LAPIN AMK
Lapland University of Applied Sciences

HOLLOW ELECTRON LENS TEST STATION

Predesign of cryostat

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Thesis
Industry and Natural Resources
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Opinnäytetyön tiivistelmä

Tekniikka ja liikenne
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Tekijä	Ville-Veikko Nikkanen	Vuosi	2015
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Tämän opinnäytetyön aiheena on Hollow Electron Lens -testiaseman kryostaatin esisuunnittelu. Testiasemalla on tarkoitus testata erilaisia elektronitykkejä ja -keräimiä ennen varsinaisen Hollow Electron Lens -laitteiston rakentamista. Laitteisto suunnitellaan ja valmistetaan testien pohjalta CERN:ssä. Työ tehtiin työharjoittelun aikana CERN:ssä.

Työn tavoite oli tuottaa 3D-malli tulevaa jatkosuunnittelua varten sekä ratkaista valmistamiseen ja kokoonpanoon liittyviä mahdollisia mekaanisia ongelmia siten, että kryostaatti on valmistettavissa ja toimiva.

Työn teoriapohja perustuu kryostaattien suunnitteluun vaikuttaviin tekijöihin kuten tyhjiötekniikkaan, lämpökuormiin sekä kryogeniikkaan. Nämä tekijät vaikuttivat koko suunnitteluun alusta loppuun asti.

Työssä käytetty 3D-ohjelmisto vaati oman osansa huomiosta, koska myös sen käyttö täytyi opetella. Työn suorittamisen aikana ohjelma tulikin erittäin tutuksi, eikä uudesta ohjelmistosta aiheutunut ongelmia.

Opinnäytetyön tuloksena saatiin 3D-mallit kryostaatista ja sen osista, joiden pohjalta muun laitteiston suunnittelu voidaan toteuttaa ja projektin edetessä kryostaatti tullaan muokkaamaan lopulliseen muotoonsa siten, että tarvittavat laitteet saadaan liitettyä mukaan kokonaisuuteen.

Asiasanat kylmätekniikka, 3D- mallinnus, suunnittelu, suprajohtavuus

Abstract of Thesis

Industry and Natural Resources
Mechanical and Production Engineering

Author	Ville-Veikko Nikkanen	Year	2015
Supervisor	Ari Pikkarainen		
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Subject of thesis	Hollow Electron Lens test station predesign of cryostat		
Number of pages	74+18		

The subject of this thesis was Hollow Electron Lens – test station cryostat premodel. The test station will be used to test different electron guns and collectors before Hollow Electron Lens is manufactured at CERN and assembled to LHC.

The objective of this thesis was to produce 3D models for designing the instrumentation and to solve mechanical problems in such a manner that the cryostat is functioning and can be manufactured and assembled.

The theoretical part of the thesis is based on the fundamental aspects of cryostat design such as vacuum technology, heat loads and cryogenics. These aspects had to be taken into account when designing the cryostat.

3D software used in this thesis work took its own share of time as it was new for me. Though in the end working with the new software did not cause any problems.

The result of this thesis were 3D models of the cryostat and its parts. Those models can be used in the future to design and implement necessary instrumentation to the test station.

Key words cryogenics, design, 3D modelling, superconductivity

TABLE OF CONTENTS

ABBREVIATIONS

CERN	Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research)
EN	Engineering Department
HEL	Hollow Electron Lens
HTS	High Temperature Superconductor
LHC	Large Hadron Collider
MLI	Multilayer Insulation
MME	Mechanical and Materials Engineering Group
PS	Proton Synchrotron
RTS	Room Temperature Superconductor
SC	Synchrocyclotron
SPS	Super Proton Synchrotron

1 INTRODUCTION

This thesis is a documentation of design work done during my internship at CERN. Hollow electron lens is an apparatus that is now being designed at CERN and it will be part of the LHC after it is assembled in 2020. Before that there is a need to test the setup and instrumentation. My part in this project was to carry out the pre-design and 3D models of the test station cryostat. Other objectives of this thesis were providing information about CERN and CATIA and giving the reader a brief introduction to cryogenics and cryostat designing.

The main reason for choosing this subject was to document my internship, the designing process of the cryostat and possibility to provide information to other students possibly going to do internship in CERN.

The subject was restricted to cryostat predesign as calculations would have complicated and prolonged the thesis and they will be done later when the design is finalized and the instrumentation designed.

2 CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

At CERN physicists and engineers are studying the fundamental structure of the Universe. They have the world's largest and most complex scientific instruments that are used to study the fundamental particles – the basic constituents of matter. The most famous and important part of that instrumentation is the LHC – Large Hadron Collider. With these instruments physicists are able to gain knowledge about particle physics and the fundamental laws of nature. (CERN 2015.)

