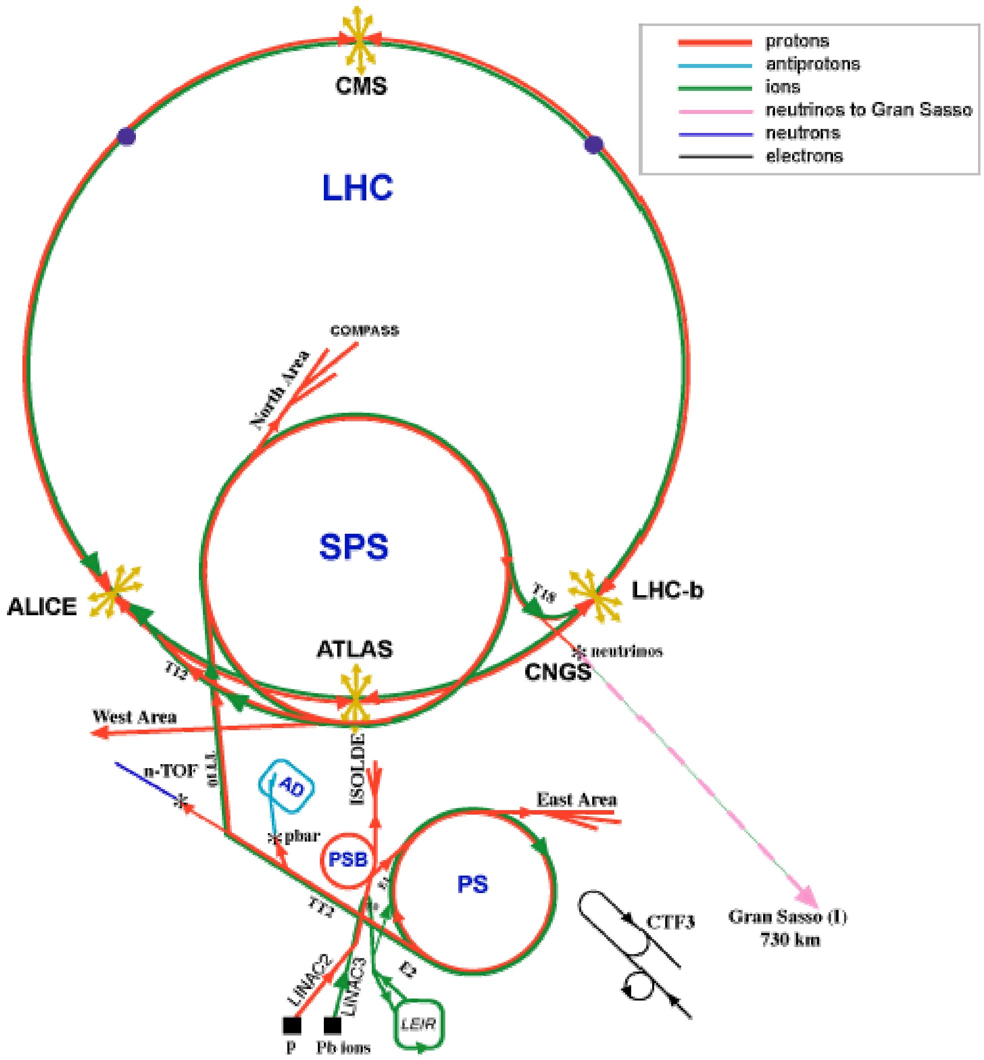

Fig.2.3.The accelerator complex at CERN [16]

In the tunnel each beam will consist of nearly 3000 bunches of particles and each bunch will contains as many as 100 billion particles. The particles are so small

[2] The T in front of eV stands for tera which means 10^{12}.

that the chance of any two colliding is very small. When bunches cross each other in the tunnel, there will only be about 20 collisions among 200 billion particles. However, bunches will cross each other 40 million times per second, so the LHC will generate up to 600 million collisions per second.

The reason why CERN is building the LHC is that it can provide particle collisions at the highest energies ever observed in laboratory conditions. Each proton flying around in the LHC will have energy of 7 TeV, and when two protons collide the collision energy will be 14 TeV. Lead ions have many protons, and will together give an even greater energy. The lead ion beams will have collision energy of 1150 TeV. The physicists are eager to see what can be revealed. Four huge detectors will observe the collisions so the physicist can explore new territory in matter, energy, space, and time.

The configuration of the LHC

The LHC can be divided into 8 zones or octants, fig.2.4. These octants are built up by three main parts:

- Arc cells
- Dispersion Suppressor sections (DS)
- Long Straight Sections (LSS)

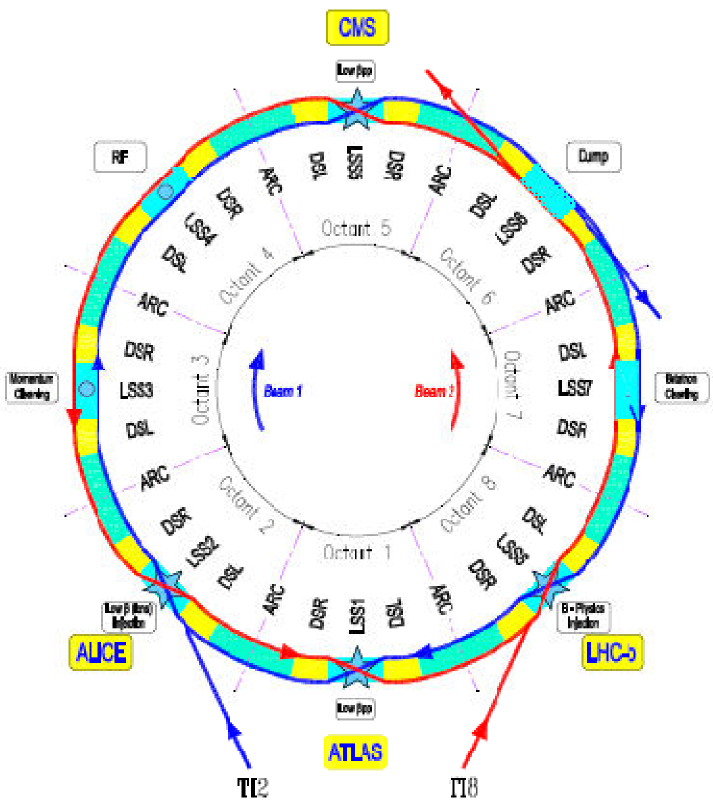

Fig.2.4. Schematic layout of the LHC [2]

The location of components in the LHC is defined by giving the number of the octant it is in. Moreover, DS sections are also given a letter R or L, depending if it is placed on the right or the left end of the LSS. Right or left is given by looking from the center of the ring, e.g. DS1L denotes the DS placed in octant number one, on the left of the LSS [2]

In the middle of each octant LSS is located. The LSS is approximately 528 m long and can serve as an experimental or utility insertion. In this section are also the accelerating cavities placed. These are electromagnetic resonators that accelerate particles and keep them at a constant energy by compensating for energy losses.

In both ends of the LSS there is a DS section followed by an arc cell. Each of the arc cells is composed of 46 regular half-cells, each 53.45 meters long. The arc cell is where the particle beams are bent. This is done by using dipole magnets, which it is 1232 of in the LHC. They are 15 meters long, each weighing 35 ton, and are the most complex component of the machine.

The arc cell is optimized for a maximum integrated dipole field along the arc, with a minimum number of magnet interconnections and the smallest possible beam dispersion. The typical arc half-cell consists of a string of focusing/defocusing main quadrupole (MQ) and three main bending dipoles (MB).

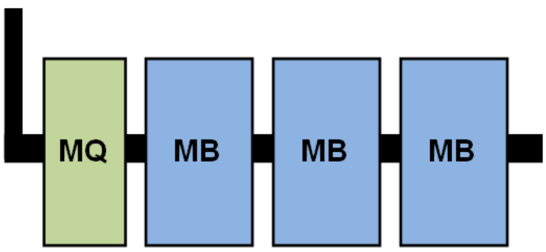

Fig.2.5. LHC half-cell

A DS zone consists of four individually powered quadrupole magnets which each of them are accompanied by two dipole magnets, fig. 2.6. The aim of these sections is to adapt the LHC reference orbit to the geometry of the LEP tunnel and cancel the horizontal dispersion arising in the arcs. In each DS zone there is also a component called connection cryostat, which connects the DS zone to the arc cell. Here no magnets are needed, but continuity of all cryogenics and electrical circuits has to be provided, [17].

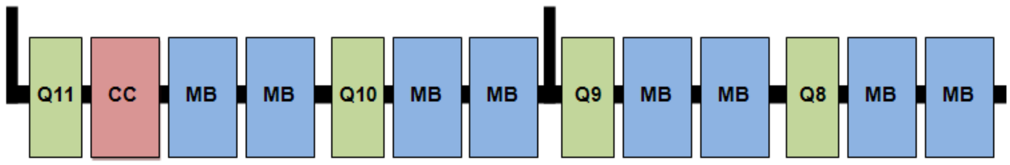

Fig.2.6. LHC Dispersion Suppressor

The LHC is equipped with four collision points. Atlas experiment is located at point 1, the Alice experiment at point 2, the CMS experiment at point 5 and the LHC-b experiment at point 8. Points 2 and 8 also contain the injection system for Beam 1 and Beam 2. The beams only cross from one magnet bore to the other at these four locations. The remaining four long straight sections do not have beam crossings. At the four collision points different types of experiments will be installed. Here is a short introduction to the four experiments:

- **ALICE** (A Large Ion Collider Experiment)

  To study the quark-gluon plasma, this consists of (almost) free quarks and gluons which are the basic building blocks of matter. It is believed to have existed during the first 20 to 30 microseconds after the universe came into existence in the Big Bang, [18].

- **CMS** (Compact Muon Solenoid)

  Is a general-purpose detector to capable of studying many aspects of proton collisions at 14 TeV. It contains subsystems which are designed to measure the energy and momentum of photons, electrons, muons, and other products of the collisions. One of the goals is to discover the Higgs boson, [19].

- **ATLAS** (A Toroidal LHC ApparatuS)

  Is also a general-purpose detector, which will study the same aspects as CMS. The difference between these two detectors is that they not have the same configuration, [20].

- **LHCb** (LHC-beauty)

  In the Big Bang, the beginning of our Universe, matter and antimatter were created in equal amounts. But somehow the antimatter disappeared and our Universe formed from just the matter that remained. Physicists think a strange effect called "CP violation" plays an important part in the story. The LHC is particularly aimed at measuring the parameters of CP violation in the interactions of b-hadrons, [21].

2.2 Basic heat transfer

In thermal physics, heat transfer is the transfer of thermal energy from a hot to a cold body. When a physical body, e.g. an object or fluid, is at a different temperature than its surroundings or another body, transfer of thermal energy occurs. This continues until the body and the surroundings reach thermal equilibrium. The heat transfer always occurs from a hot body to a cold one, as a result of the second law of thermodynamics. It takes time before the body and the surroundings reach the same temperature, and in cases with infinite small temperature difference, the heat transfer is infinite slow. You can nevertheless not completely stop the heat transfer, but it can be slow down by insulation.

Several material properties serve to modulate the heat transferred between two regions at differing temperatures. Examples include thermal conductivities, specific heats, material densities, fluid velocities, fluid viscosities, surface emissivities, and more. Taken together, these properties serve to make the solution of many heat transfer problems and the involved processes, [22] [23].

The heat transfer mechanisms can be divided into three groups:

- Conduction
- Convection
- Radiation

2.2.1 Conduction

Conduction is the transfer of thermal energy from a region of higher temperature to a region of lower temperature. This can happen through direct molecular communication within a medium or between mediums in direct physical contact without a flow of the material medium. The heat is transferred by conduction when adjacent atoms vibrate against one another or as electron moves from atom to atom. Metals are usually the best conductors of thermal energy. This is due to the way that metals are chemically bounded. Metallic bonds have free moving electrons and form a crystalline structure, which is greatly aiding in the transfer of thermal energy. Fluids and gases are not typically good conductors. This is due to the molecules which usually are further apart, and is giving a smaller chance of molecules colliding and passing on thermal energy. In a perfect vacuum, conduction or convection does not appear at all.

To quantify the ease with which a particular medium conducts, engineers employ the thermal conductivity, also known as the conductivity constant or conduction coefficient, k. This is a material property that is primarily dependent on the medium’s phase, temperature, density, and molecular bonding.

The heat transfer, heat flux, can be calculated by this equation:

$$Q = \frac{k \cdot A \cdot (t_1 - t_2)}{\delta} \quad [W]$$

Where,

k = thermal conductivity

A = cross-section

δ = length

t_1 = temperature on the hot side

t_2 = temperature on the cold side

2.2.2 Convection

Convection is heat transfer from a gas or liquid to a physical body, or the other way around. This means that the heat transfer happens by interior currents in the gas or liquid. Convection can happen in two ways; free convection or forced convection. Free convection is when a gas or liquid is in contact with a warm surface, and the particles closest to the surface will get warmer than the other particles. Due to the reduced density, these particles will rise and create motions in the gas or liquid.

If the fluid or gas motion is created or increased in an artificial way, it is called forced convection. This can for example be when you maintain an enforced current in a pipe where the liquid or gas is either warmed up or cooled down by a pump or a fan. Free and forced convection can occur at the same time.

The characteristic for both the free and forced convection is that the fluids warm and cold particles are mixing. The warm particles will bring their heat to the area with cold particles and heat them up. The biggest part of the temperature change will happened in a thin layer close to the surface. The thickness of this layer is dependent on the fluid characteristics, velocity, the shape of the surface and its position, surface properties and the surface material.

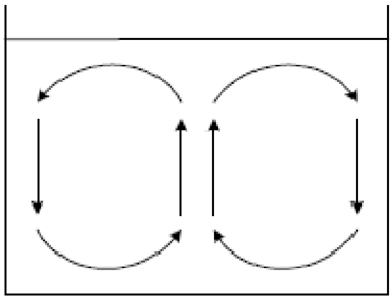

Fig.2.7. Example of free convection currents in a boiling vessel

The heat flux Q, which each time unit is transferred from the surface to the liquid (or opposite) is directly proportional with the area of the surface and the temperature difference t_s - t_f. If we assume that this is a stationary flow condition can the heat flux be calculated by the following equation, [24]:

$$Q = h \cdot A \cdot (t_s - t_f)$$

Where,

h = heat transmission coefficient

A = Area of the surface

t_s = temperature of the surface

t_f = temperature of the fluid

2.2.3 Thermal radiation

Thermal radiation is heat through electromagnetic radiation, sent out from an object because of its temperature. All objects radiate energy, either if they are cold or warm. No medium is necessary for radiation to occur; radiation works even in and through a perfect vacuum. For instance the energy of the Sun is traveling through the vacuum of outer space before warming up the earth. There is no energy loss when the radiation pass through a vacuum, but when radiation meets a body, part of, or all of, the radiation will be transferred. The absorbed radiation is usually transferred into heat, [25].

The emissivity (ε) of a material is the ratio of energy radiated by the material to energy radiated by a black body at the same temperature. It is a measure of a material's ability to absorb and radiate energy. A true black body would have an ε = 1 while any real object would have ε < 1. Emissivity is a numerical value and does not have units, [26].

The emissivity depends on factors such as temperature, emission angle, and wavelength. However, a typical engineering assumption is to assume that a surface's spectral emissivity and absorptivity do not depend on wavelength, so the emissivity is a constant. This is known as the grey body assumption. When dealing with non-black surfaces, the deviations from ideal black body behavior are determined by both the geometrical structure and the chemical composition, and follow Kirchhoff's law of thermal radiation: emissivity equals absorptivity (for an object in thermal equilibrium), so that an object that does not absorb all incident light will also emit less radiation than an ideal black body.

The radiant energy from a black body is according to Stefan-Boltzmann law:

$$Q_{rad} = A \cdot \varepsilon \cdot \sigma \cdot T^4$$

Where,

Q_{rad} *= heat flux from radiation*

A = radiated surface

T = surface temperature

ε = emissivity

2.3 Cryogenics

Cryogenics is the science and technology of producing low-temperature environments. The word cryogenics has its origin in the Greek language where “cryos” means frost or cold and “gen” is a common root for the English verb to generate. Strictly speaking, cryogenic means to produce cold, but over years of usage by engineers and scientists the term has developed into a more general meaning. Today, cryogenic is associated both with the study and the production of low-temperature environments, [27].

As mentioned earlier the word cryogenic has developed several common usages, such as cryogenic fluid and cryogenic machinery. Cryogenic fluid is used in the production of cold, while the cryogenic machinery is the hardware used in achieving the low-temperature environments. When we use the word cryogenic about a cooling process, we usually mean processes which are below 100-150K. This distinction is established because it represents the point where permanent gases such as N_2, O_2, and Ar begin to liquefy.

There are many areas of application for cryogenics. Some of them are commercial enterprises, while others still are in the early stages of research and development. These applications can be put into five major categories, [27]:

1. Storage and transport of gases
2. Separation of gases
3. Biological and medical applications
4. Altering material properties by reduced temperature
5. Superconductivity

In the LHC, cryogenics is used to achieve superconductivity. The LHC is unique among superconducting synchrotrons because its operating temperature is below 2 K. The magnets will operate at 1.9 K, a temperature which is achieved by use of liquid helium. This low temperature is to maximize the field strength of the superconducting magnets, [2].

Fig.2.8. Cryogenic equipment in the lab

2.4 Superconductivity

Superconductivity is a phenomenon which can be observed in certain materials when they are cooled down below their critical temperature. It is characterized by the complete absence of electrical resistance. Superconductivity occurs in a wide variety of materials, including simple elements such as tin and aluminum, various metallic alloys and certain ceramic compounds containing planes of copper and oxygen atoms. Superconductivity, however, does not occur in noble metals like gold or silver, or in ferromagnetic metals[3], [28].

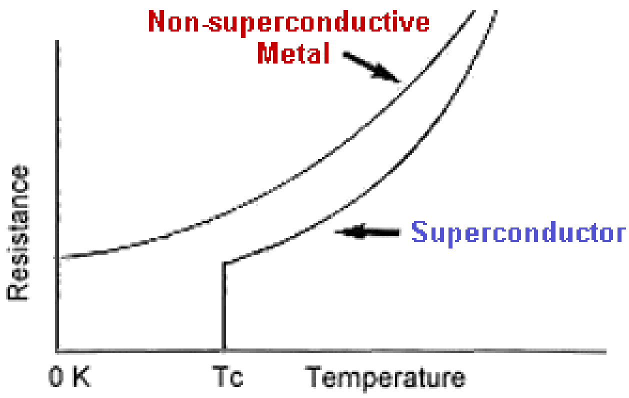

Fig.2.9. Difference between a non-superconductive metal and a superconductor [29]

Every superconductor is characterized by its critical temperature T_c, the critical value of magnetic field H_c and the critical value of the current density J_c. As far as the material not is influenced by an external magnetic field, the electrical resistance drops down to zero at the critical temperature, see fig.2.9. If the material is affected by a magnetic field, superconductivity will first appear at a lower temperature, and if the magnetic field is too strong superconductivity will not appear at all.

When the temperature is below the critical temperature, a superconductor becomes perfectly diamagnetic. This means that it is cancelling all magnetic flux in its interior by creating surface currents in itself which produces a magnetic field countering the external field. According to this it is common to divide the superconductors into two groups, type I and type II, [11]:

- Type I - will as far as it is superconducting be totally impermeable for an external magnetic field. This means that the permeability is equal to zero.

[3] The ferromagnetic metals (for example, Fe, Ni, etc.) must be excluded from this discussion. It appears likely that they cannot become superconducting in the ferromagnetic state. However, it has shown that a non-magnetic high-pressure phase of iron can become superconducting with a transition temperature up to 2 K.

- Type II – will have the same magnetic properties as type I in weak magnetic fields, but the magnetic field will start to penetrate the material when the field exceeds the critical value. The superconductivity will cease when the magnetic field exceeds another higher critical value.

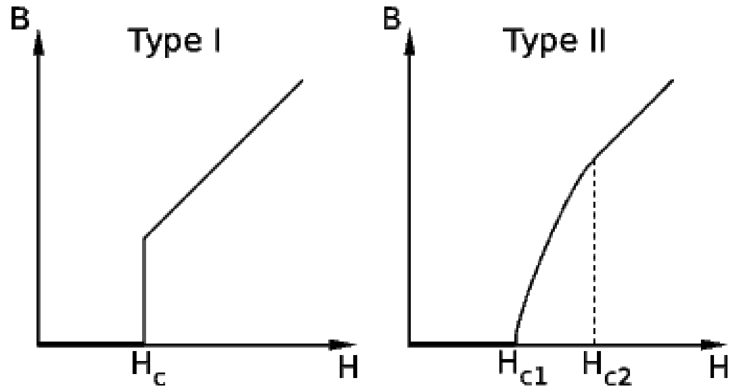

Fig.2.10. Variation of internal magnetic field (B) with applied external magnetic field (H) for Type I and Type II superconductors [30]

Since the LHC magnets will make a type II superconductor when it is cooled down, this type is of special interest. All the magnets in the arcs are making use of classical niobium titanium (NbTi). The NbTi has good mechanical properties, such as ductility, which allows simple manufacturing. The critical temperature for the NbTi alloy is slightly above 4.2 K, but to increase the performance it is cooled down to below 2 K in the LHC. At 1.9 K a magnetic field of an extra 1.5 T is attainable, i.e. from around 6.5-7 T to 8-8.5 T central field, with corresponding 20% gain in the beam energy, [2].

In the LHC it will also be used superconducting cables for the magnets. This will consist of NbTi filaments in a copper matrix. The copper matrix around the NbTi filaments is to protect the cable. This is due to the relatively high resistivity of the NbTi alloy in normal-conducting state. If the cable is not in the superconducting state, the current passes through the copper and protects the cable from heat loads and damage.

Quenching is a term used to describe the process which occurs when any part of a magnet changes from superconducting to the normal resistive state. This can take place when critical values of temperature, current, or magnetic field are exceeded. When one of these parameters exceeds the critical value, the superconductor becomes normal-conducting. If the cooling power is insufficient to recover the superconducting state, the normal-conducting zone expands. This process is called a quench. A quench causes a local overheating of the magnet, since the magnet no longer has zero electrical resistance, and can lead to damage of the magnet, [31].

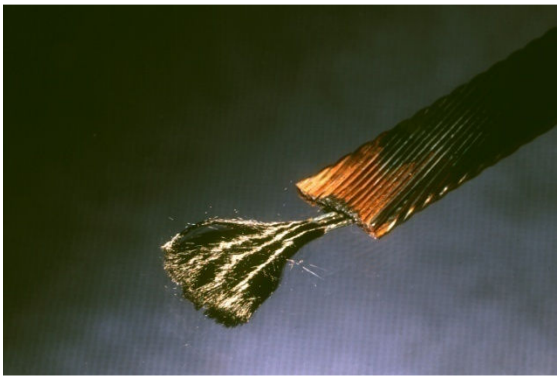

Fig.2.11. Inner cable comprises 28 strands, each made of some 8900 7-micron filaments of niobium-titanium coated with a copper matrix, [32].

2.5 Properties of liquid helium

Liquid helium was chosen to cool down the superconducting magnets in the LHC due to its unusually efficient heat transfer properties. The phase diagram of helium is atypical compared to other fluids. There is no traditional triple point, and there is no curve separating the solid state from the gas state. Moreover helium has the lowest critical point of all fluids, T_c=5.2 K, p_c=0.226 MPa, [27].

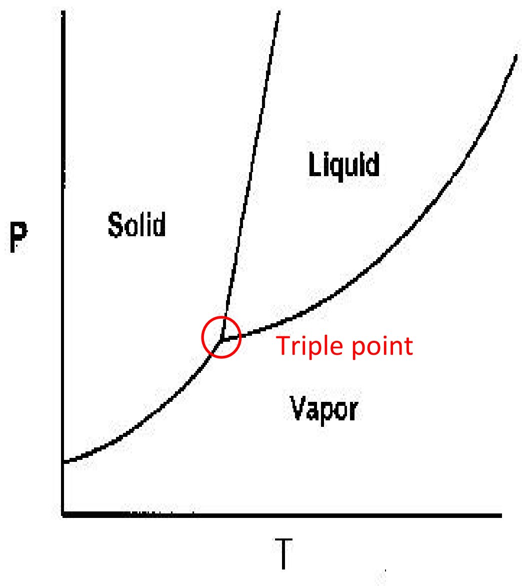

Fig.2.12. Typical phase diagram for fluids

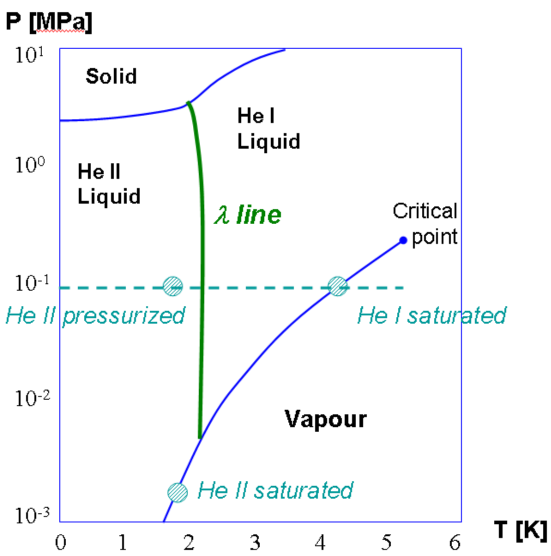

Fig.2.13. Phase diagram of 4He, [33]

There are several unique features about the phase diagram which should be noted. One of these features is that the solid state is not obtainable at any temperature unless the pressure is above 2.5 MPa. Another feature is that helium can exist in either of two very different states; the normal helium (He I) and the superfluid helium (He II). He I has the same characteristic as a classical fluid, but the superfluid state has physical features that are truly exceptional.

The phase shift between these two states happens at a temperature of about 2.17 K, known as the λ point (T_{λ}) or critical point. The reason this point is called the λ point is that the specific heat graph looks kind of like λ. These two states are separated in the phase diagram by a line called λ line. This transition is a phase shift of second order, i.e. it does not have a latent heat transformation. This means that the two phases of liquid helium cannot coexist with balance. The liquid helium reveals a brutal change in density, specific heat and viscosity when it crosses the λ line. As the temperature decreases below this point, an increasingly fraction of liquid helium flows with no internal friction. But the most important property is that it makes a nearly perfect heat conductor.

Helium is the compound that makes a good superfluid, due to its weak intermolecular forces. In this particular case we are interested in ^4He, which is the most common isotope of helium, [34]. This isotope is also much easier to cool down to a superfluid state than ^3He, because ^3He requires a much lower temperature to become superfluid.

Superfluidity was first discovered in ^4He by P. Kapitsa in 1938. For a long time it was believed that only ^4He could show superfluid properties. But in 1972 was the phenomena also proven in ^3He. All superfluids have the unique quality that their atoms are in the same quantum state, [35]. This means that they all have the same momentum, and if one moves, they all move. This quality allows superfluid to move without friction through even the tiniest of cracks. It will even flow up the sides of a jar and over the top until the jar is empty. This apparent defiance of gravity comes from a special type of surface wave present in the superfluid helium, and this effect pushes this extremely thin film up the sides of the container. This was discovered in 1962 by Tisza, who named the phenomena “third sound”. Another unusual result of the third sound is the fountain effect, where superfluid excited by photons will form a fountain vertically upward of its surface.

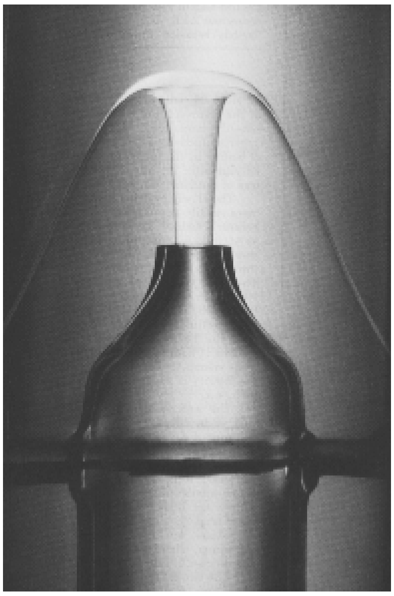

Fig.2.14. Shows a fountain of superfluid helium [29]

Superfluids also have amazingly high thermal conductivity. When heat is introduced to a normal system, it diffuses through the system slowly. In a superfluid, heat is transmitted so fast that thermal waves become possible. This fourth kind of wave found in superfluids is called second sound.

Here are some of the graphs showing the properties of liquid helium:

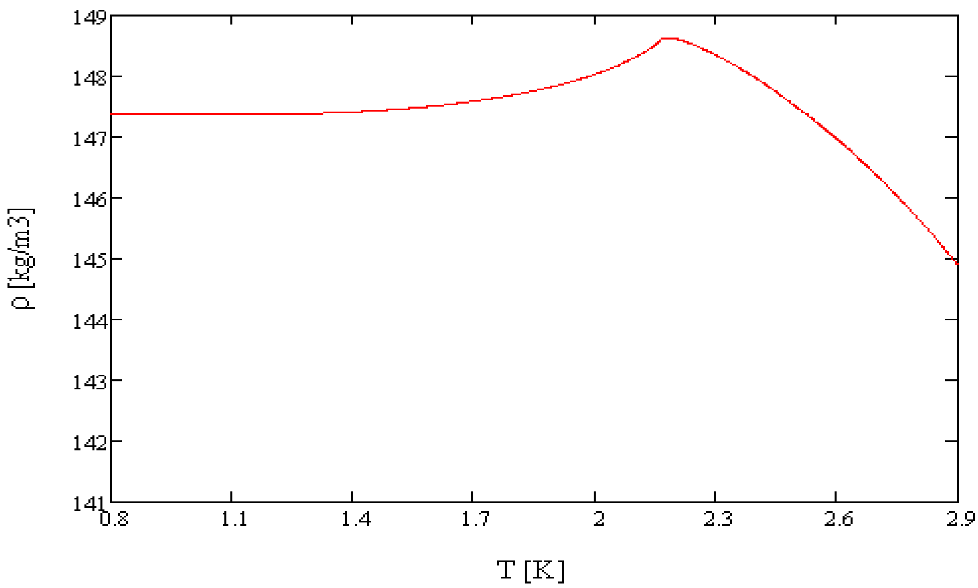

Fig.2.15. Helium density function under 1.3 bar pressure (Made in Mathcad with data from HEPAK)

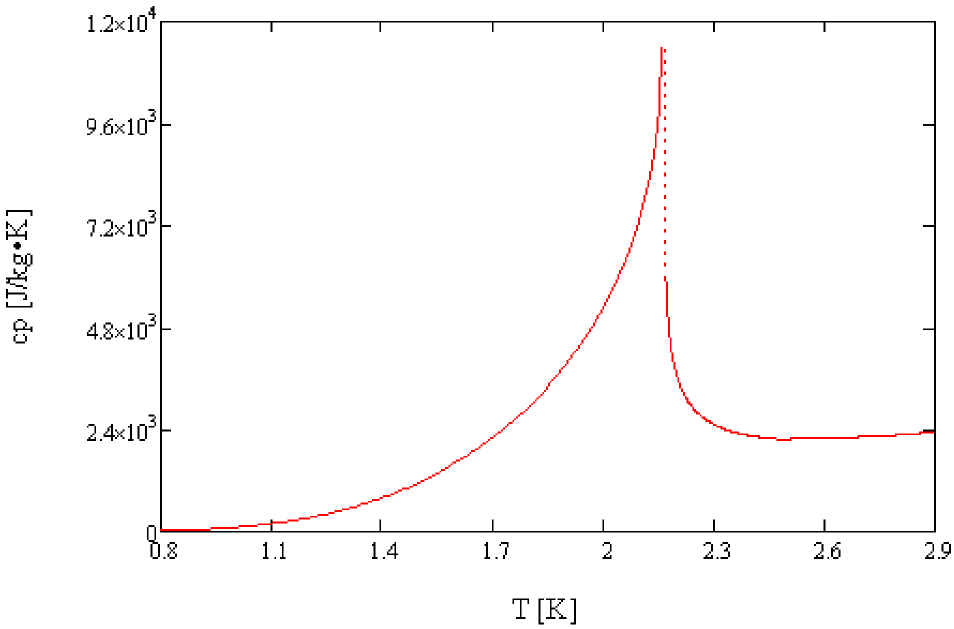

Fig.2.16. Helium specific heat function under 1.3 bar pressure (Made in Mathcad with data from HEPAK)

Observations of the graphs:

- A maximum density occurs at 2.182 K or 6 mK above T_λ in saturated liquid helium. Below T_λ the density is only weakly temperature dependent and becomes essentially constant for T < 2.0 K.

- The graph for the specific heat has a discontinuity at T_λ.

2.5.1 Heat transport properties

The behavior of He II when subjected to a mass or heat flow clearly demonstrates the unique character of this fluid. The observed effects cannot, in general, be treated by classical fluid mechanics models. The most accepted approach to understanding the transport properties is by means of the two-fluid model, [36].

Laszlo Tisza and Lev Landau proposed the two-fluid model at about the same time (1941), describing helium below the lambda point as a mixture of normal helium (He I) and superfluid helium (He II). He I is made of helium atoms in excited energy states, and therefore carries entropy and heat. It has density ρ_n, velocity v_n, and viscosity η_n. He II is made of atoms all in the ground state and carries no entropy. The superfluid density is designated by ρ_s, velocity by v_s and it has zero viscosity. As the temperature drops farther below the lambda point, a greater fraction of the helium becomes superfluid. This component can move without friction, which thereby explains the distinctive low-temperature phenomena observed [37].

To model heat transfer in liquid helium, Gorter-Mellink equation for one dimensional problem is used in the form, [38]:

$$f(T) \cdot \frac{dT}{dx} = \dot{q}^3$$

Where,

q = heat flux

f(T) = the heat conductivity function.

dT/dx = denotes the heat conductivity function

To be able to calculate the heat flux in He II a transformed Gorter-Mellink equation is used:

$$q(l_{HeII}) = \left[\frac{\int_{T_0}^{T_\lambda} f(T)dT}{l_{HeII}}\right]^{\frac{1}{3}}$$

Where,

T_0 = temperature at the beginning.

T_λ = temperature at the end.

l_{HeII} = length of He II.

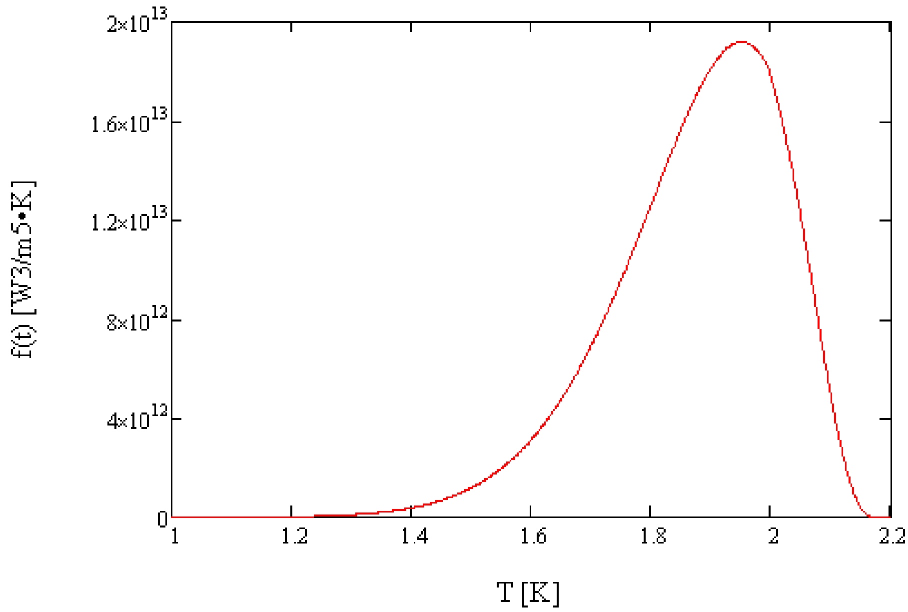

Fig.2.17. Helium heat conductivity under 1.3 bar pressure (Made in Mathcad with data from HEPAK)

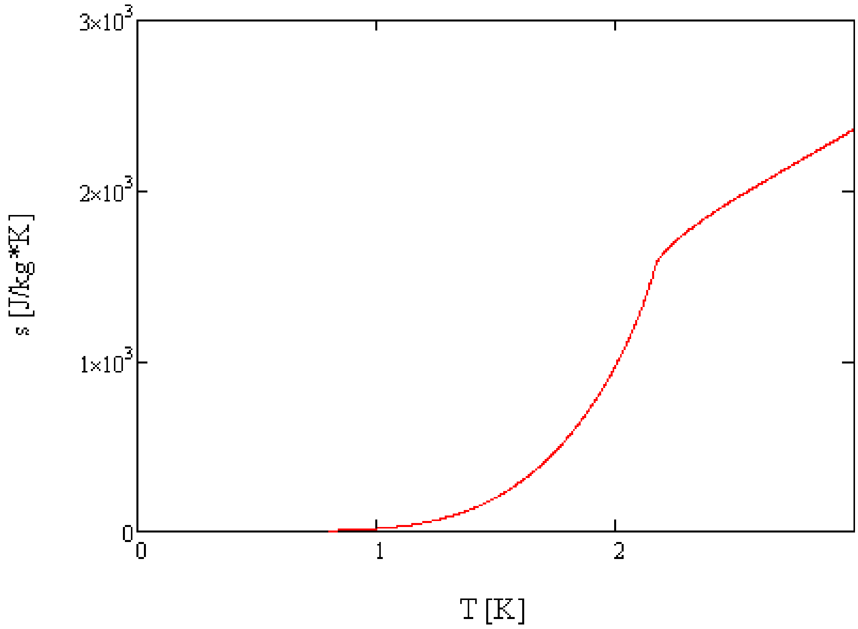

Fig.2.18. Helium entropy function under 1.3 bar pressure (Made in Mathcad with data from HEPAK)

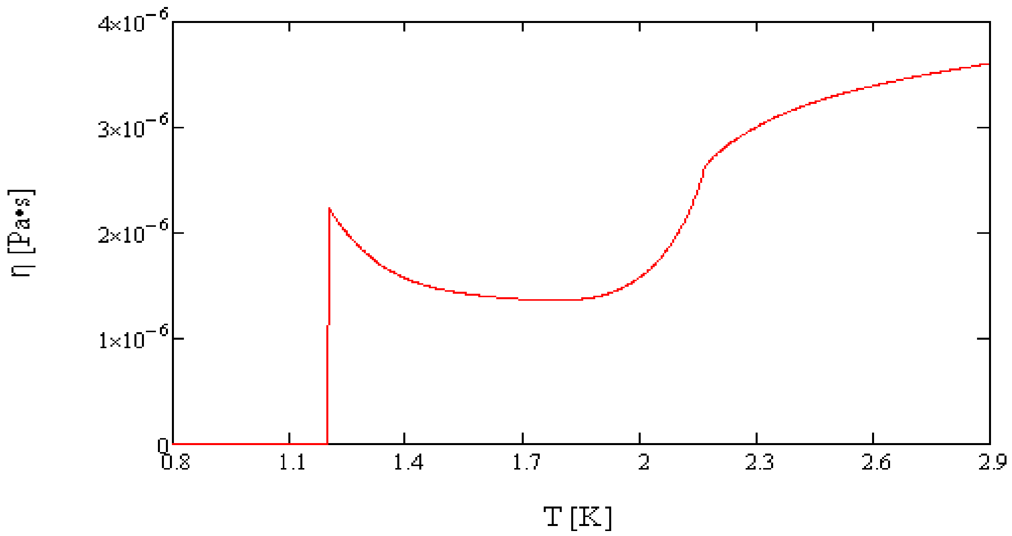

Fig.2.19. Helium viscosity function under 1.3 bar pressure (Made in Mathcad with data from HEPAK)

2.5.2 Kapitza resistance

A unique characteristic of heat transfer in He II is the process that occurs at an interface between a solid and the liquid. In contrast to ordinary convection heat transfer, surface heat transfer in He II is more controlled by the nature of the interface, including the properties of the solid material, rather than the condition of the bulk fluid. At relatively low heat flux, there is no boiling at the surface, and the heat transfer is dominated by a phenomenon known as Kapitza resistance. For heat fluxes greater than the peak value q the surface is blanketed by a film of He I or vapor or both. In this region the heat transfer is controlled primarily by the character of this film.