Fig. 1 Map of Europe (Google Maps 2015.)

CERN is located in Meyrin, Switzerland near the city of Geneva (Fig. 1). Approximately half of the CERN site is actually on the French side of the border as can be seen from figure 2 where the line of black crosses illustrates the border of France and Switzerland and the green areas are the CERN sites, the main site being the one on the border. The name CERN comes from its French name "Conseil Européen pour la Recherche Nucléaire". (CERN 2015.)

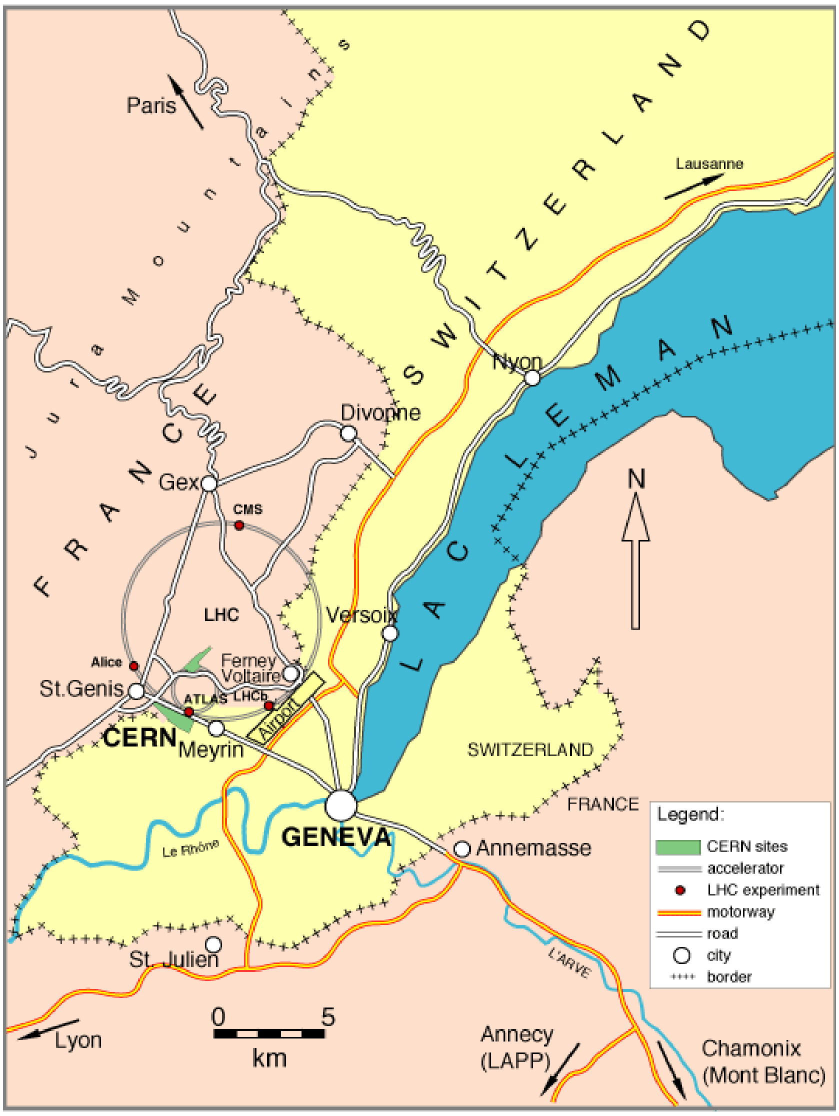

Fig. 2 Map of CERN area (CERN 2015.)

In CERN there are 2250 staff members but on the CERN site there may be up to 13,000 people on the site at same time as CERN is open to public. Visitors are welcome to CERN as it is publicly funded by the member states. There are 21 member states. They all have their duties and privileges. The member states pay their share to capital and take part in important decisions about the organization and its activities. (CERN 2015.)

2.1.1 Organization

In the CERN organization the highest authority is the CERN council which is formed by the government representatives from each member state. The council has two missions; governance of the CERN laboratory in Geneva and sponsoring the international co-operation in the field. Each member state has two representatives in the meetings: one representing the government and one representing the science community. Director-General, the Chief of the CERN laboratory, is selected by the Council. The term is 5 years. In 2014 the Council selected an Italian physicist Fabiola Gianotti as the next Director-General. (CERN Council 2015.)