The thermal boundary conductance occurring at the interface between a solid and liquid He II was first discovered by Kapitsa in 1941 during an experiment to study the flow of heat around a copper block immersed in the liquid. Within the liquid helium the temperature gradients were seen to be negligible; however, a sizable temperature difference did occur between the copper block and the He II.

Kapitza resistance is of great technical interest because it often results in the largest temperature differences in a He II transfer problem. The measurement of Kapitza resistance is achieved by a method shown schematically in fig.2.20. The temperature at various points within the solid and He II are measured as they vary with applied heat flux. In a steady state a temperature profile as shown in the fig.2.20. is obtained. At this point it is easy to see the temperature discontinuity in the profile. The profile can be extrapolated to the He II-solid interface to determine the surface temperature difference ΔT_s.

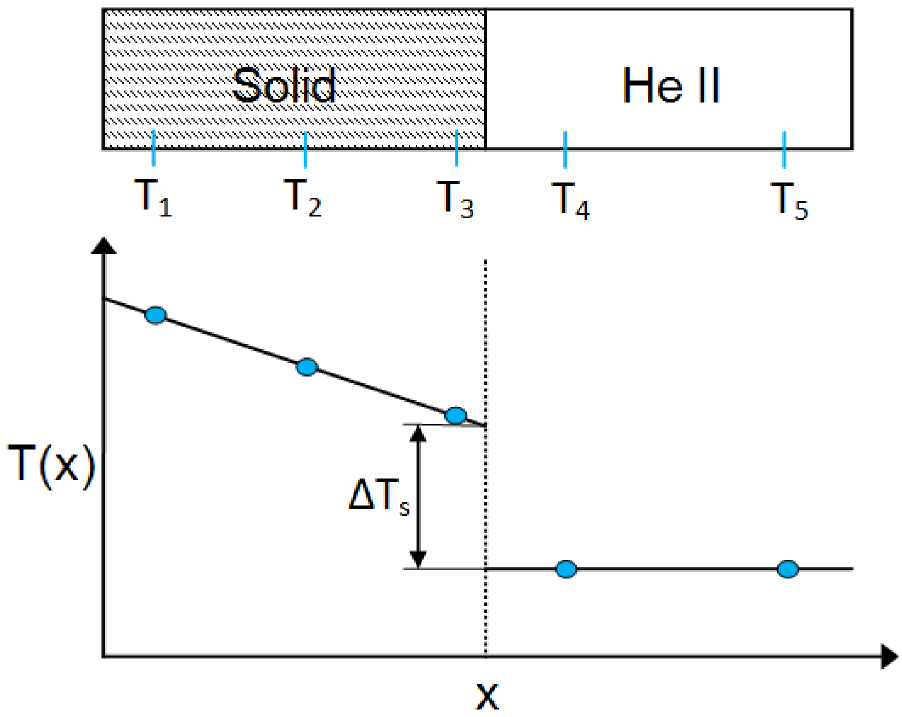

Fig.2.20. Illustration of Kapitza resistance

Although there have been many theories on the subject, Kapitza resistance is usually defined in terms of empirical data, [36]. Ideally, the Kapitza resistance is defined in the limit where q and ΔT_s are vanishingly small, that is,

$$h_{K0} = \lim_{\Delta T_s \to 0} \frac{q}{\Delta T_s}$$

Where,

q = heat flux

ΔT_s = temperature difference between the face of the solid and the helium II.

h_K = Kapitza resistance

However, in practical applications a simple equation related to finite quantities is used:

$$h_K = \frac{q}{\Delta T_s}$$

2.6 Line N

The corrector magnets and the main quadrupoles of the LHC dispersion suppressors are powered by a special superconducting line called auxiliary bus-bars line N, or just line N. Line N is external to the cold mass and housed in a stainless steel tube with 50 mm internal diameter. This tube is fixed to the cold mass, see fig.2.21.

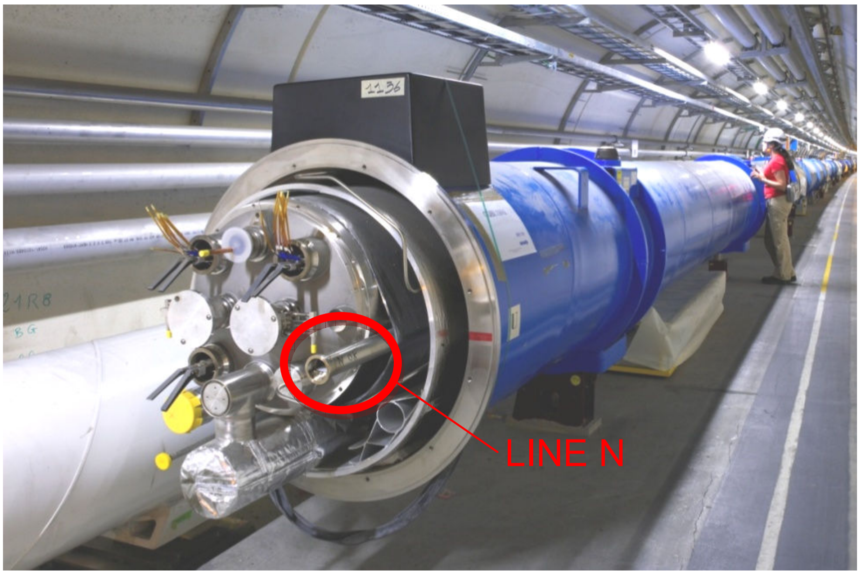

Fig.2.21. Shows line N in the LHC tunnel, [39]

The cooling of the magnets before injection of the beam is carried out in several stages. At the first stage the elements are cooled down from 300 K to 4.5 K with helium gas injections. The superconducting magnet windings in the arcs, dispersion suppressors and inner triplets will be immersed in a pressurized bath of He II. This bath will have a pressure of about 1.3 bars and a maximum operating temperature of 1.9 K. To reach this temperature, the second stage also known as the sub cooling, is initiated. In this stage the elements are cooled from 4.5 K to 1.9 K. This cool down is done by extraction of heat trough the heat exchanger pipe, which circulates saturated He II.

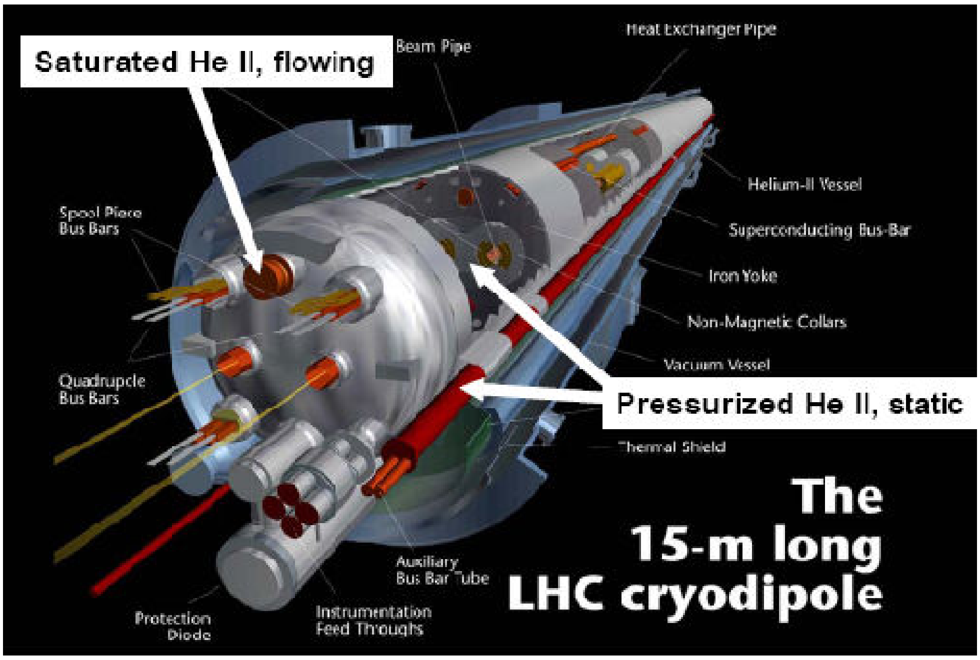

Fig.2.22. Model show the condition of the helium [40]

During the sub cooling there is a second order phase shift in the liquid helium, from He I to He II. This creates a λ-face that is propagated trough the cold mass and line N. The velocity of the face depends on the distance and the geometry of the tube, and this is vital for the cool down time.

The line N is attached directly to the LHC main magnets and connected via interface boxes to the cold mass every half cell. Due to this line N has the same operating conditions as the cold mass, temperature 1.9 K and pressure of 1.3 bars. It also follows the same cool down sequence, where the heat is extracted from the line N through the magnets via their point of junction.

In the dispersion suppressor zones, which are approximately 40 m long, the sub-cooling of the line N is slightly delayed in respect of the magnets. This is due to the geometrical design, and might have an impact on the readiness for operation of the accelerator, [41].

2.6.1 String 2 model

String 2 was in phase 2 and 3 a full size model of the LHC cell, consisting of 6 dipoles and 2 short straight sections (SSS). In one side it was terminated by the electrical feed-box (DFB) and on the other side by the magnet return box (MRB). This model was built to validate the LHC systems in working condition, and to investigate the collective behavior under various conditions. In phase one, only 3 dipoles and 2 short straight sections were used, [38].

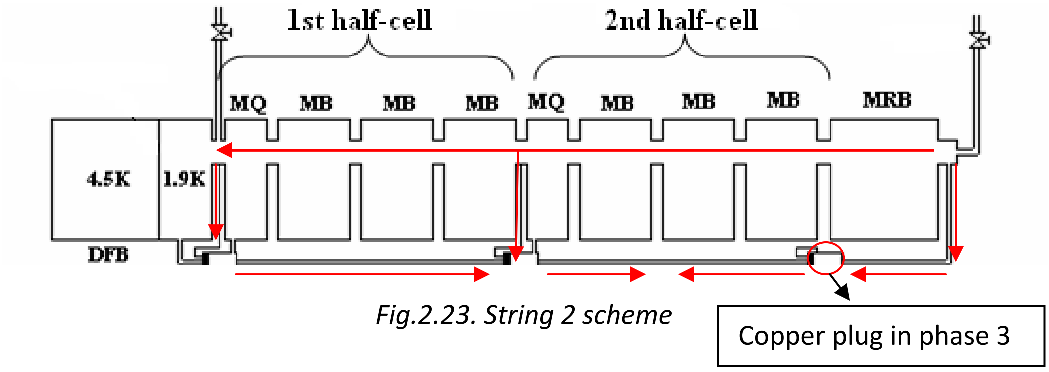

Fig.2.23. String 2 scheme

During phase 2 standard polyethylene inserts were installed in line N in the 1st half-cell and special inserts in MG6 area of 2nd half-cell, in order to reduce the helium cross-section area. In this way the helium volume is reduced and the lambda front velocity increases.

In phase 3 two additional pipes connecting line M3 and connection boxes in line N were installed in order to increase the internal helium cross section. In the 2nd half-cell the special inserts were removed. In addition, a copper plug was installed on the MRB side to accelerate the sub-cooling process.

Line N		Measurements
Phase 2	1st half cell	3.1 h
	2nd half cell	5.5 h
Phase 3	1st half cell	1.9 h
	2nd half cell	2.2 h

Table.2.1. Cool down time of line N

These results show that the time to cool down the line was more than 2 hours with the copper plug installed.

In order to accelerate the cool down process, a special heat exchanger has been designed. It is located in the middle of the dispersion suppressor portion of the line. Its main function consists in providing a local point of heat extraction, creating two additional lambda fronts that propagate in opposite directions towards the extremities of the line, [41].

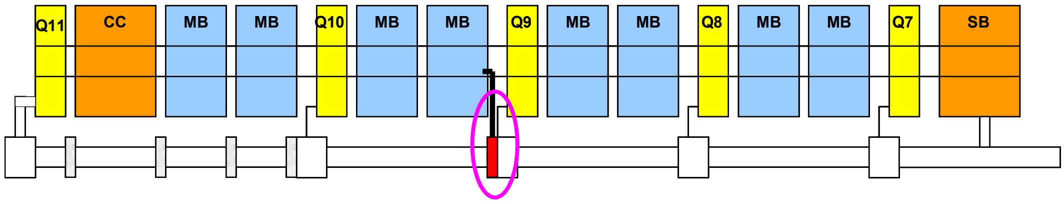

Fig.2.24. The placement of the heat exchanger in DS1L

The design for the heat exchanger was chosen after calculations of the cool down time. The Kapitza resistance in these calculations was estimated and has not been tested yet.

2.6.2 Heat exchanger

The new heat exchanger can be seen in fig.2.25. Due to space constraints, the link between the cold mass and the line N is made of two pipes of 32 mm inner diameter and the connection to the copper heat exchanger pieces comprises 4 pipes, each with an inner diameter of 22.9 mm. The heat exchanger consists of 4 copper boxes. Each box is composed of a main body and a cap that are soldered together using Ag-Pd-Cu at ~810°C. Then the boxes are soldered on the stainless steel flange with a Cu-Ag eutectic at 780°C. To ensure a good soldering, the maximum gap between pieces is limited to 0.05 mm.

The heat exchanger is linked to two sleeves that close the bus-bar lines in the interconnections, see fig.2.26. Metal hoses have been introduced to allow for differential thermal contraction and to compensate for the geometrical defects during the installation, [41].

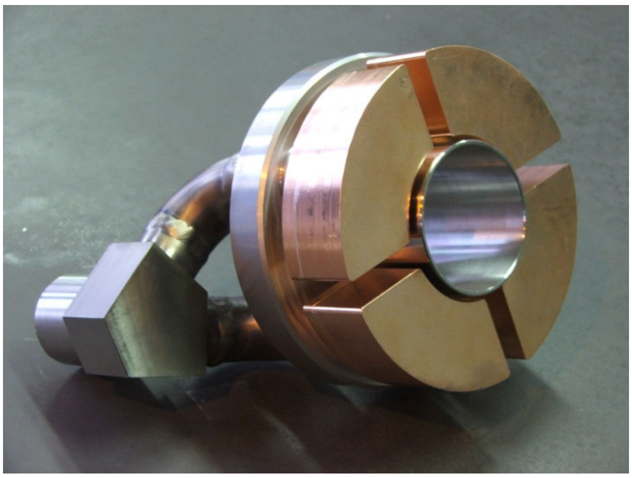

Fig.2.25. The heat exchanger

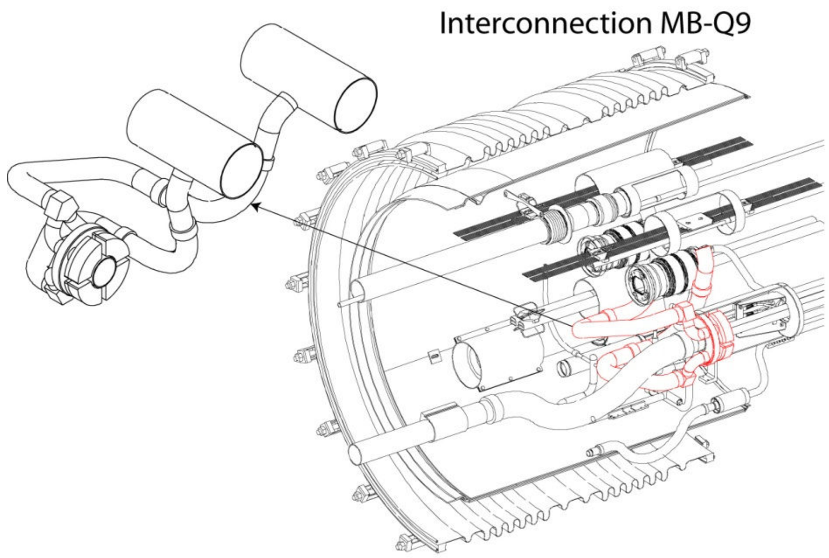

Fig. 2.26. Connection between the heat exchanger and the cold mass

3 Equipment used in the project

In this project it has been used equipment from the laboratory for the test of the heat exchanger. I have used several computer programs for simulation and calculation. These programs are:

- **ANSYS Workbench 11.0**
  ANSYS Workbench is a general-purpose finite element analysis software, which consists of several parts. By several steps in the program you can build your model, mesh it and make different kinds of simulations. The simulation can be stresses such as thermal-, structural-, or a combination of several. It is also easy to import 3D models from other design program such as Solid Works.

- **ANSYS CFX 11.0**
  ANSYS CFX software delivers powerful computational fluid dynamics (CFD) technology for simulations of all levels of complexity. It is today fully integrated in ANSYS Workbench. The latest versions of CFX have been more extensive, and the latest version contains advanced models for calculation of fluid structure interaction (FSI), rotary currents, turbulence, rotating applications etc, [42].

- **MathCAD**
  MathCAD is a program developed by Mathsoft. It is a desktop software for performing and documenting engineering and scientific calculations. It is oriented around a worksheet, in which equations and expressions are displayed graphically, as opposed to plain text. This makes it very easy to use. Among the capabilities of MathCAD are, [43]:

  - ✓ Solving differential equations, with several possible numerical methods
  - ✓ Graphing functions in two or three dimensions
  - ✓ Symbolic calculations
  - ✓ Vector and matrix operations
  - ✓ Symbolically solving systems of equations
  - ✓ Curve fitting
  - ✓ Implementing subprograms
  - ✓ Finding roots of polynomials and functions
  - ✓ Statistical functions and probability distributions

- **HEPAK**
  HEPAK is a software developed by the US Company Cryodata, Inc. It is made to help you to calculate the thermo physical properties of helium-4 (^4He), based on fundamental state equations. When using pressure and temperature as input parameters, HEPAK can find the corresponding value in density, heat capacity, entropy or many others output parameters, by using numerical iteration. The first version of HEPAK was released in 1972 under the name of HEPROPS, [44] [45].

In addition to this I have used Microsoft Office 2007 to make the report.

4 Execution

One of my tasks is try to make a computer model of the heat exchanger in line N. To be able to verify this model, a test of the heat exchanger will be done at the cryogenic laboratory (cryolab) at CERN. By using the results from the test, I can adjust the model and find the Kapitza resistance. This can later be used in a computer model of line N to find the new cool down time.

4.1 Simulation in ANSYS

During the first meeting at the cryolab, the leader of the lab suggested that we could make a computer model by using the results from the test and import it into ANSYS. Since I already had some experience with ANSYS from my college university, my supervisor thought that this would be a good idea.

To make this computer model in ANSYS, I needed a 3D model of the heat exchanger and the tube. First I got a 3D model which was made by the designers here at CERN. This model only consisted of the heat exchanger, but to make a model in ANSYS I needed the complete model which was going to be used in the test. After talking to some of the designers they quickly made a new model for me.

Since I never have used the Workbench version of ANSYS before, I used some time to understand the basics of the software. After this I imported the model, which was made from drawing L0082757PL, appendix A. This model did not contain the cable or the cover at the end of the tube.

After I had imported the model, I tried to draw the cable and the cover. First I draw the cable and then I tried to draw the cover. The problem occurred after I had extruded the cable. Then it was one of the many parts in the designer tree, but when I started a new sketch for making the cover, the software automatically merged many of the parts together. I needed to have separate parts because I later have to define the different material properties. I tried to draw the two parts many times in many different ways, but I ended up getting the same problem every time. I then spent some time reading the help file and searching the internet for similar problems. After spent some time looking, I found that I could use a command called freeze. This command would keep the software from merging the parts. After I figured this out, it was no problem to add the two parts to the model.