On scientific matters the CERN council is advised by the Scientific Policy Committee. The Scientific Policy Committee was created in the Council's first meeting in 1954 to examine scientific achievements, make recommendations for researches and announce and assess annual goals for research. The Scientific Policy Committee's members are proposed to the Council by the Scientific Policy Committee Chair and the Council make appointments based solely on scientific competence. (CERN Council 2015.)

CERN Finance Committee is responsible for budgetary, procedural, personnel and commercial matters of the CERN. They meet five times a year to address these matters. The Finance Committee announces yearly budgets and plans for the Council to be approved in each June. (CERN Council 2015.)

2.1.2 History

The founding member states signed the CERN convention in 1953. Geneva was selected as the site for the CERN. Construction work on the site began in May 1954. The first accelerator, Synchrocyclotron (SC), was built in 1957. Its power was 600 MeV and it provided beam for CERNs particle and nuclear experiments. In 1964 Synchrocyclotron started to concentrate only on nuclear physics and a new, more powerful accelerator, Proton Synchrotron (PS) started experiments on particle physics. Synchrocyclotron was in service for 33 years. (CERN 2015.)

The construction of Super Proton Synchrotron (SPS) was approved by the member states in 1971. It was CERN's first giant underground ring accelerator. Its circumference was 7 kilometers. It was the first accelerator to cross the Swiss-Franco border. The construction work was finished in 1976 and in June 1976 it was operating at its maximum power, 400 GeV, for the first time. SPS is still operating and nowadays its power has increased to 450 GeV. (CERN 2015.)

Next big construction was a Large Electron – Positron Collider (LEP). The tunnel with a circumference of 27 kilometers was finished in February 1989. The first beam circulated LEP on 14 July in 1989. For 11 years LEP was operating and it was shut down for good in November 2000 to make way for the LHC. (CERN 2015.)

Work on Large Hadron Collider started in 2000 right after LEP was closed and the tunnel was open for construction work. Atlas, CMS, Alice and LHCb experiments were built together with the LHC. On 10 September 2008 the LHC was switched on. Just nine days after the first proton beam in the LHC there was an accident that was caused by a fault in electrical connection between two magnets. As a result of that accident there was a mechanical damage in the accelerator and helium was released into the tunnels. There were no human casualties but the accelerator was out of operation for 7 months as 53 magnets had to be refurbished or replaced. (CERN 2015.)

After the damages were repaired the LHC was operational again. On 4 July 2012 Higgs boson was observed in both Atlas and CMS experiments. The founding led to the Nobel Prize in physics to be awarded jointly to François Englert and Peter Higgs. (CERN 2015.)

2.1.3 LHC – Large Hadron Collider

The Large Hadron Collider illustrated in figure 3 is the largest and most powerful particle accelerator in the world. The designing of the LHC started as early as 1984 and building it was approved by the CERN Council in 1994. The LHC was built to gain knowledge about the Universe and the particles that form it and to fulfil Standard Model. One goal of the LHC was to prove the theory of Higgs mechanism by detecting the Higgs boson. Other main goals were proving super-symmetry and finding dark matter. (CERN Communication group 2009.)