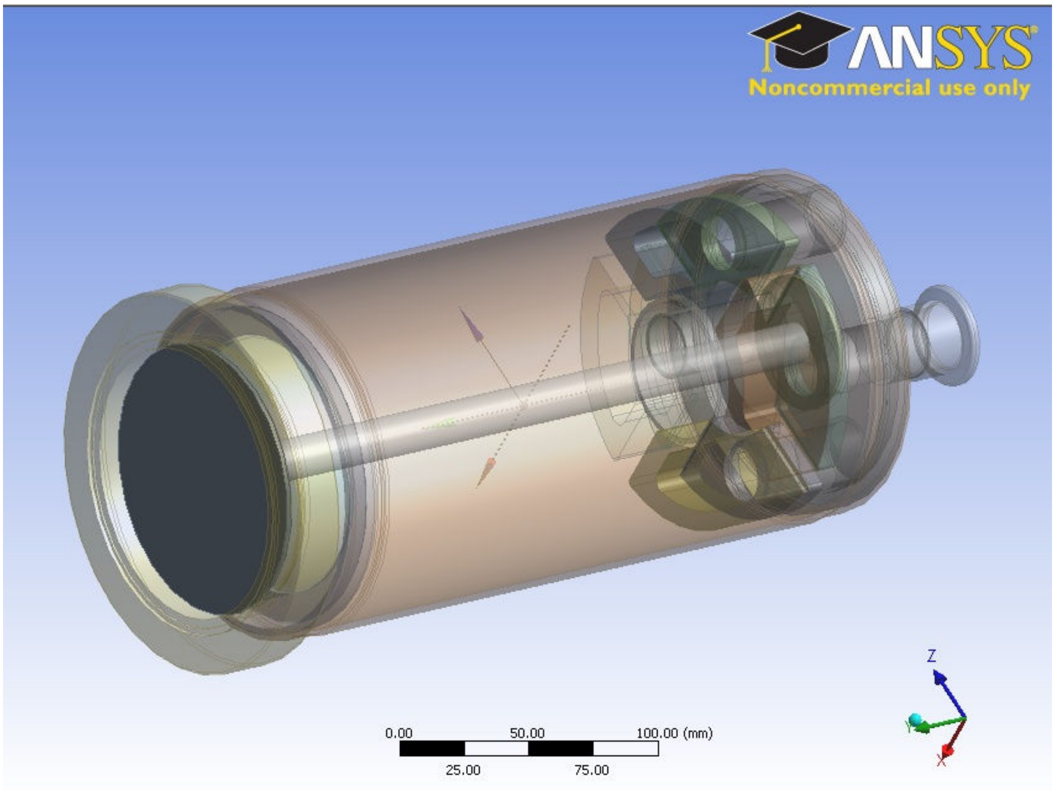

Fig.4.1. The complete computer model with the cable and the covers

When the model was ready, I opened it in the mesh part of Workbench. Here you can make many adjustments to have your model meshed the way you want. After looking a bit at all these adjustments I decided to try the automatic meshing. This seemed to turn out quite well. After having the first mesh done I found out that since I was going to do a simulation with liquids, I need to use something called inflation boundaries. By using this command you can select the parts of your model where the fluid will interact. In these areas there will be made a fine mesh to increase the degree of accuracy. When I started to select faces that the fluid would interact with, I found a mistake in the model. The hole between the connection plate and the body of the heat exchanger was missing. I contacted the designers, but they had a lot of work to do, and would not be able to fix the mistakes in some time. I then decided that it would be just as easy for me to make my own model in Solid Works. This way I can easily make all the adjustments myself and do not have to go to other people to make simple adjustments. I used the drawing L0082757PL and L0082753PL, see appendix A, to make a new 3D model.

In Solid Works I first made a 3D model of each of the parts, and then afterwards I made an assembly of the model. When the model was finished it was easy to import it into ANSYS Workbench, since the connection between the programs is very good.

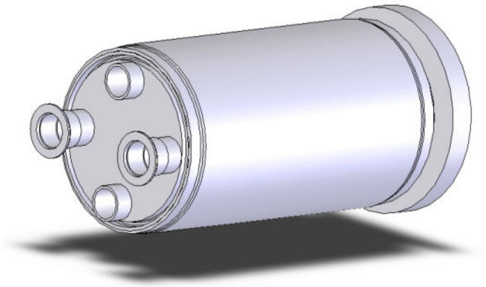

Fig.4.2. The 3D Solid Works model with the tube

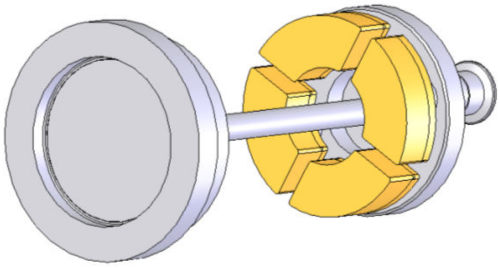

Fig.4.3. The 3D Solid Works model without the tube.

After I imported the new model I made the inflation layers and a mesh. This time I had to adjust the maximum spacing and the maximum edge length to 5 mm to make the surface mesh. When the mesh was done I tried to open this file in the simulation. I then realized that you can't import meshed files into the simulation. This is because the simulation is making its own mesh. When you open a meshed model here the software only deletes the mesh, and you can continuing to work with the model.

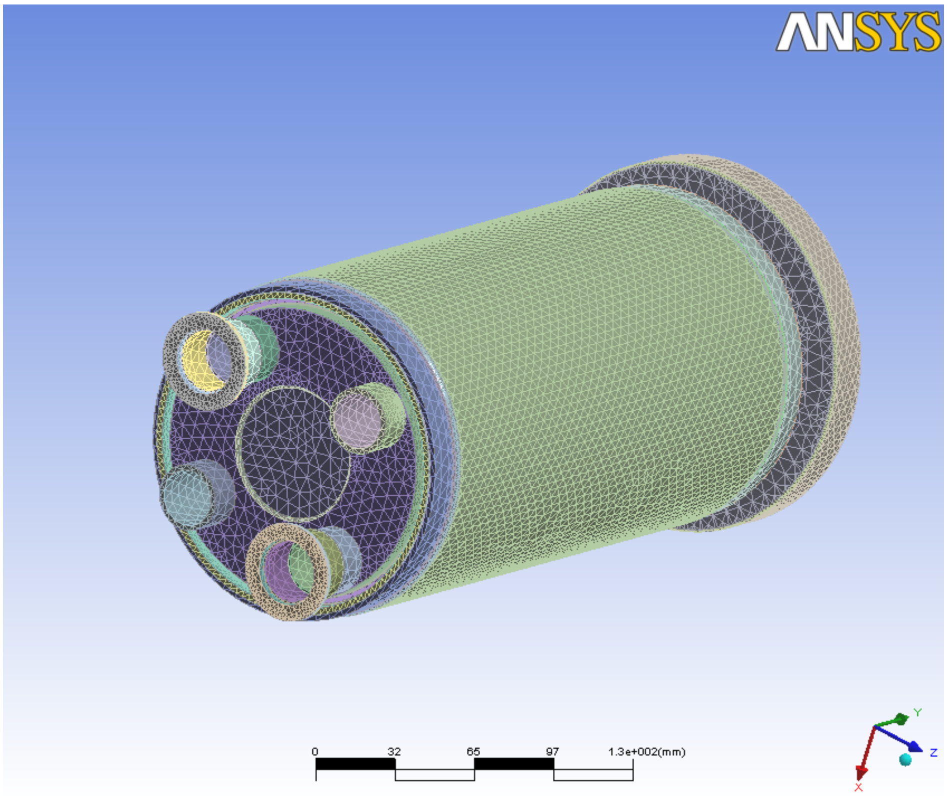

Fig.4.4. The mesh of the model

In ANSYS Workbench you can make many different simulations. In this case I needed to make a simulation which contained liquid and gas, but I could not find a simulation of this kind. After I've been reading about simulations of liquids I found out that I needed an additional program to add to the ANSYS Workbench. This program was called ANSYS CFX.

In CFX you have to mesh the model before you can import it, so now my meshed model would come in handy. I found out that I had to add 2D regions in the mesh. 2D regions are faces which you can define by name, such as the inlets and the inside of the heat exchangers. This makes it easier to define properties to these faces later on.

After I had spent some weeks trying to understand CFX and how to make the simulation I was not any closer to a solution. The problem in CFX was that I could not find any examples of a stagnant fluid or gas, only of fluid or gas flows. When it came to a point where I could not come up with any more ideas, and no one could help me, my supervisor recommended me to make a simplified model. By doing this I could at least be able to see if the model worked.

4.1.1 The simple computer model

We decided that the simplified model should consist in a square tube with a copper block at the end, see fig.4.5. The block is a very simplified model of the heat exchanger. The reason for making the tube square is that it is easier to mesh in ANSYS. Just to have something to work with, the dimension of the tube was set to 75x75x350 mm with a wall thickness of 3 mm. The heat exchanger has a thickness of 5 mm.

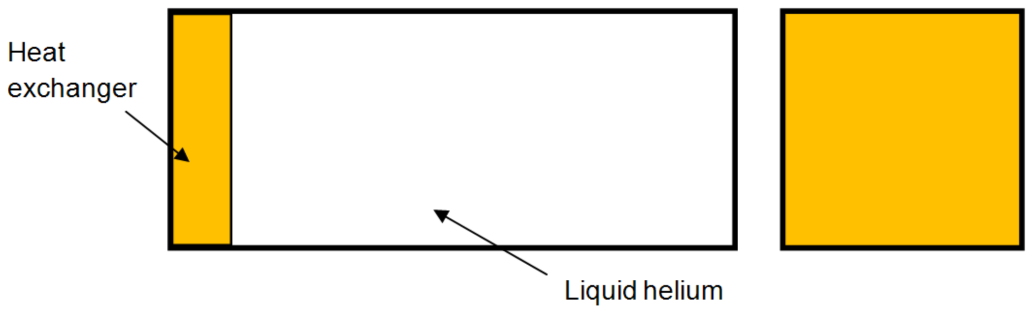

Fig.4.5. The simplified model

First I made a 3D model in Solid Works and imported it to ANSYS Workbench. After this I meshed the model and opened it in ANSYS CFX. When I came to this point I still had the same problem as earlier. I kept reading about CFX and found out that I could divide the model in half because of the symmetry. In addition I had to fill the inside of the model with solid material to be able to simulate liquid.

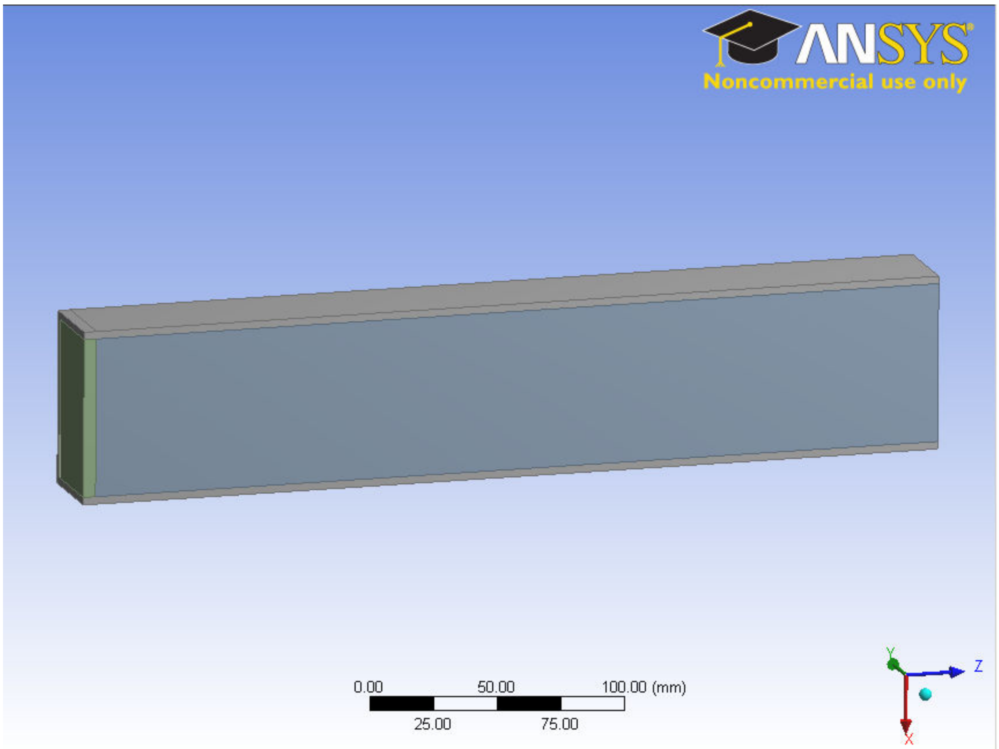

Fig.4.6. Shows the model divided into half and filled.

After further studying I found out that I had to use something called a two-way FSI. The reason for this is that the temperature of the heat exchanger and the tube will affect the temperature of the liquid helium. At the same time the temperature of the helium will affect the heat exchanger and the tube. The two-way FSI is a way to transfer the result from simulation to ANSYS CFX as a load. Similarly the results from the ANSYS CFX analysis are passed back to the simulation analysis as a load. This is done many times, to make a simulation that can take both the heat loads and the temperature of the helium into account. At this point I realized that this simulation would be too complicated for me to handle. We then decided to simplify the model even more.

For the next model I had to eliminate the liquid in the model. I then made a model that only had a 5 mm block for the heat exchanger and a 345 mm block solid for helium, see fig.4.7.

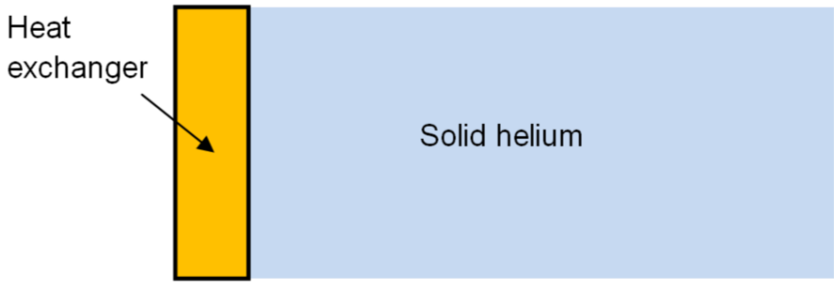

Fig.4.7. Simplified model with solid helium.

As the previous model, I made it in Solid Works and imported it into ANSYS. Since I now had no liquids in my model I could use simulation and make a thermal simulation. I then typed in the thermal conductivity of copper and helium, [45], and defined the different materials in the model. The next step was to add the temperature loads. First I had to be able to get the model to work at temperatures which didn't include the second order phase shift in helium. I choose to use a temperature of 2°C on the outside of the heat exchanger and 4°C on the backside of the tube.

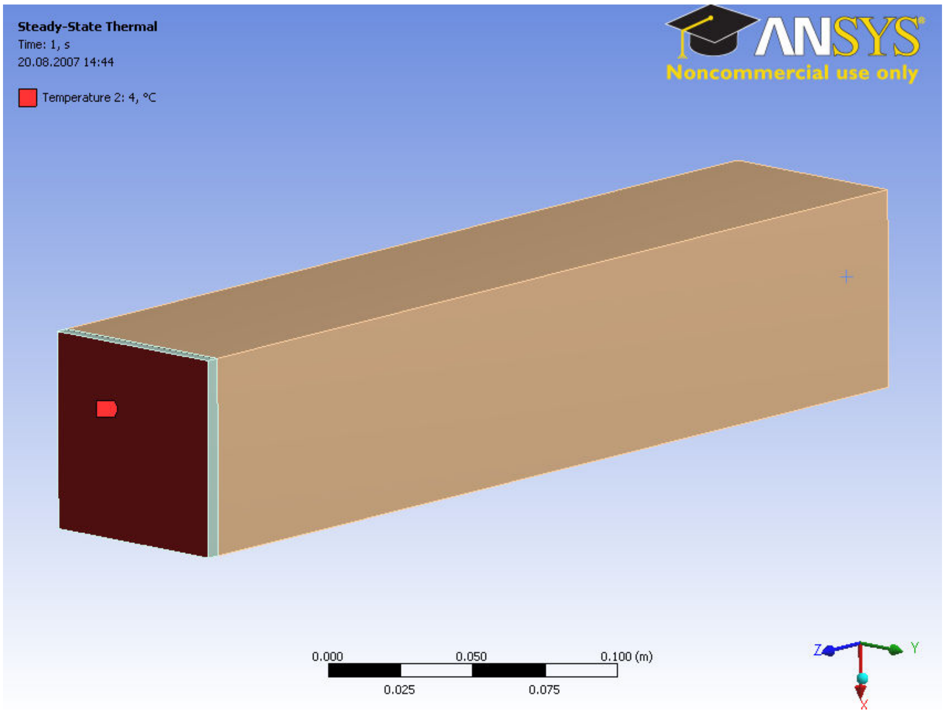

Fig.4.8. Model after applied the temperature loads

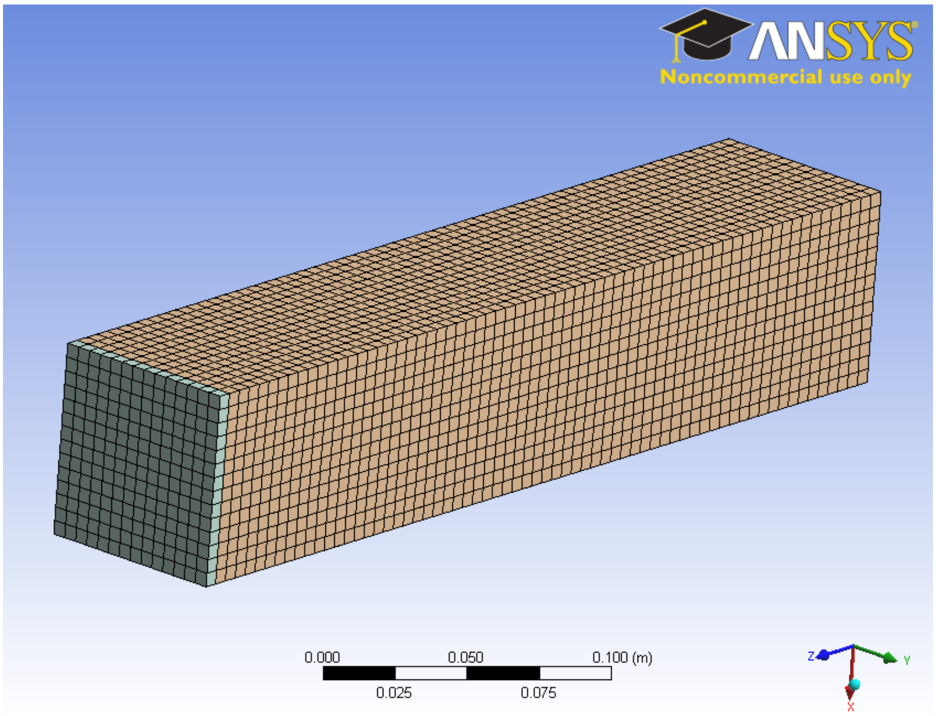

Fig.4.9. Mesh of the model

The result of the simulation showed that the temperature was rising linearly all through the model, as shown in fig.4.10. This would be correct since the Kapitza resistance only occur between copper and liquid helium. Helium is not liquid before the temperature is below 4.2 K. Afterwards I realized that the Kapitza resistance would not occur in this model due to that in my helium would not turn to liquid.

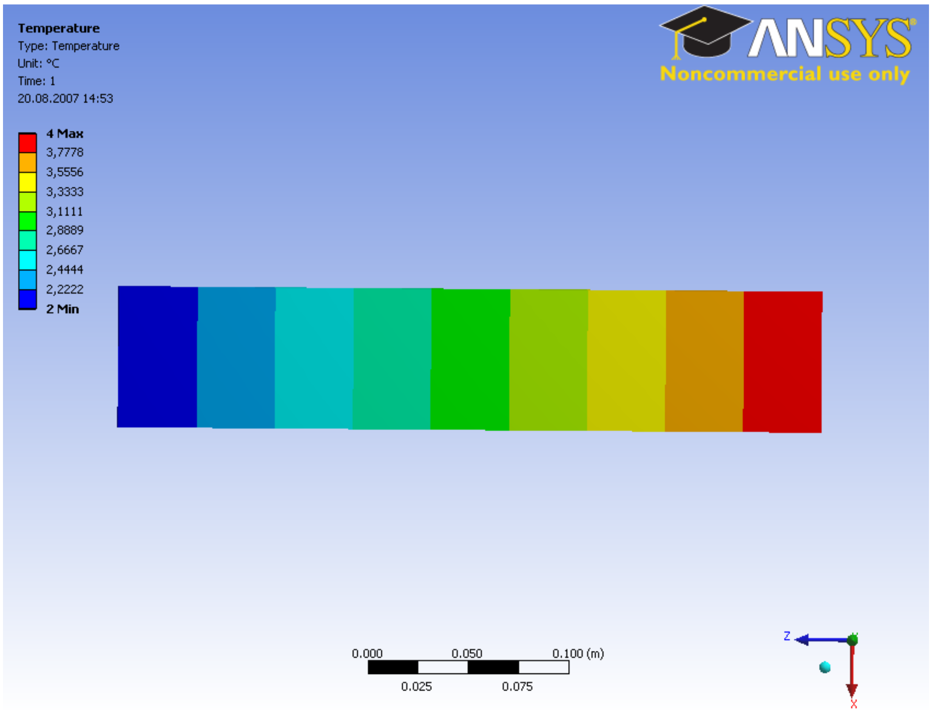

Fig.4.10. Linear temperature profile along model

To straighten up this problem I tried to add the Kapitza resistance to my model as convection. This way I should have the resistance even though the temperature was not low enough. I could not get that to work, but then I got a tip that I could “cheat” the program. This I could do by inserting a thin plate between the copper and the helium and give it the properties of the Kapitza resistance.

First I made a thin surface of only 0,001mm which I placed in-between the copper and the helium. This didn’t work; I still had the same result. Then I made the plate a little bit thicker and tried with 0.5 mm, but it still didn’t work. I kept increase the thickness, and when the plate was at 1 mm it seemed to work.

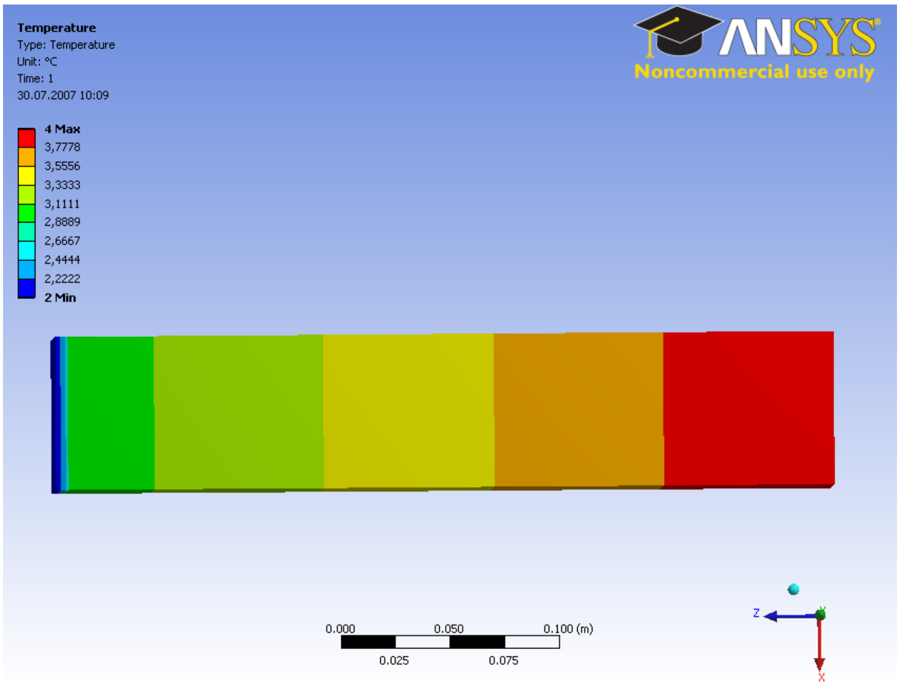

Fig.4.11. Temperature profile along the model after applying a thin plate.

To verify this model, I made some conditions and calculated the thermal conductivity of the materials, see appendix B. Then I inserted these values for the thermal conductivity in ANSYS. After I had done the simulation once more it looked like the model was working properly. Both the temperatures and the heat flux were right according to my calculations.

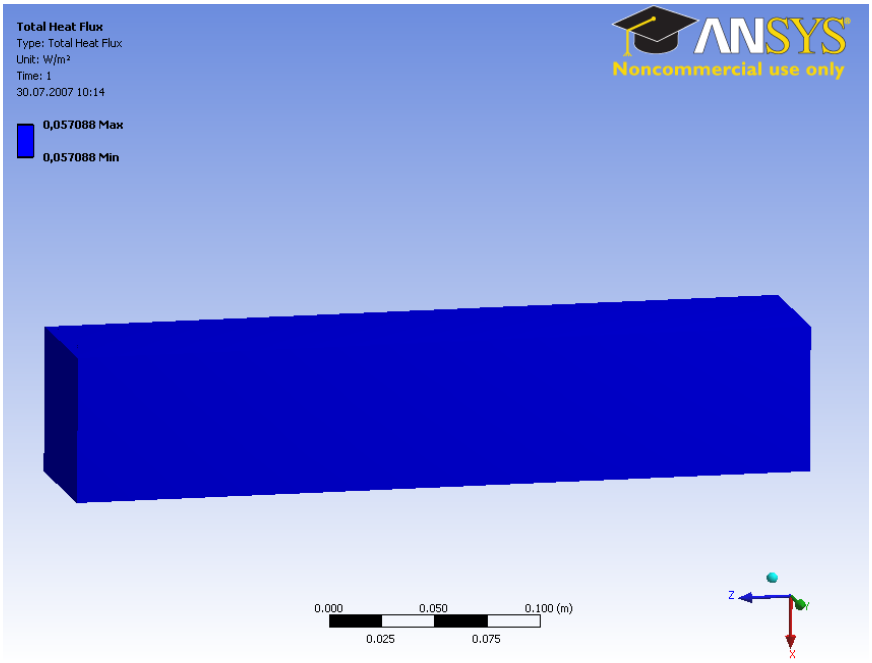

Fig.4.12. Heat flux in the model

To be completely sure, I was asked to plot the temperature as a function of the length of the model. This turned out to be rather difficult to do in ANSYS Workbench, and I could not figure out a way to do it.

After asking around I found out that the easiest way was to make the same model in regular ANSYS.

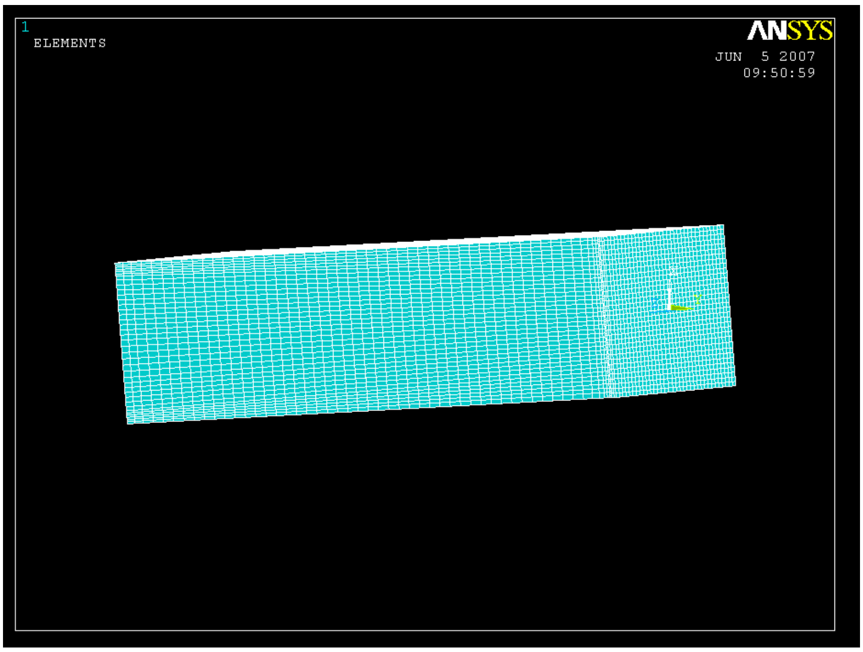

Fig.4.13. Mesh in ANSYS

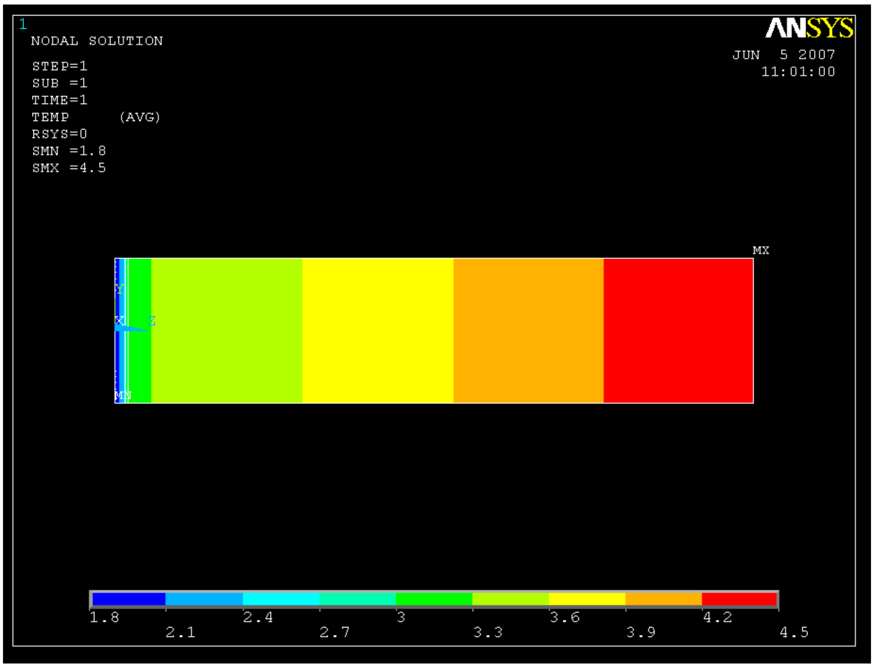

Fig.4.14. Temperature profile along the model in ANSYS

After I had made the model I could pick out one node on the center of one end, and the node in the opposite end of the model. I could then use these two nodes to make a patch between them. Along this patch I could get the temperature gradient, and I was able to plot the function, fig.4.15.

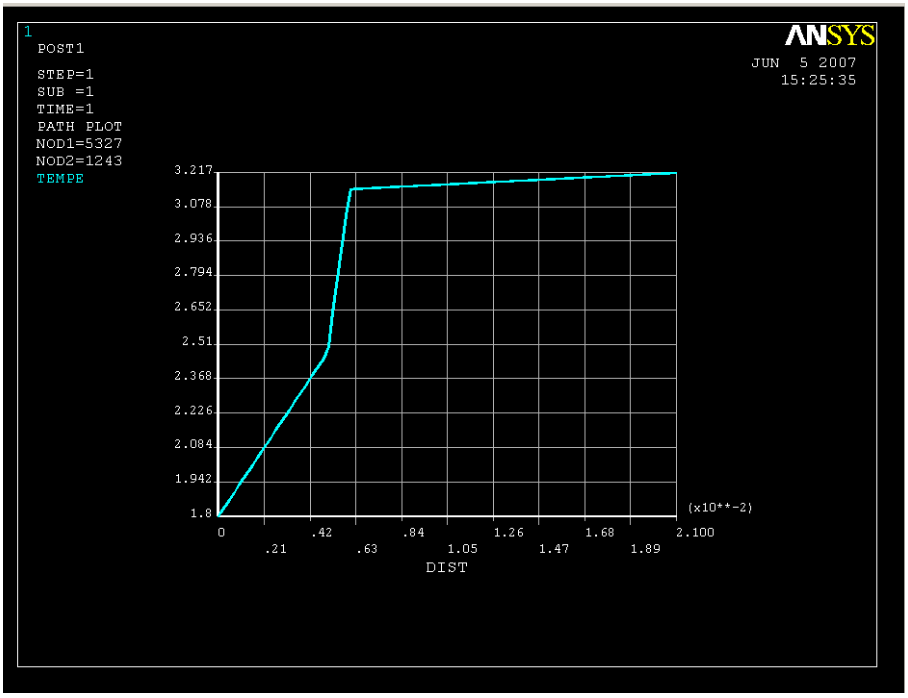

Fig.4.15. The temperature plot as a function of the length

From the plot of the function you can see that the temperature rises linearly through the copper and then makes a leap in the transition between copper and helium. The reason that this line is not completely vertical is the thickness of the thin plate I had to place between the copper and the helium to simulate the Kapitza resistance. After the Kapitza resistance the temperature raises linearly through the liquid helium. According to the result I got in ANSYS Workbench and the result and the function plot from ANSYS, the model was now working properly.

My next problem was to be able to simulate helium at cryogenic temperatures. The problem was arising with the second order phase change in helium, which made it very difficult to make a model. After I had spent some time trying to find a solution to this problem, I meet Slavek at CERN. He had worked at CERN before, and was now at a visit. He told me that this was an extensive task and would take a lot of work.

Since I only am staying here at CERN in 6 months, my supervisor and I decided that this could not be done by me. So then we started to look for other possibilities to make a model.

4.2 Model in MathCAD

After having to give up the ANSYS model we decided to try to make a mathematical model instead. To do this I will be using a program called MathCAD. It was chosen because this program can be combined with a program called HEPAK, which helps you calculate the properties for He II. It has already been made a connection between these two programs in an earlier project, which will be very useful for me.

In MathCAD I will be using the same dimensions on the model as the simple model in ANSYS and a starting temperature of T_0 = 1.9K until I get the results from the lab. This temperature will rise linearly through the copper until it reaches the temperature T_1 at the other side. At the boundary between the copper and the He II the temperature will make a leap to T_2 due to the Kapitza resistance. From here the temperature slowly rises in the He II until it reaches T_λ, where He II will turn into He I. From this point the temperature will rise much faster up to T_k = 4.5 K. The values that I need to calculate are the temperatures T_1, T_2 and the length L_{HeI}.

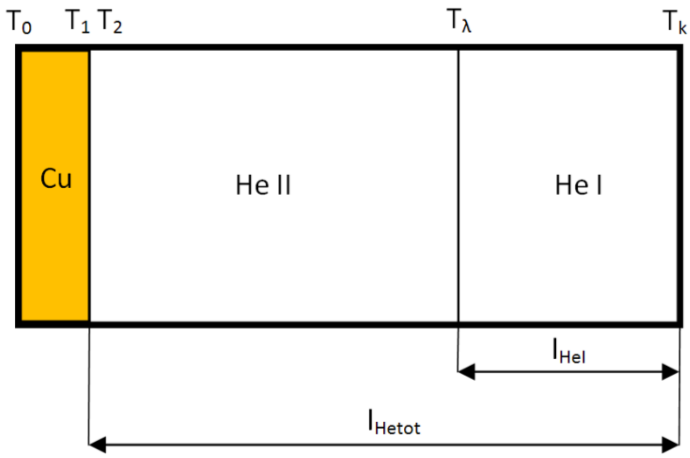

Fig.4.16. Model in MathCAD

I started with defining all the values I already knew at the top of the work sheet in MathCAD. Afterwards I used the command for getting values from HEPAK to make a function for the conductivity of He II. To define the thermal conductivity for copper and He I I used matrixes where I inserted temperatures and values found in the book, Selected Cryogenic – Data Notebook Volume I, [46].

After this I started to define the different equations. I first started with the heat flux in copper. This can be calculated with the equation for convection.

$$Q_{Cu} = k_{Cu}(T) \cdot \Delta T$$

Where,

Q_{Cu} = heat flux in copper

$k_{Cu}(T)$= thermal conductivity of copper

ΔT = temperature difference between the two surfaces of the copper

I have to integrate the conductivity between the two temperatures in copper, since the thermal conductivity is changing with the temperature.

The second equation I need is the equation for the Kapitza resistance, which occurs at the interface between copper and He II.

$$Q_{Cu\_HeII} = h_K \cdot \Delta T_s$$

The third equation is heat transfer in He II. Here I have to use the transformed Gorter-Mellink equation as presented in chapter 2.5.1:

$$Q_{HeII} = \left[\frac{\int_{T_0}^{T_\lambda} f(T) dT}{l_{HeII}} \right]^{\frac{1}{3}}$$

The fourth and last function I need is the heat flux in He I. For this I can use the same equation as the copper, only changing the thermal conductivity.

$$Q_{HeI} = k_{HeI}(T) \cdot \Delta T$$

Where,

Q_{Cu} = heat flux in copper

k_{HeI} = thermal conductivity in He I

In this calculation I assume that the model is adiabatic, due to the vacuum insulation in line N. This means that no heat is transferred through the walls of the model. When I assume this I have the following equations for the heat flux in the model:

$$Q_{Cu} = Q_{Cu\_HeII} = Q_{HeII} = Q_{HeI}$$

When all the values and equations are inserted, I have to define guessed values for the variables. In MathCAD you have to guess these values to estimate the answers. These values will have no affect on the answers.

At first I had some problem getting an answer. After I had tried to solve this problem in many different ways I found out that this was a problem in MathCAD 14, which did not appear in the earlier versions. The problem occurs when you ask for the answer of several variables that don't have the same unit. When I discovered that this was the problem I removed all the units from the model and then tried to solve the equations. This time it worked, and I got the answers to the equations.

After I got the answers I started to make a plot of the temperature along the length. To do this I used the equations I had used before; only this time I solved them with consideration of the length. Then I calculated some values to make a graph for each of the copper, He II and He I. When I tried to make a graph of the values for He II I got problems since the temperature just before 2.17 K was not in an ascending order. Because of this, MathCAD could not make a graph. I found that the reason for this was that the lambda point was not accurate enough. I had defined it to 2.17 K, but when I used the thermal conductivity function from HEPAK and a pressure at 1.3 bars I found the lambda point was close to 2.165 K.

When I inserted all the graphs into one to make the temperature profile I could see that something was wrong. All the graphs looked correct, but the end of the graph did not end at 350 mm as expected.

To see if I did something wrong when I calculated the values for the graphs or if the results were wrong I made another check. But when I tried this MathCAD started to give me the same results as I guessed.

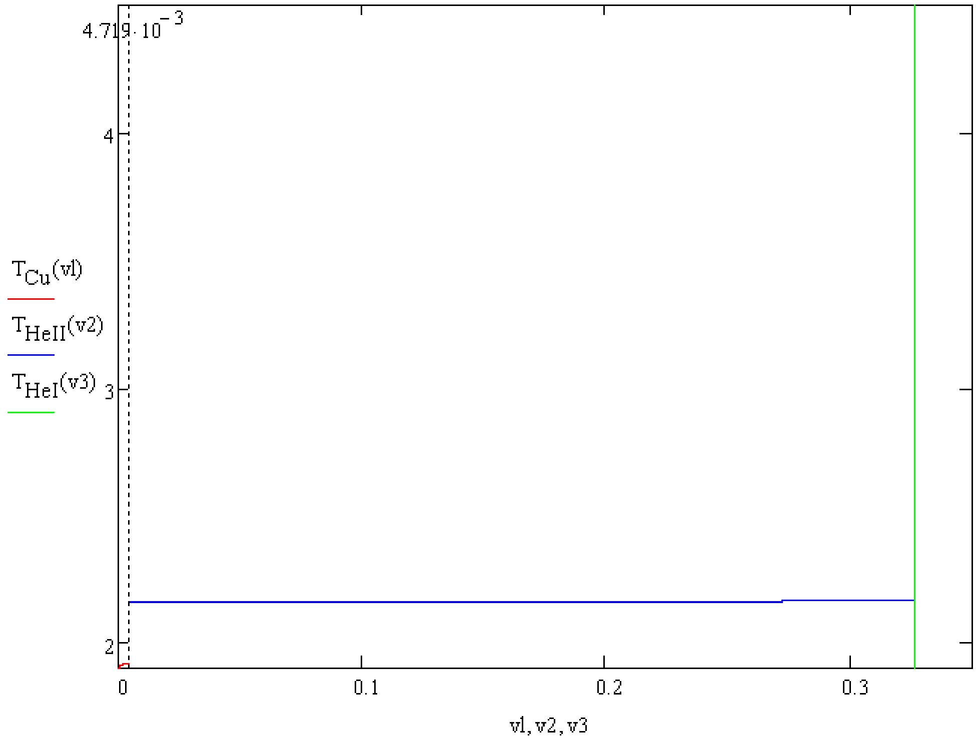

Fig.4.17. The temperature profile along the length of the model

To check if I did something wrong when I calculated the values for the graphs or if the results were wrong I made another check. This was done by putting up the equations and asking for the defined value to see if answers were correct. It worked for the equation of the heat flux through the copper, but at the equation for He II MathCAD gave me the same results as I guessed.