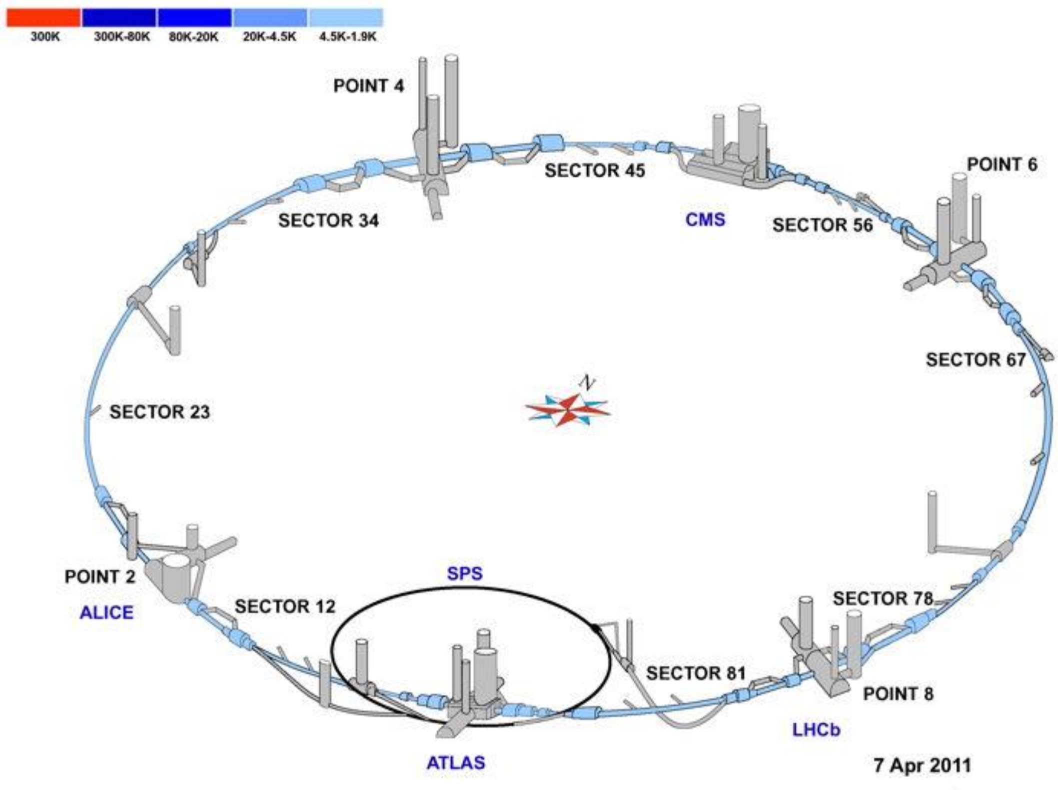

Fig. 3 Large Hadron Collider (Swiss Physical Society 2015.)

It was built between the years 2000 and 2008 and the first beam circulated the LHC on 10 September 2008. Building the LHC cost around 3 billion euros. Its circumference is 27 kilometers and there are 9593 magnets in the accelerator (Fig. 4). The operating temperature of dipole magnets which the LHC has 1232 is 1,9K or -271,3ºC to achieve and maintain superconductivity. (CERN Communication group 2009.)

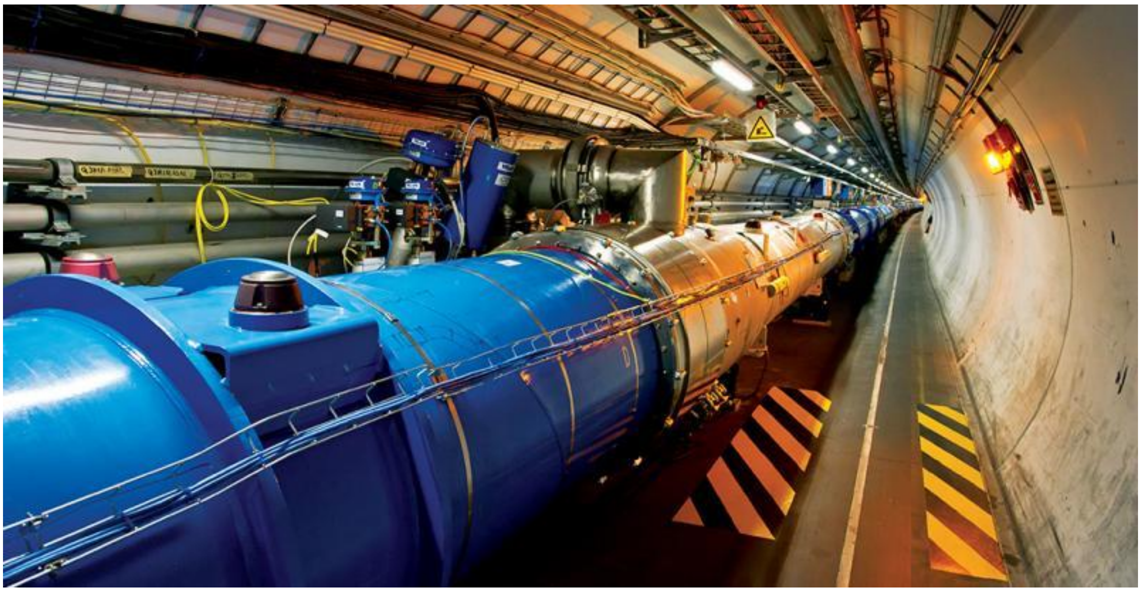

Fig. 4 Large Hadron Collider (CERN 2015.)

A proton beam is created by taking hydrogen atoms from a bottle that has hydrogen gas in it, then electrons are stripped from the atoms and what is left are the protons for the beam. The protons are first accelerated by Linac2 then they are injected to the PS Booster from where they go to the Proton Syncrothon. At that point the beam has energy of 1,4GeV. PS accelerates it to 25GeV before sending the beam to the Super Proton Syncrotron which will keep it accelerating to 450GeV. After that the beam is transferred to the LHC. In the LHC the beam will be accelerated for 20 more minutes to achieve the nominal energy of 7 TeV. The beams travel in beam tubes that are kept in ultrahigh vacuum. Dipole magnets keep the beams on their course around the ring. (CERN Communication group 2009.)