I found out that this maybe could be because of the command that connects HEPAK and MathCAD. I therefore decided to remove this command and make a function for the heat conductivity in He II by using values from the HEPAK. These values I could easily get from the HEPAK example in Excel. After I had done this everything seemed to work.

4.3 Test at the cryogenic laboratory

The test model is made of several parts, see appendix A for drawings. The preparation of the model started in the workshop, where the heat exchanger was prepared. For more information about the configuration of the heat exchanger see chapter 2.6.2.

After this two small copper housings were made and soldered onto two of the faces of the heat exchanger. A thermometer was putted into each of these small housings. Afterwards they were filled with epoxy to protect the thermometers from the liquid helium. This way it is assumed that the temperature measured by these thermometers is the same as the copper surface.

The heat exchanger is welded into one side of a 270 mm long tube, by edge welding. The other side of the tube will be closed by a cover, which has an inlet for the liquid helium. All the wires from the thermometers inside the tube will also be connected through this cover. A cable of the same type as in line N is installed in center of the heat exchanger. It is approximately the same length as the tube.

Fig.4.18. Cable inside model connected to heat exchanger

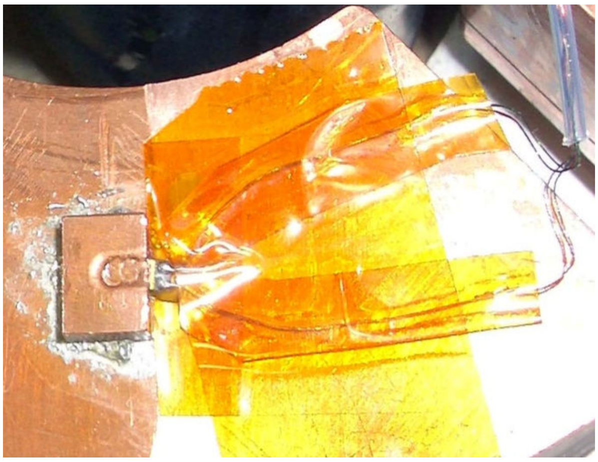

Fig.4.19. The thermometer placed on the face of the heat exchanger

When the model was ready it was sent to the cryolab for preparations. Here three small rods are attached to the cover in the back of the tube. The thermometers inside the tube will be attached along these rods.

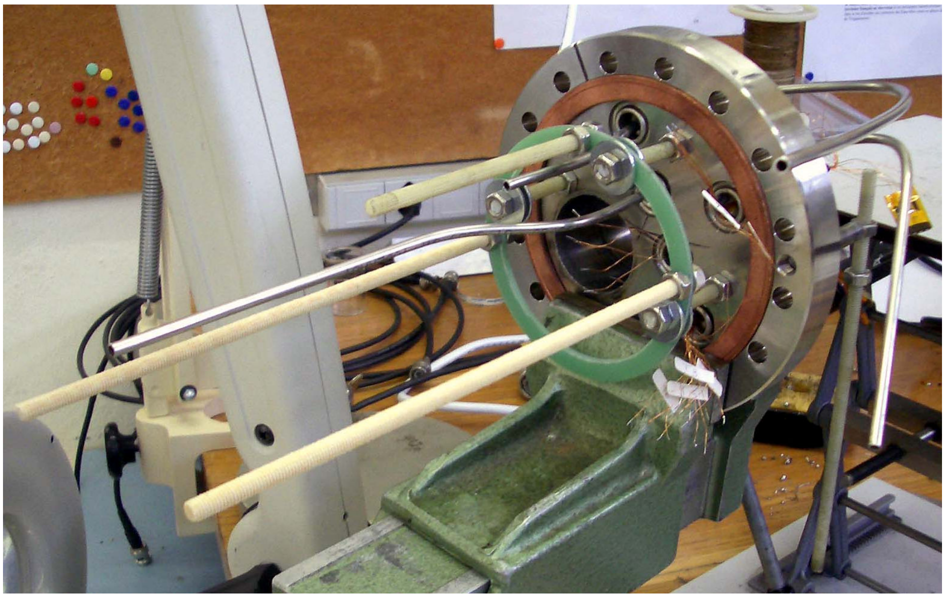

Fig.4.20. The rods inside the model where the thermometers are placed.

It will be used ten Cernox[4] thermometers during the test, which have a good sensitivity. Nine of these thermometers are inside the model. The last one is placed in the pipe, which is supplying the heat exchanger with liquid helium. This is to be able to monitor the temperature of the liquid helium in the heat exchanger. Thermometer 2 and 3 are placed on the two faces of the heat exchanger and thermometer 10 is placed on the wall in the center of the tube. The rest of the thermometers are placed along the rod inside the tube, see fig.4.21. These will give us the temperature profile along the inside of the tube.

In the end of the tube a heater is installed. By this the heat flux in the model can be controlled. During the test there will be made measurements with no heat flux, 250 mW, 500 mW, 750 mW, 1000 mW, and 1250 mW.

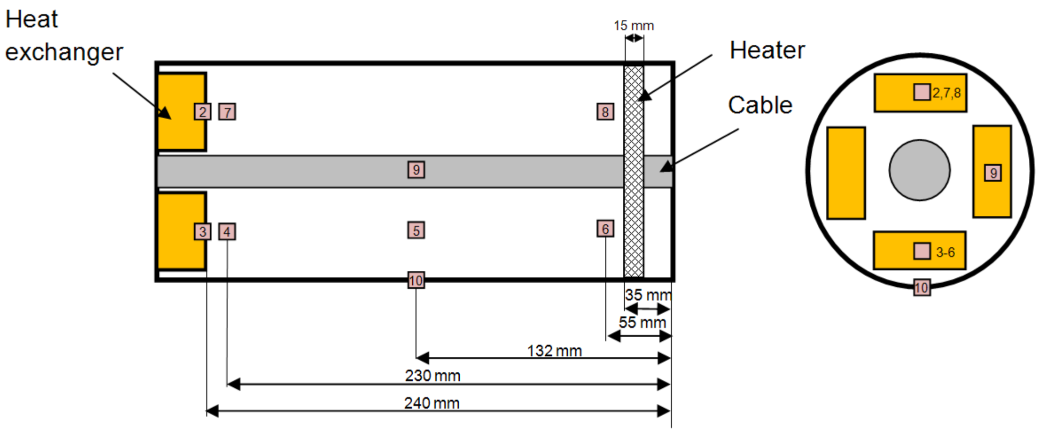

Fig.4.21. Placing of the thermometers in the model

[4] You can read more about these in chapter 1.6

When all the preparation is done the model is suspended inside the cryostat by two glass fiber/epoxy rods in a horizontal position as shown in fig.4.22. The reason to use these rods is to limit the heat leaks to the model. The cryostat will provide a low temperature environment for the test. Due to the short length of the tube and the pumping proven for this test, only one of the four sections of the heat exchanger will be connected. This part of the heat exchanger will be supplied with He II, at 1.9 K. Since there is a possibility for a difference in temperature between using the upper and lower section of the heat exchanger, both possibilities have to be tested. The tube will be filled with He I at 4.5 K from the back of the tube. This means that during the test, a phase change of second order will occur inside the tube.

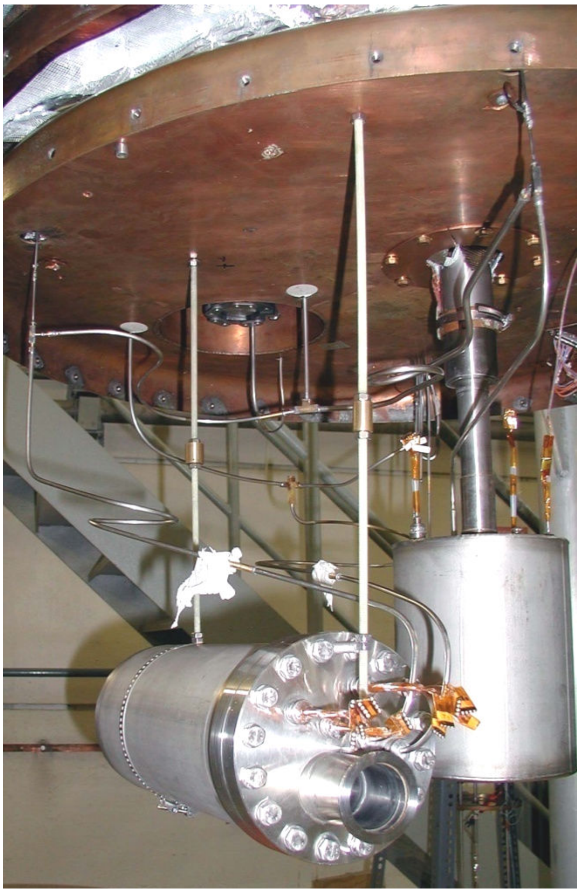

Fig.4.22. The model during the connecting to the cryostat

The cryostat consists of two main parts, fig.4.23. This is the tank on the top and the pot. A 500 liter tank is connected to the tank on the top of the cryostat to supply the system with liquid helium at 4.2 K and approximately 1000 mbar of pressure. This tank is supplying the model and another tank with liquid helium. In the second tank the helium is cooled down to 1.9 K by a pump which lowers the pressure inside to approximately 20 mbar. This helium is used to supply the heat exchanger.

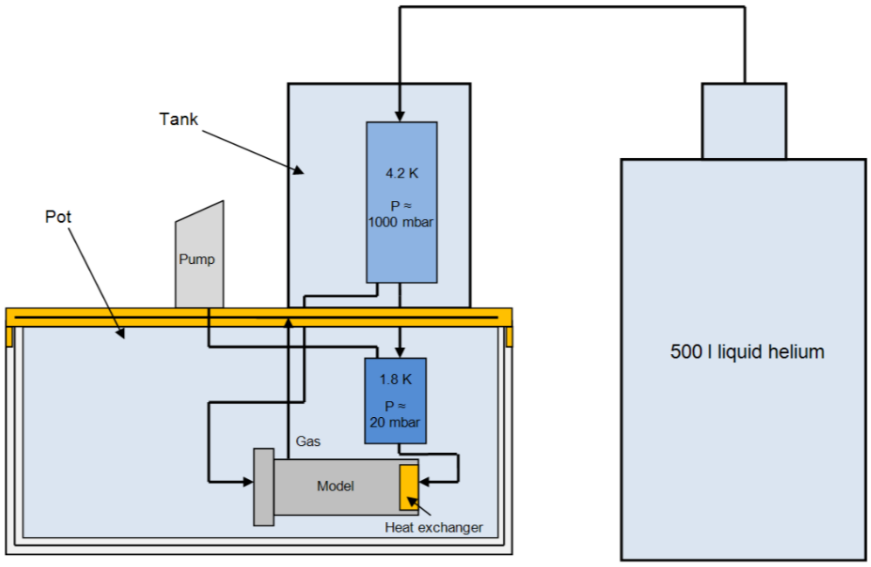

Fig.4.23. Assembly of the cryostat

There is a pipe for transporting out the helium gas produced in the end of the tube. This pipe leads the gas to the cover of the cryostat, where it circulates before it is transported out of the cryostat. This gas will cool down the cover made of copper. The pot has two screens inside made of aluminum. These two screens have some distance to better isolate the pot. Since the screens are connected to the cover by screws, the pipes in the cover will also cool down the screens by convection.

Fig.4.24. The pot with the two screens

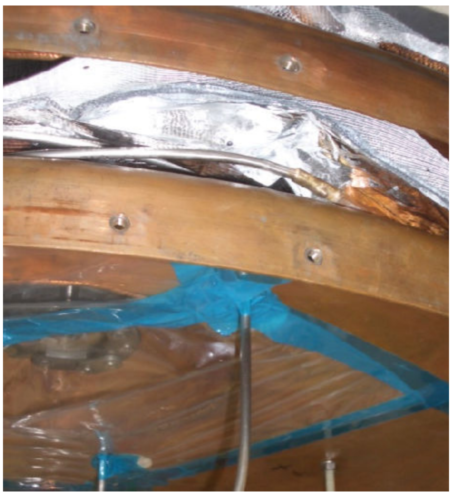

Fig.4.25. The pipes in the copper cover

The test at the cryolab was started on Tuesday 10th July. Already the next day the first problem appeared. Thermometers number 3 and 6 started to have very uneven measurements. After a discussion it was decided to continue the test even though these two thermometers didn't work properly. The reason why was that it would take to long to heat up the model and fix the problem.

Fig.4.26. The complete assembly of the test equipment in the lab

The test was finished on Friday 13th. The results from this test suggested that the thermal losses from the heat exchanger to the chamber housing were above 1W. Since the losses were this high the static losses had to be evaluate as well, otherwise the interpretation of the data would be suspect. This meant that the test had to be done once more. Unfortunately, the pipes in the cryostat had been blocked by impurities in the liquid helium and the cryostat had to be heated up to room temperature to be fixed.

While the cryostat was fixed, it was necessary to try to find the reason for the thermal losses. After discussing several possibilities, we came up with two possible reasons that we would like to have a better look at. One was radiation from the shield, and the second was convection from the cables of the thermometers. To have a look at these possibilities I used MathCAD and made the calculations. To calculate the radiation from the shield I calculated the radiation at worst case scenario, which is when one of the surfaces completely surrounded by the other. When I was calculating the convection from the cables I also calculated it in a worst case scenario. Since I did not have the thermal conductivity for manganin[5] below 20 K, I made it the same all the way down to 1 K. In reality it will probably drop down towards zero. The result of these calculations showed that these thermal losses were too low to have been the cause, appendix C.

[5] The material the cables of the thermometers are made of.

Fig.4.27. The cables from the thermometers coming out from the model

During the preparation of the cryostat for the new test, a leak was found in the system. This leak may have affected the system, and can have been the cause of the thermal losses. The leak was taken care of and a new test was started.

4.4 Adjustments to the MathCAD model

After I got the results from the cryolab, we found out that we needed to make some changes to the model. The power applied to the heater will decide the heat flux in the model since we assume to have an adiabatic model. In the test, only one of the copper boxes in the heat exchanger was used. I therefore have to adjust the model to the fact that the cross section of the heater is much bigger than the copper box. After the adjustments a sketch of the model would look like this:

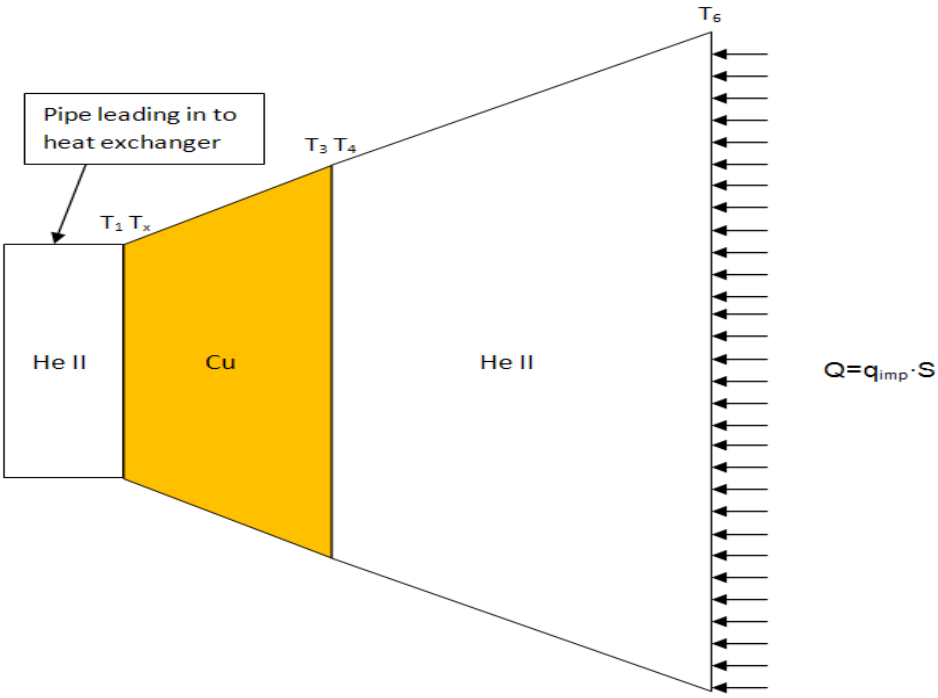

Fig.4.28.New model in MathCAD

Since the area of the copper and the He II now is conic, I had to integrate the surface area as a function of the length to find the heat flux:

$$Q_{HeII} = \frac{\int_{T_b}^{T_e} k_{HeII}(T)dT}{\int_0^{L_{HeII}} \frac{1}{(S_{HeII}(x))^3}}$$

$$Q_{Cu} = \frac{\int_{T_b}^{T_e} k_{Cu}(T)dT}{\int_0^{e_{Cu}} \frac{1}{S_{Cu}(x)}}$$

To compare the model to the results of the test I used the values for a heat flux of 750 mW. At this value I know the temperature of T_1, T_3, and T_6. I then adjusted the model to fit these values. This was done by adjusting the surface area of the inside and outside of the copper box, the surface area of the heater and the Kapitza resistance.

When the model fitted these values, I changed the T_1 and the heat flux in the model. I then calculated T_4-T_1 for all the different heat fluxes and made a graph showing T_4-T_1 as a function of the power applied to the heater. I used this to compare the model with the results from the lab.

5 Results

5.1 Test at the cryogenic laboratory

These are the results from the first test done at the cryolab. During this test the lower copper box in the heat exchanger was used. The results show the temperature measured in Kelvin at each thermometer from T_1 to T_{10} . In addition to these 10 thermometers there are two more thermometers. Ptecran measures the temperature on the thermal screen furthest out and c1147 is measuring the temperature on the screen farthest in. The measurements have been done with six different heat fluxes applied by the heater. At each of these heat fluxes the temperature has been measured over a period of time. In the results we can see the average of these measurements and the deviation.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	Ptecran	c 1147	P	T4-T1
	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(K)	(mW)	(mK)
29-Aug-07														
20:54:47 - 21:49:47														
average	1,790	1,846	1,777	1,816	1,828	1,840	1,823	1,846	1,869	1,844	59,608	7,818	0	26,33
deviation	0,001	0,000	0,032	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,028	0,007		
30-Aug-07														
12:13:32 - 13:04:47														
average	1,848	1,929	1,824	1,902	1,915	1,924	1,911	1,929	1,950	1,930	57,793	5,799	1000	54,08
deviation	0,002	0,001	0,051	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,106	0,007		
30-Aug-07														
15:13:32 - 15:43:32														
average	1,849	1,916	1,875	1,889	1,901	1,910	1,897	1,915	1,940	1,918	57,165	7,195	750	39,89
deviation	0,001	0,000	0,040	0,000	0,000	0,000	0,000	0,000	0,001	0,000	0,038	0,185		
31-Aug-07														
10:04:47 - 10:31:02														
average	1,850	1,906	1,923	1,878	1,890	1,900	1,886	1,905	1,927	1,904	79,204	9,026	250	28,05
deviation	0,001	0,001	0,005	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,364	0,693		
31-Aug-07														
14:15:22 - 14:45:22														
average	1,862	1,922	1,902	1,896	1,908	1,917	1,904	1,922	1,944	1,922	70,870	8,449	500	33,29
deviation	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,234	0,380		
3-Sep-07														
12:45:48 - 13:15:48														
average	1,856	1,982	1,956	1,958	1,969	1,977	1,966	1,981	1,987	1,972	61,148	6,771	1250	101,85
deviation	0,002	0,004	0,003	0,004	0,004	0,004	0,004	0,004	0,004	0,004	0,033	0,006		

Table 5.1. The temperatures at the different thermometers while applying different effects on the heater.

The results also give the relationship between T_4-T_1 and the power applied to the heater.

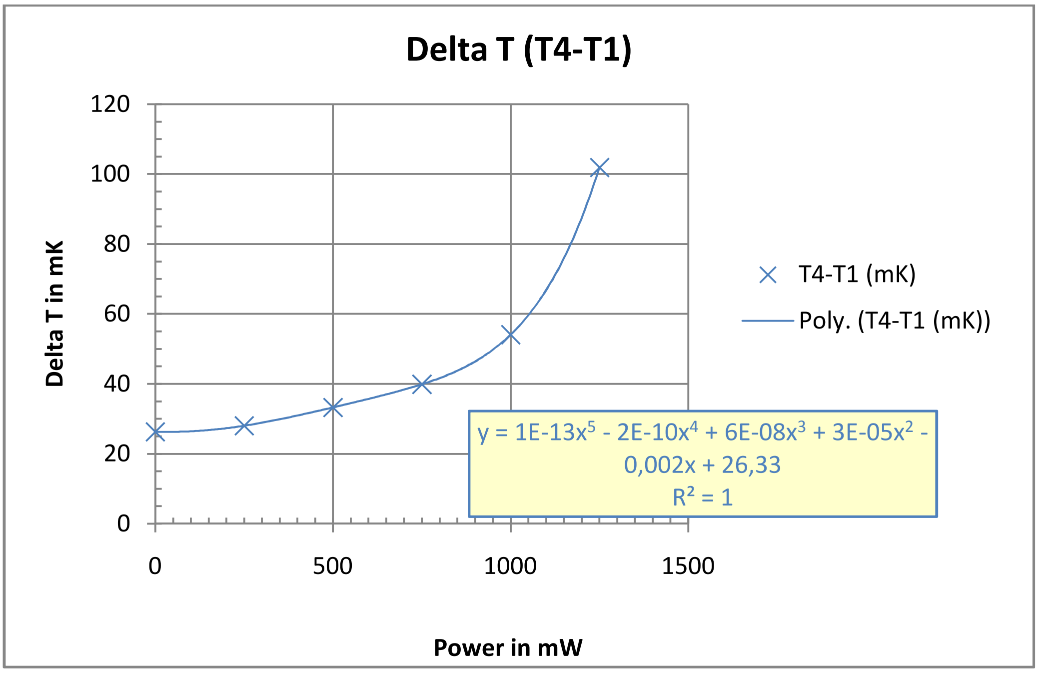

Fig.5.1. The temperature difference between T4 and T1 as a function of the effect applied to the heater

From the result from the lab I also made a graph showing the cool down from approximately 4.2 K to 1.8 K for all ten thermometers used.

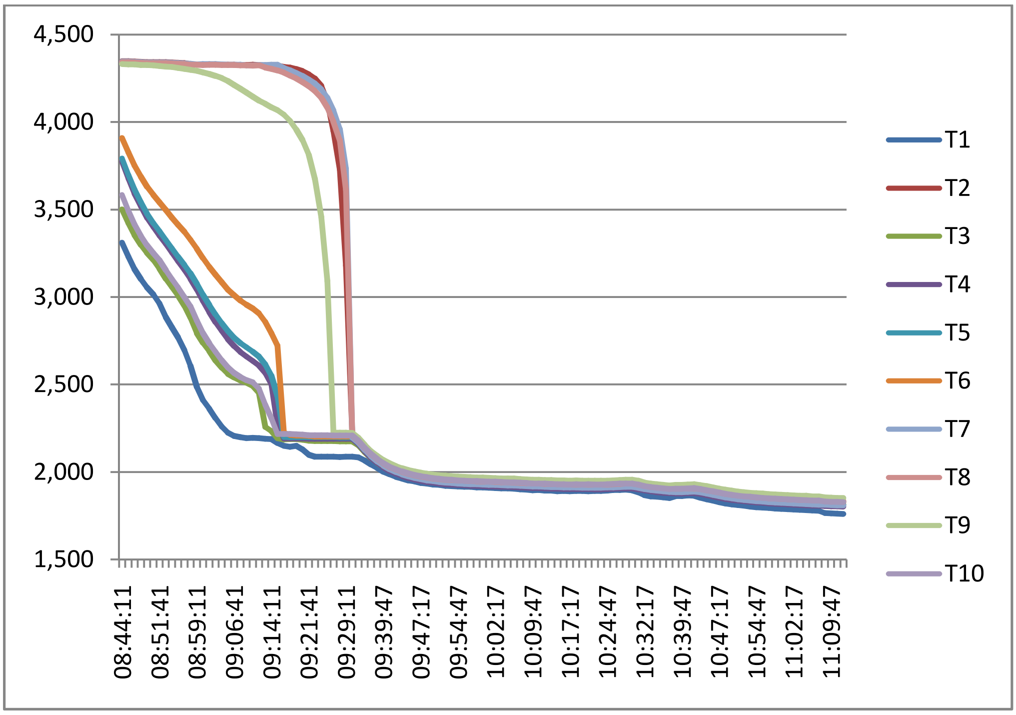

Fig.5.2. The cool down of the model

5.2 The model

I used the second MathCAD model I made, and adjusted it to the results from the lab at heat flux of 750 mW. The model then looked like this:

CALCULATION OF HEAT EXCHANGER IN LINE N

$$T_1 := 1.849$$

$$S_1 := 0.0125^2 \cdot \pi \qquad S_2 := 0.6 \cdot 10^{-3} \qquad S_3 := 0.62 \cdot 10^{-3} \qquad S_4 := 1.4 \cdot 10^{-5}$$

$$L_1 := 0.661 \qquad L_2 := 0.185 \qquad e_{Cu} := 3 \cdot 10^{-3}$$

$$h_K := 9 \cdot 10^4 \qquad q_{imp} := \frac{0.75}{S_4}$$

$$SHeII(x) := S_3 + \frac{(S_4 - S_3)}{L_2} \cdot x \qquad SCu(x) := S_2 + \frac{(S_3 - S_2)}{e_{Cu}} \cdot x$$

Thermal conductivity for copper:

$$Temp_{copper} := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{pmatrix} \qquad k_{copper} := \begin{pmatrix} 156 \\ 312 \\ 468 \\ 624 \\ 779 \\ 933 \\ 1085 \\ 1235 \\ 1380 \\ 1520 \end{pmatrix}$$

$$vs := pspline(Temp_{copper}, k_{copper})$$

$$k_{Cu}(vI) := interp(vs, Temp_{copper}, k_{copper}, vI)$$

The conductivity function for helium II:

$$\mathrm{Temp}_{he} := \begin{pmatrix} 1.8 \\ 1.85 \\ 1.90 \\ 1.95 \\ 2.0 \\ 2.05 \\ 2.10 \\ 2.15 \\ 2.155 \\ 2.16 \\ 2.165 \end{pmatrix} \qquad k_{he} := \begin{pmatrix} 1.1578\cdot 10^{13} \\ 1.4204\cdot 10^{13} \\ 1.6172\cdot 10^{13} \\ 1.6705\cdot 10^{13} \\ 1.4615\cdot 10^{13} \\ 9.0873\cdot 10^{12} \\ 2.9527\cdot 10^{12} \\ 5.5502\cdot 10^{10} \\ 1.6121\cdot 10^{10} \\ 1.8463\cdot 10^{9} \\ 0 \end{pmatrix}$$

$$vsb := \mathrm{pspline}\left(\mathrm{Temp}_{he}, k_{he}\right)$$

$$k_{HeII}(vIII) := \mathrm{interp}\left(vsb, \mathrm{Temp}_{he}, k_{he}, vIII\right)$$

Heat flux in helium II:

$$Q_{HeII}\left(T_b, T_e, S_{HeII}, L_{HeII}\right) := S_{HeII}\cdot\left(\frac{\int_{T_b}^{T_e} k_{HeII}(vIII)\, dvIII}{L_{HeII}}\right)^{\frac{1}{3}}$$

$$Q_{HeII2}\left(T_b, T_e, L_{HeII}\right) := \left[\frac{\int_{T_b}^{T_e} k_{HeII}(vIII)\, dvIII}{\int_0^{L_{HeII}} \frac{1}{(SHeII(x))^3}\, dx}\right]^{\frac{1}{3}}$$

Heat flux between helium and copper:

$$Q_{HeII\_Cu}(T_b, T_e, S_{Cu}, h_K) := h_K \cdot S_{Cu} \cdot (T_e - T_b)$$

Heat flux in copper:

$$Q_{Cu}(T_b, T_e, e_{Cu}) := \frac{\left(\int_{T_b}^{T_e} k_{Cu}(vI)\, dvI\right)}{\left(\int_0^{e_{Cu}} \frac{1}{SCu(x)}\, dx\right)}$$

Guessed values:

$T_x := 1.802 \quad T_3 := 1.803 \quad T_4 := 1.805 \quad T_6 := 1.807$

Given

$$Q_{HeII\_Cu}(T_1, T_x, S_2, h_K) = q_{imp} \cdot S_4$$

$$Q_{Cu}(T_x, T_3, e_{Cu}) = q_{imp} \cdot S_4$$

$$Q_{HeII\_Cu}(T_3, T_4, S_3, h_K) = q_{imp} \cdot S_4$$

$$Q_{HeII2}(T_4, T_6, L_2) = q_{imp} \cdot S_4$$

$$Ans := Find(T_x, T_3, T_4, T_6)$$

$$Ans = \begin{pmatrix} 1.863 \\ 1.876 \\ 1.889 \\ 1.909 \end{pmatrix}$$

From the results I got from this model I made a graph showing the relationship between the temperature difference T_4-T_1 and the power supplied by the heater. I then could compare the results from the model with the one from the test.

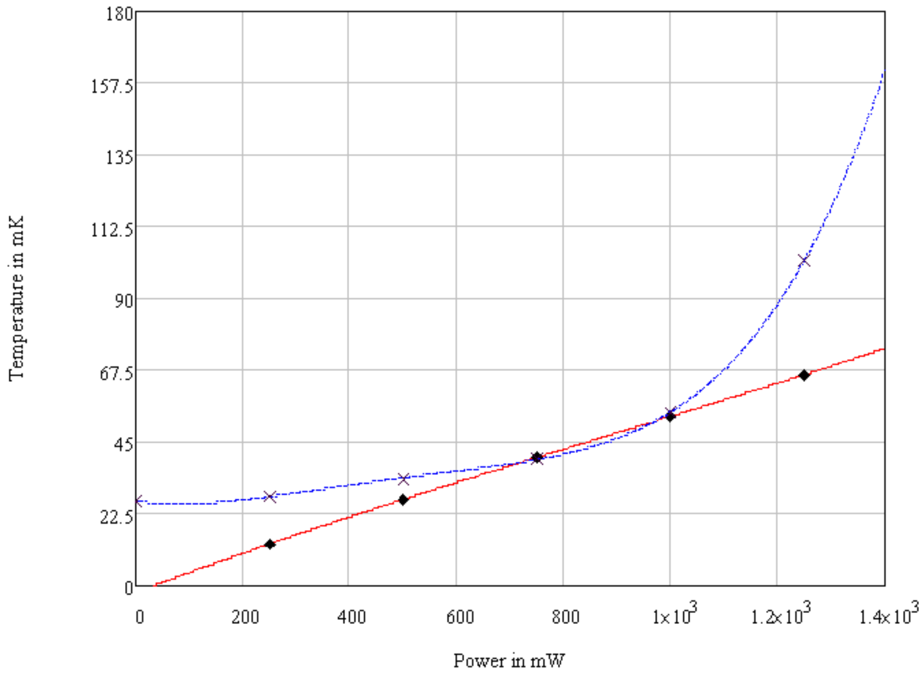

Fig.5.3. The temperature difference between T4 and T1 as a function of the power applied to the heater. Blue is the result from the lab, and red is the result from the model.

6 Discussion of the results

6.1 Test at the cryogenic laboratory

Due to all the problems at the cryolab the first results were not ready until the 12th of September. During this test thermometer T_3 did not work properly. There are readings from this thermometer in the results, but these readings are not accurate measurements. This can be seen by looking at the results. If we for example look at the result for a heat flux equal to 1000 mW, the temperature measured at T_1 is higher than the temperature in T_3. This cannot be correct, since the temperature will rise as an effect of the Kapitza resistance and through the copper before T_3. Also at a heat flux of 250 mW T_3 is obvious wrong. Here the temperature in T_3 is much higher than the temperature in T_4.

Another problem with these results is the heat losses during the test. The reason for these heat losses in the model is still unknown. The first measurements that was done, also suggested quite large thermal losses. As a consequence of this I made some calculations of the thermal losses due to radiation from the shield and convection trough the cables of the thermometers, see also chapter 4.3. These two causes were at the time assumed to be the most likely reasons for the thermal losses. According to the calculations I made these two reasons only constitute with $6.85 \cdot 10^{-5}$ W of the heat losses in a worst case scenario, appendix C, which is insignificant compared to the total losses.

Some days later a leak was discovered in the cryostat and the results from this first test was rejected. It was now assumed that the leak was the reason for the thermal losses, and the search for other reasons was therefore ended. Based on the results from the last test this is obvious not the case, since there still is quite large thermal losses.

To see the thermal losses in the model there were made a graph showing the relationship between the temperature difference between T_4-T_1 and the power applied to the heater. This graph crosses the y-axis at about 20 mK. If there had been no thermal losses this graph should have crossed at the origin. To find how large the thermal losses are, you can extend the graph until it is 0 mK. Since the graph in this case is almost flat when it crosses the y-axis it means that the thermal losses are quite large.

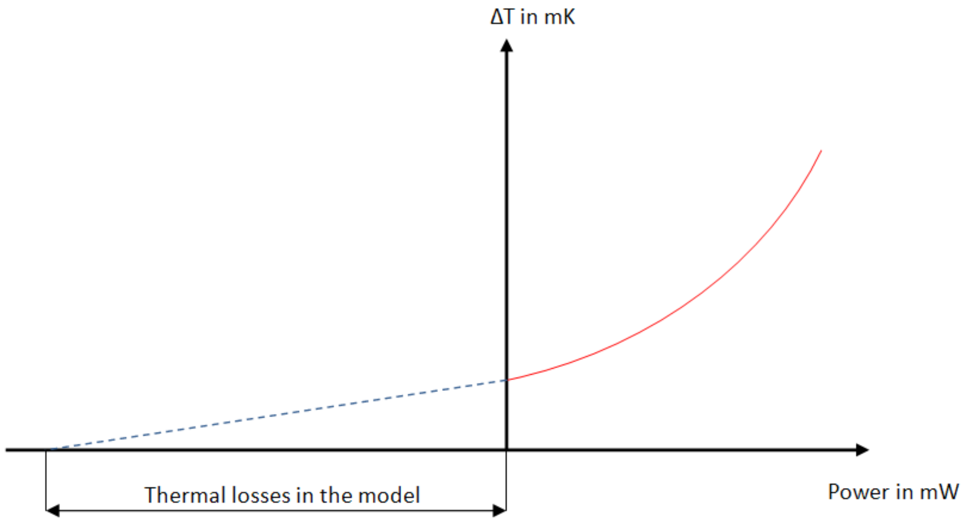

Fig.6.1. Example of how to find the heat losses

During the test there are several possible sources of error. Some of them can be:

- The thermometers are not correctly calibrated.
- There are thermal losses to the heat exchanger.
- Leaks in the cryogenic system.

From the results I made a graph showing the cool down of the different thermometers from approximately 4.2 K to 1.8 K. This show how long time it takes to sub-cool the model. In this first test it took approximately 30 minutes. Another interesting observation is that it looks like He II is filling the tube from the bottom and up. The reason it looks like this is that the thermometers that is in the top of the tube, T_2, T_7, T_8 and T_9, is cooling down slowly at the beginning. At a point they have a very fast cool down to the same temperature as the rest of the thermometers. The reason for this observation can be that we are using the lower copper box and due to little circulation in the helium the lower part of the tube is cooled down faster. Another reason may be that He II starts filling the tube from the bottom, and makes this part cold fastest. As the tube is filling up with He II the top of the tube will not reach 1.8 K before the tube is almost filled with He II. By looking at the results from the next test, where the upper copper box will be used, it is possible to compare the two tests and see if there are some similarities.

A new test is now in progress at the lab now. Before this test was started the input pipe was moved from the lower copper box to the upper. These two results will then be compared to see if there are any differences. In addition to this T_3 was fixed, and it was also installed a new thermometer inside the copper box. This will measure the temperature of the He II just before the copper wall to have a good starting point for the calculations.

6.2 The model

The model I have made is a quite simple mathematical model. We chosen to do it this way, since making a model in ANSYS turned out to be a project that was too much work for a six months period. The mathematical model will not be as accurate as a 3D simulation would have been, but it is accurate enough to be able to find the Kapitza resistance. The biggest problem with making this model has been the calculations of the heat flux trough He II. Since He II does not have the same properties as common liquids, there is a lot that have to be taken into account when you are working with it.

The making of the models in ANSYS and the first mathematical model was a good way for me to increase my understanding for what was happening during the cooling process. It shows the temperature changes in the model and the Kapitza resistance as well as the very high thermal conductivity in He II. After I got the results from the cryolab I made some changes to the mathematical model, so it would be easier to compare results from the model with the one from the lab. Afterwards I started to fit the result with a heat flux of 750 mW to the model. The reason for me to choose this heat flux was that this was one of the heat fluxes where the temperature measured at T_3 did not look so far away from the truth.

To fit the model I first started with the cross section areas given by the drawings and the Kapitza resistance assumed in the paper “Lambda front propagation and the heat exchanger in LHC dispersion suppressors line N”, [37]. I then adjusted these values so the result of the model fitted the result from the lab. Unfortunately I am very dependent on the value of T_3 to make this fitting. Since T_3 did not work properly during the first test, this probably will have an affected the result of the model. The value of T_3 will affect on the value of T_4 and T_6 due to the configuration of the model. I am not able to eliminate the value of T_3, because it then would be almost impossible to fit the model without it. As can be seen by the graph the values of the model is good at 750 mW, since it was at this value I fitted it. The relation is also quite good at 1000 mW. For higher values it is going from bad to worse. The same is for lower values than 750 mW.

This makes the model which is fitted by the first results from the lab not very credible. There has to be made another test where T_3 is working properly to be able to have a better relation.

7 Conclusion

After I have been working on this project for six months I can make the following conclusions:

- I have followed the test at the cryolab, and been working to keep up the communication between the cryolab and my group. Due to some unforeseen problems, the tests were not completely finished when I left CERN.

- I have made a mathematical model in MathCAD that can be fitted to the results from the test made in the cryolab. This computer model can then used to calculate the Kapitza resistance which occurs in line N. Due to some delays in the test at the cryolab it could not be tested completely. To be able to know for sure if it works good enough it has to be fitted to the new test results from the cryolab. The value of the Kapitza resistance can later be used to calculate the cool down time of line N.

- The first test has to be compared with the second one to see if the use of the upper or the lower copper box has any affect on the result. Due to my little experience with liquid helium this should be done by someone with the right experience.

7.1 Further work

When the model is fitted to the results from the cryolab, and the results and the model has a good agreement, the work can continue. When the model has a good agreement, the Kapitza resistance found and used to further calculations. As mentioned in the introduction there is already made a model of the cool down of line N in the DS section. The result of the Kapitza resistance can be implemented here to calculate the new cool down time of line N.