The two proton beams are travelling almost at the speed of light. After the desired beam energy is achieved the beams are steered to collide with each other. The collider accelerator has an advantage if compared to accelerators where a beam collides with a stationary object as in a collider the collision energy is the sum of energies of the two beams. Those collisions take place in experiments where the particles released from the collision are detected and the data is stored and sent forward. (CERN Communication group 2009.)

2.1.4 Research

At CERN there are multiple different researches going on all the time. The experiments carried out at CERN can be divided into two groups: the LHC experiments and non-LHC experiments. There are altogether 10 different accelerators at CERN, the Large Hadron Collider being the most well-known and popular. (CERN 2015.)

LHC experiments

On the ring of LHC there are 7 different experiments. They all have detectors designed and built to analyze particles that are produced by the accelerator. Scientists from different institutes all over the world are running these experiments together. (CERN 2015.)

ATLAS (Fig. 5) and CMS are the biggest experiments. They both have general-purpose detectors that are designed to detect and analyze as large range of particles as possible. They both have the same scientific goals but they have different design to have cross-confirmation of new discoveries. The Higgs boson was discovered in ATLAS experiment and the discovery was confirmed by CMS. (CERN 2015.)

Fig. 5 Mural painting on ATLAS experiment (CERN 2015.)

More specified experiments are the ALICE and the LHCb that are focused on more specific phenomena. ALICE is a heavy-ion detector. It is designed to study quark-gluon plasma. LHCb is designed to study the differences of matter and antimatter. (CERN 2015.)

Figure 3 shows how these experiments are positioned on the ring of LHC. Each of them are in caverns 100 meters underground. (CERN 2015.)

The other three LHC experiments are smaller detectors focused on certain particles. These experiments are TOTEM, LHCf and MoEDAL. TOTEM and LHCf are both focused on "forward particles" that will not collide head on but continue past each other after a beam collision. The TOTEM detectors are on each side of CMS and LHCf has its detectors 140 meters to both directions from ATLAS. MoEDAL is next to LHCb and searching for a particle called magnetic monopole. (CERN 2015.)

Non-LHC experiments

There are multiple non-LHC experiments at CERN that take place on other accelerators and facilities than the LHC. There are “fixed-target” experiments where the beam is aimed at and collided with a target that may be solid, liquid or gas. These smaller experiments get their beams from smaller accelerators like SPS and PS and together with the LHC-experiments they cover a wide range of topics in physics. (CERN 2015.)

3 MY INTERNSHIP IN CERN

Our school and CERN Engineering Department (EN) has had co-operation for a few years in form of internships and projects. Therefore I had a change to do my internship in the Engineering Department. The internship took place in the Mechanical and Materials Engineering Group (MME). It was supervised by Diego Perini, the Deputy of EN-MME. The job was to design and create 3D models for Hollow Electron Lens Test Station cryostat (Appendices 13–18). With me there was another student, Jarkko Harjuniemi, from my class. He designed a support structure and magnetic shielding for the HEL test station cryostat. In 2014 there had been one student, Samuel Riekki, in internship in EN-MME. Samuel Riekki had done the pre-design for full size Hollow Electron Lens. We partly continued his work.

3.1 Work environment

Before CERN I had only worked in a few small companies in Finland and Outokumpu Stainless steel factory in Tornio, Finland. Compared to the steel factory CERN is a very different kind of work environment as the results cannot be measured in tons and the projects and experiments may take years. That changes the game completely if compared to a big organization living one quarter at a time.

There are physicists, engineers and many other professionals from all over the world working in the same place and on same projects at the same time. Many different worlds collide and as a result there is top-end research facilities. Before going to CERN I was a bit worried how I will fit in and do I have enough knowledge to work there. After meeting my colleagues all those worries were gone. Everybody at CERN are very friendly and supporting. We were given actual tasks right after we arrived and we were learning the software and document management while we were working. We had our own office and we reported our progress directly to Diego Perini and Alessandro Bertarelli in our weekly meetings. Antti Kolehmainen was tutoring us always when we needed help.

2.2 My work

I had no earlier experience in cryogenics or particle physics and the CATIA V5 design software was also new for me, although I knew AutoDesk Inventor very well and it has much in common with CATIA. After we arrived at CERN I started looking into the pre-model of the HEL which gave us the guidelines for the test station design. Alexey Dudarev gave us a short introduction to the basics of superconductivity, magnets and cryogenics and Antti Kolehmainen taught us the basics of CATIA. Diego Perini provided us with the information and input data needed to design the test station. The whole summer was continuous learning. Now I can say that I handle CATIA quite well and I have gained knowledge in many different fields of engineering.

My work was mostly 3D modelling and sketching solutions for mechanical problems we encountered in the design. We did constant co-operation with Jarkko Harjuniemi as we had to merge our designs together. At first we did a rough model of the test station, support system and shielding and then started to add details and find out problems and solve them.

Though all the work was done in the office we visited some of the experiments and accelerators. It was most interesting to visit both CMS and ISOLDE. Unfortunately we were not able to visit the LHC itself as it is restricted when cooling system is filled with helium. At the CMS we almost managed to see the LHC. We were already underground when something happened and the access to the CMS detector cavern and the LHC was restricted and we had to turn back from the last checkpoint before the detector. That was during a maintenance break when the helium system was emptied for cleaning.

4 THEORY OF CRYOSTATS

Cryostats are used to cool instruments to very low temperatures. At CERN those instruments are mostly superconductive magnets or Radio Frequency cavities. In everyday life cryostats can be found in magnetic resonance imaging units in hospitals and in industry as cryogenic fluid containers. These cryostat are produced thousands units per year. Cryostats used in laboratories and research facilities are usually designed on occasion for specific use. (Parma 2015, 1.)

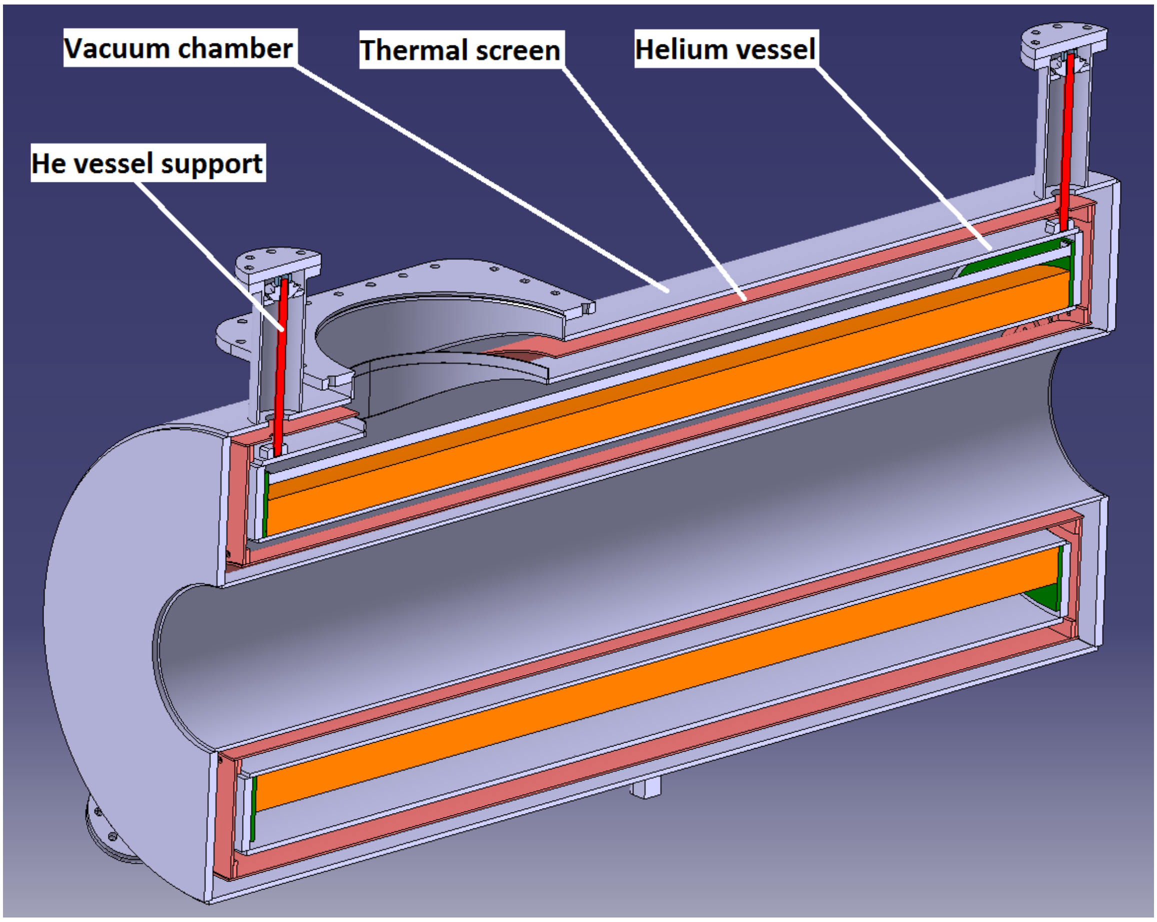

Fig. 6 Structure of cryostat

In figure 6 the basic structure of a cryostat is shown. The shape and size of the cryostat vary depending on what it is used for.