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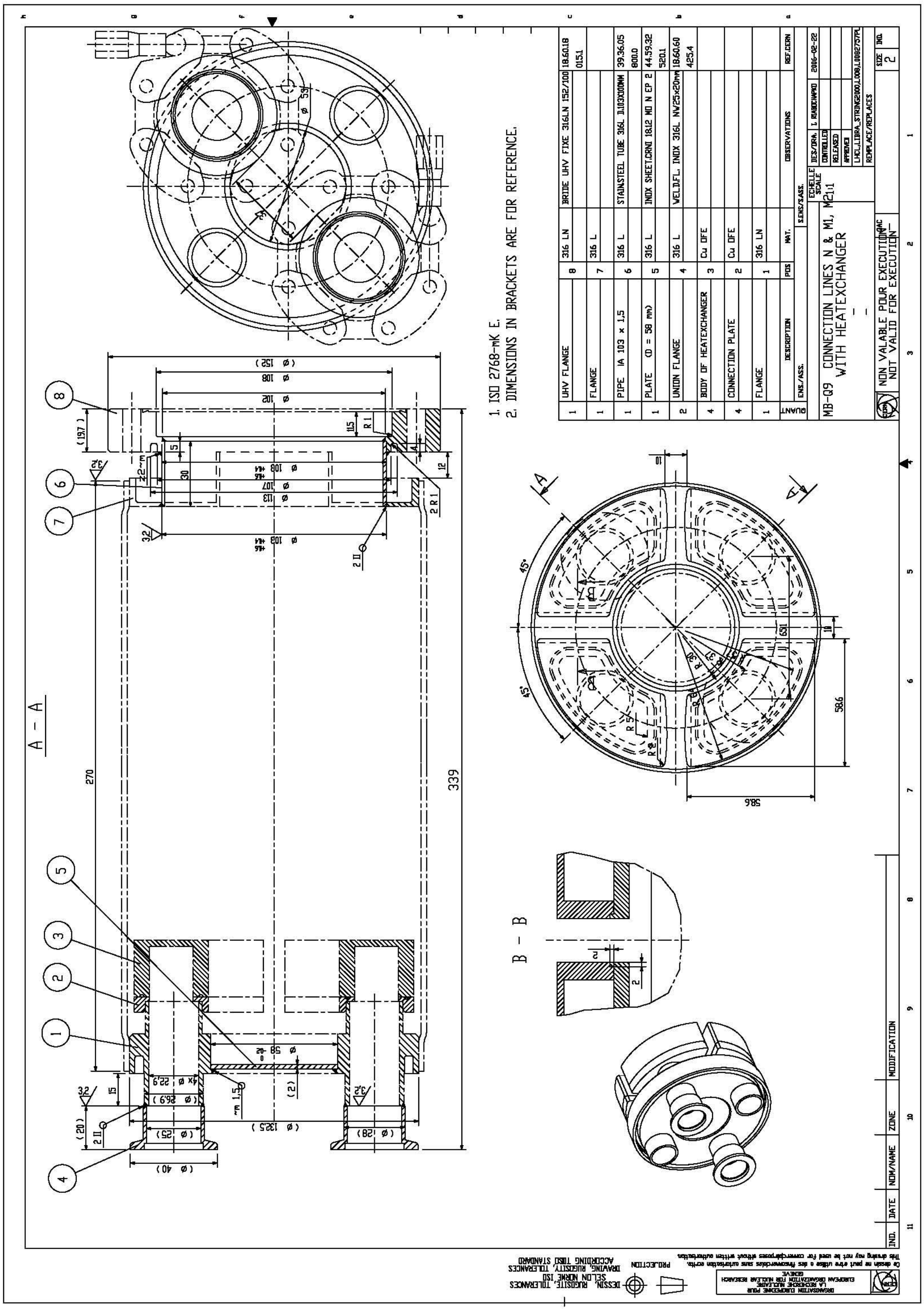
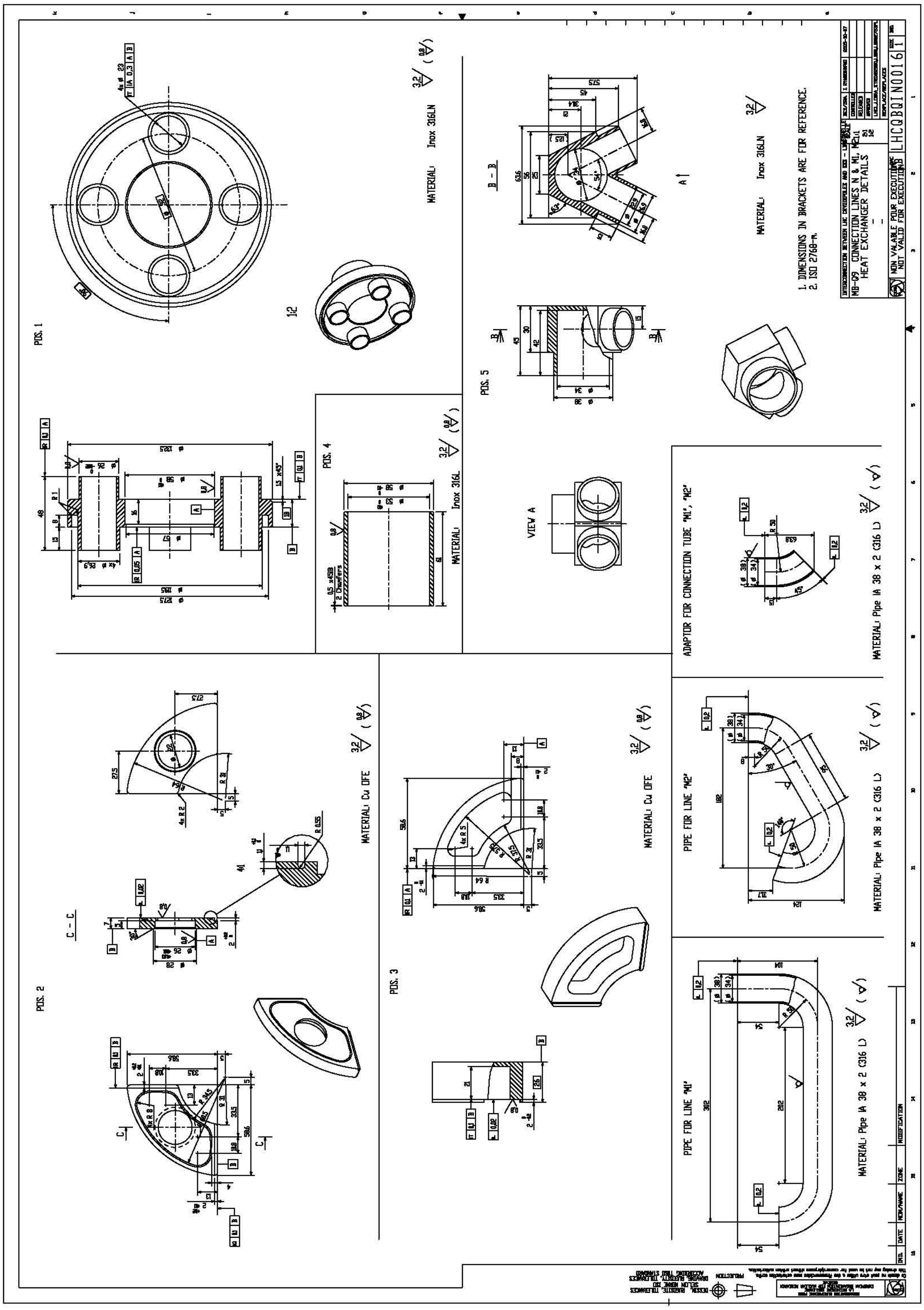
9 Appendixes

A. Drawings

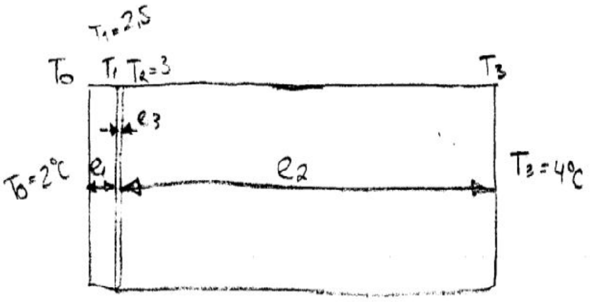
L0082757PL



L0082753PL


MB-09 CONNECTION LINES N & M1, M2
HEAT EXCHANGER DETAILS
1. DIMENSIONS IN BRACKETS ARE FOR REFERENCE.
2. ISO 2768-m.
MATERIAL: Inox 316LN
POS. 1
POS. 2
POS. 3
POS. 4
POS. 5
VIEW A
MATERIAL: Cu OFE
MATERIAL: Inox 316L
ADAPTOR FOR CONNECTION TUBE "M1", "M2"
PIPE FOR LINE "M2"
PIPE FOR LINE "M1"
MATERIAL: Pipe IA 38 x 2 (316 L)
LHCQBQIN0016

B. Calculations done by hand



- Heat flux skal være den samme over det hele (konstant)
  $q_{cu} = q_k = q_h$
- Går ut fra helium.
- Siden platen med [illegible] resistanser [illegible] tykkelse [illegible] i betraktning.

$$q_{cu} = \frac{k_{cu}}{e_1}\overbrace{(T_1 - T_0)}^{0,5} \Rightarrow k_{cu} = \frac{q_{cu} \cdot e_1}{0,5} = \frac{\frac{k_{he}}{e_2} e_1}{0,5} = \frac{k_{he} \cdot e_1}{e_2 \, 0,5} = \boxed{2 \cdot e_1 \cdot \frac{k_{he}}{e_2}}$$

$$q_k = h\overbrace{(T_2 - T_1)}^{0,5} \Rightarrow h = 2 \cdot \frac{k_{he}}{e_2} \qquad k_k = 2 \cdot \frac{k_{he}}{e_2} \; e_3$$

$$q_{he} = \frac{k_{he}}{e}(T_3 - T_2) \Rightarrow q_{he} = \frac{k_{he}}{e_2} \cdot 1$$

- Ut fra tabellverdier finner vi en middelverdi for k_{he} på ca $k_{he} = 2 \cdot 10^{-2}$

Verdier til bruk i Ansys:

$$k_{he} = 2 \cdot 10^{-2}$$

$$Q = \frac{k_{he}}{e_2} = \frac{2 \cdot 10^{-2}}{350} = \underline{5,71 \cdot 10^{-5}}$$

$$k_{cu} = 2 \cdot 5 \cdot \frac{2 \cdot 10^{-2}}{350} \approx 5,71 \cdot 10^{-4}$$

$$k_k = 2 \cdot \frac{2 \cdot 10^{-2}}{350} \cdot 1 \approx 1,14 \; 10^{-4}$$

$$0,05 \approx 5,71 \cdot 10^{-6}$$

$$0,1 \approx 1,14 \cdot 10^{-5}$$

$$0,5 \approx 5,71 \cdot 10^{-5}$$

$$0,7 \approx 8 \cdot 10^{-5}$$

C. Calculation of thermal losses in cryostat

Thermal losses in the cryostat

Thermal radiation from shield

Emissivity coefficients:

$$\varepsilon_s := 0.09 \qquad \varepsilon_m := 0.82$$

Stefan-Boltzmann constant:

$$\sigma := 5.67 \cdot 10^{-8} W \cdot m^{-2} \cdot K^{-4}$$

Diameters and heigths:

$$d_m := 136.5mm \qquad h_m := 270mm$$

$$d_s := 1.5m \qquad h_s := 1m$$

Temperatures:

$$T_s := 10K$$

$$T_m := 3K$$

Surface of the shield:

$$A_s := \pi \cdot d_s \cdot \left(h_s + \frac{d_s}{2}\right)$$

Surface of the model:

$$A_m := \pi \cdot d_m \cdot \left(h_m + \frac{d_m}{2}\right) \qquad F_{12} := \frac{A_s}{A_m}$$

Radiation from the shield:

$$W_s(\varepsilon_s, A_s, T_s) := \sigma \cdot \frac{A_m \cdot \varepsilon_m \cdot \left(T_s{}^4 - T_m{}^4\right)}{\left[1 + \frac{\left[\left(1 - \varepsilon_s\right)\varepsilon_m\right]}{\varepsilon_s} \cdot \frac{A_m}{A_s}\right]}$$

$$W_s(\varepsilon_s, A_s, T_s) = 5.838 \times 10^{-5} W$$

Heat from the cables connected to the shield

Cross-section of cables:

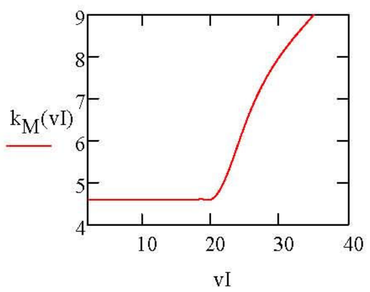
$r_c := 0.05\text{mm} \quad n_c := 40 \quad l_c := 100\text{cm}$

$S_c := \pi \cdot r_c{}^2 \cdot n_c$

$$Temp_{manganin} := \begin{pmatrix} 2 \\ 4 \\ 6 \\ 8 \\ 10 \\ 15 \\ 17 \\ 18 \\ 19 \\ 20 \\ 25 \\ 30 \\ 35 \\ 40 \end{pmatrix} \cdot K \quad k_{manganin} := \begin{pmatrix} 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.046 \\ 0.064 \\ 0.08 \\ 0.09 \\ 0.1 \end{pmatrix} \frac{W}{cm \cdot K}$$

$vs := \text{pspline}(Temp_{manganin}, k_{manganin})$

$k_M(vI) := \text{interp}(vs, Temp_{manganin}, k_{manganin}, vI)$



$$Q_c(T_b, T_e, S_c, l_c) := \frac{S_c}{l_c} \cdot \int_{T_b}^{T_e} k_M(vI)\, dvI$$

$$Q_c(T_m, T_s, S_c, l_c) = 1.012 \times 10^{-5}\,W$$

D. The first mathematical model

CALCULATION OF HEAT EXCHANGER ON LINE N

$T_0 := 1.9 \qquad T_\lambda := 2.165 \qquad T_k := 4.5 \qquad e_{Cu} := 3\cdot 10^{-3} \qquad l_{Hetot} := 0.2375$

$S_{Cu} := 4.2566\cdot 10^{-3} \quad S_{HeI} := 1.4208\cdot 10^{-2} \quad S_{HeII} := 1.4208\cdot 10^{-2} \quad h_K := 0.5\cdot 10^{4}$

Thermal conductivity for copper:

$$Temp_{copper} := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \\ 10 \end{pmatrix} \qquad k_{copper} := \begin{pmatrix} 156 \\ 312 \\ 468 \\ 624 \\ 779 \\ 933 \\ 1085 \\ 1235 \\ 1380 \\ 1520 \end{pmatrix}$$

$$vs := pspline(Temp_{copper}, k_{copper})$$

$$k_{Cu}(vI) := interp(vs, Temp_{copper}, k_{copper}, vI)$$

The conductivity function for helium II:

$$Temp_{he} := \begin{pmatrix} 1.8 \\ 1.85 \\ 1.90 \\ 1.95 \\ 2.0 \\ 2.05 \\ 2.10 \\ 2.15 \\ 2.155 \\ 2.16 \\ 2.165 \end{pmatrix} \qquad k_{he} := \begin{pmatrix} 1.1578\cdot10^{13} \\ 1.4204\cdot10^{13} \\ 1.6172\cdot10^{13} \\ 1.6705\cdot10^{13} \\ 1.4615\cdot10^{13} \\ 9.0873\cdot10^{12} \\ 2.9527\cdot10^{12} \\ 5.5502\cdot10^{10} \\ 1.6121\cdot10^{10} \\ 1.8463\cdot10^{9} \\ 0 \end{pmatrix}$$

$$vsb := pspline\left(Temp_{he}, k_{he}\right)$$

$$k_{HeII}(vIII) := interp\left(vsb, Temp_{he}, k_{he}, vIII\right)$$

Thermal conductivity for helium I:

$$Temp_{helium} := \begin{pmatrix} 2.3 \\ 2.4 \\ 2.6 \\ 2.8 \\ 3.0 \\ 3.5 \\ 4.0 \\ 4.2 \end{pmatrix} \qquad k_{helium} := \begin{pmatrix} 0.0181 \\ 0.0185 \\ 0.0195 \\ 0.0205 \\ 0.0214 \\ 0.0238 \\ 0.0262 \\ 0.0271 \end{pmatrix}$$

$$vsa := pspline\left(Temp_{helium}, k_{helium}\right)$$

$$k_{HeI}(vII) := interp\left(vsa, Temp_{helium}, k_{helium}, vII\right)$$

Heat flux in helium II:

$$Q_{HeII}(T_b, T_e, S_{HeII}, L_{HeII}) := S_{HeII} \cdot \left(\frac{\int_{T_b}^{T_e} k_{HeII}(vIII)\, dvIII}{L_{HeII}} \right)^{\frac{1}{3}}$$

Heat flux between helium and copper:

$$Q_{HeII\_Cu}(T_b, T_e, S_{Cu}, h_K) := h_K \cdot S_{Cu} \cdot (T_e - T_b)$$

Heat flux in copper:

$$Q_{Cu}(T_b, T_e, S_{Cu}, e_{Cu}) := \frac{S_{Cu}}{e_{Cu}} \cdot \int_{T_b}^{T_e} k_{Cu}(vI)\, dvI$$

Heat flux in helium I:

$$Q_{HeI}(T_b, T_e, S_{HeI}, l_{HeI}) := \frac{S_{HeI}}{l_{HeI}} \cdot \int_{T_b}^{T_e} k_{HeI}(vII)\, dvII$$

Guessed values:

$T_1 := 1.904 \quad T_2 := 2 \quad l_{HeI} := 2 \times 10^{-5}$

Given

$$Q_{Cu}(T_0, T_1, S_{Cu}, e_{Cu}) = Q_{HeII\_Cu}(T_1, T_2, S_{Cu}, h_K)$$

$$Q_{HeII\_Cu}(T_1, T_2, S_{Cu}, h_K) = Q_{HeII}(T_2, T_\lambda, S_{HeII}, l_{Hetot} - l_{HeI})$$

$$Q_{HeII}(T_2, T_\lambda, S_{HeII}, l_{Hetot} - l_{HeI}) = Q_{HeI}(T_\lambda, T_k, S_{HeI}, l_{HeI})$$

$Ans := \mathrm{Find}(T_1, T_2, l_{HeI})$

$$Ans = \begin{pmatrix} 1.91236 \\ 2.15733 \\ 1.463 \times 10^{-4} \end{pmatrix} \qquad \begin{pmatrix} T_1 \\ T_2 \\ l_{HeI} \end{pmatrix} := Ans$$

Temperature in copper:

$N1 := 10$

$i := 0..N1$

$L1 := 0, \frac{e_{Cu}}{N1} .. e_{Cu}$

$x1 := 2$

Given

$$\frac{S_{Cu}}{e_{Cu}} \cdot \int_{x1}^{T_1} k_{Cu}(vI)\, dvI - Q_{Cu}(T_0, T_1, S_{Cu}, e_{Cu}) = 0$$

$Ans1(L1) := \mathrm{Find}(x1)$

$Ans1(e_{Cu}) = 1.9$

Temperature in helium II:

$$L2 := e_{Cu}, \frac{(l_{Hetot} - l_{HeI})}{N1} .. (l_{Hetot} - l_{HeI})$$

$$x2 := 2.5$$

Given

$$S_{HeII} \cdot \left(\frac{\int_{T_2}^{x2} k_{HeII}(vIII)\, dvIII}{l_{Hetot} - l_{HeI}} \right)^{\frac{1}{3}} - Q_{HeII}(T_2, T_\lambda, S_{HeII}, l_{Hetot} - l_{HeI}) = 0$$

$$Ans2(L2) := Find(x2)$$

$$Ans2(l_{Hetot} - l_{HeI}) = 2.165$$

Temperature in helium I:

$$L3 := (l_{Hetot} - l_{HeI}), 0.34997 .. l_{Hetot}$$

$$x3 := 5$$

Given

$$\frac{S_{HeI}}{l_{HeI}} \cdot \int_{T_\lambda}^{x3} k_{HeI}(vII)\, dvII - Q_{HeI}(T_\lambda, T_k, S_{HeI}, l_{HeI}) = 0$$

$$Ans3(L3) := Find(x3)$$

$$Ans3(l_{Hetot}) = 4.5$$