When designing a cryostat there are many technical aspects that have to be taken into account. If everything is not done properly, the cryostat may not achieve and maintain the desired temperature. Those aspects are illustrated in figure 7. Mechanics and heat transfer make the basics for the design. Superconductivity, system integration, vacuum and cryogenics require specialists. Superconductivity is not necessarily always part of cryostat design. (Parma 2015, 3.)

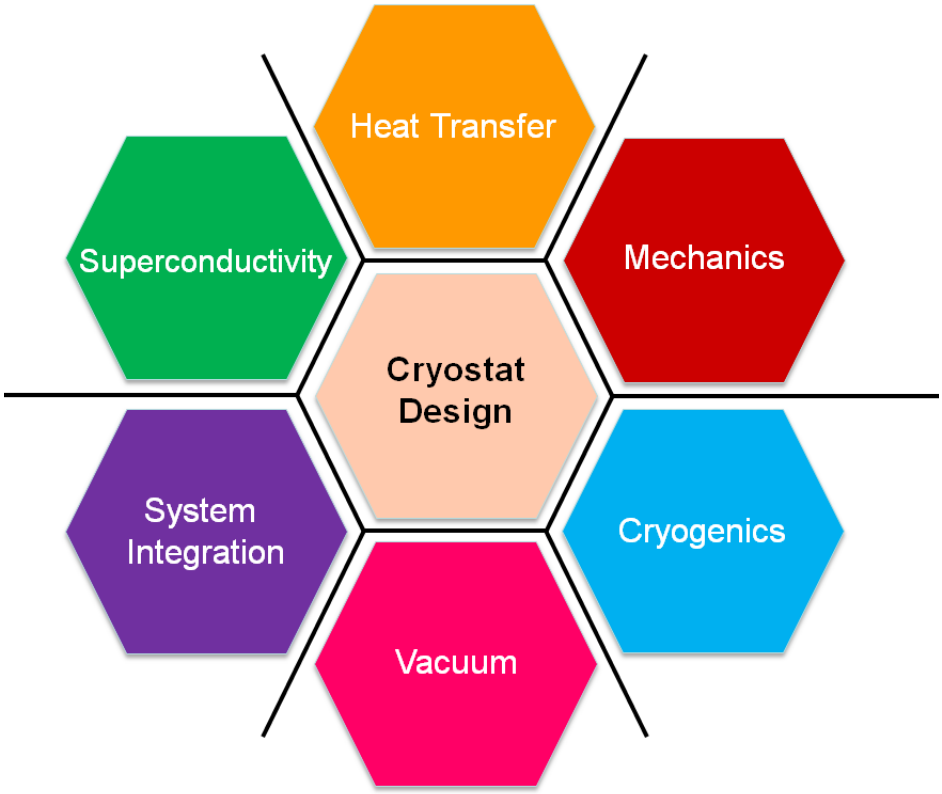

Fig. 7 Aspects of cryostat design (Parma 2015, 3.)

4.1 Heat transfer

Heat transfer can be divided into three groups: solid conduction, residual gas conduction and thermal radiation. All three have to be taken into account in order to control the heat load of the cryostat and to achieve the desired temperatures. In the test station the heat load is critical as the Cryocooler has limited cooling power. Solid conduction comes from the current leads, instrumentation wiring, helium vessel support rods etc. Residual gas conduction is the result of a possibly non-perfect insulation vacuum. Thermal radiation is normally the dominating heat load but it can be greatly reduced with a thermal shield and multilayer insulation. (Parma 2015, 5.)

4.1.1 Solid conduction

Solid conduction can be reduced with right materials and mechanical design. The equation for solid conduction is

$$Q = -k(T) \cdot A \cdot grad(T) \tag{1}$$

Where

Q	is	heat conduction
k	is	thermal conductivity of material
T	is	temperature
A	is	cross section area

As the helium vessel support rods are beams, the following equation can be used:

$$Q = k * k'(T) * \frac{A}{l} \tag{2}$$

Where

A	is	cross section area of beam
l	is	length of beam

From that equation it can be seen that by decreasing the cross section area and increasing the length of the beam, heat conduction can be reduced. Same applies to the current leads and all the pipes which are only solid heat conductors along with supports. (Parma 2015, 7.)

4.1.2 Residual gas conduction

Residual gas conduction is the result of gas residues or air leaks in the cryostat. Non-perfect vacuum causes cryo-condensation on cold surfaces and it creates a heat load. To avoid residual gas conduction the welds of containers have to be on the vacuum side of the chamber to avoid air pockets that could cause leaking, contain residues and prolong pumping. (Perini 2015.)

4.1.3 Radiation

The most significant part of heat load to the cryostat is caused by radiation. All surfaces emit and absorb electromagnetic radiation. When the surface of a body is hit with radiation part of the radiation is absorbed, part is reflected and part is transmitted. These parts are called absorptivity α, reflectivity β and transmissivity τ. Energy conservation is presented as $\alpha + \beta + \tau = 1$. In case $\tau = 0$, the body is called opaque. The opaque body does not transmit energy at all. All the energy is either absorbed or reflected. If also β is 0, then the body is called black. It means it absorbs all energy. (Parma 2015, 11.)

Most bodies in the cryostats are considered opaque. Black bodies rarely occur, although there are situations when a gap or cavity can act as one by trapping radiation inside and the energy is slowly absorbed into the body as the reflections keep bouncing around the cavity and cannot escape from it. This situation is illustrated in figure 8. (Parma 2015, 11.)

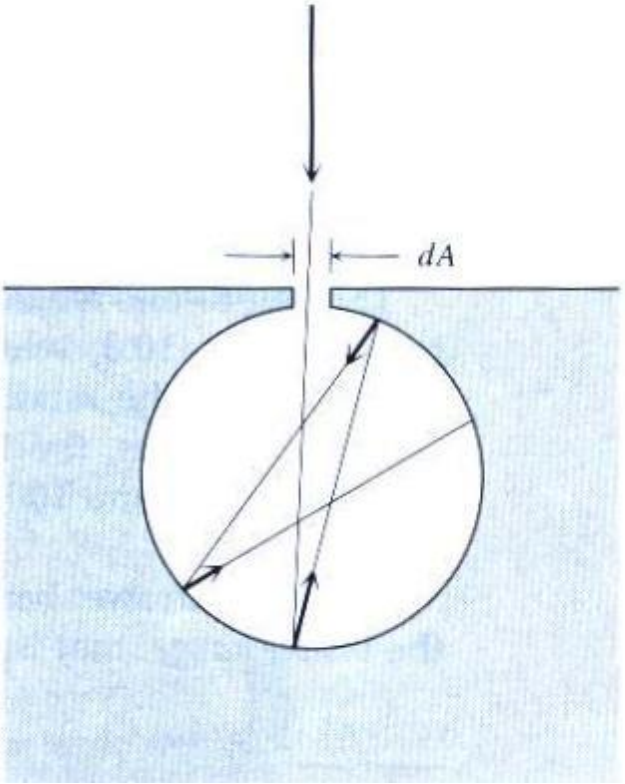

Fig. 8 Cavities can act as black body (Parma 2015, 11.)

Designing unnecessary cavities, gaps and holes should be avoided and if they cannot be avoided they should be somehow covered or coated. In most cases multilayer insulation (MLI) can be used to cover those cavities in order to stop radiation going in them. In an ultrahigh vacuum MLI cannot be used and in those cases the surroundings of the cavities can be coated with a special high-absorptivity coating to avoid multi-path reflections. (Parma 2015, 11.)

Calculating the heat load caused by radiation contains complex equations with multiple variables. Those variables are for example material's hemispheric emissivity which is material's effectivity of radiating energy if compared to a black surface and it is affected by the surface finish and cleanliness. A better finishing quality and a cleaner surface result in smaller emissivity. Non-metallic surfaces usually have higher emissivity. These values differ in different temperatures and can be found in the table. In table 1 there are some examples of these values. (Parma 2015, 14.)

Table 1. (Parma 2015, 14.)

		Temperature (K)		
		4	80	300
Copper, mechanically polished		0,02	0,06	0,1
Copper, black oxidised				0,8
Aluminium, electropolished		0,04	0,08	0,15
Aluminium, mechanically polished		0,06	0,1	0,2

4.1.4 Thermal shielding

A thermal shield is a floating intermediate shield made of aluminum or copper. It is located between the cold surface of the helium vessel and the warm surface of the vacuum chamber. Applying the thermal shield can reduce the heat load of cold surface to half. The thermal shield is usually cooled down to 50-80K to decrease the emissivity of the shield and lower the cryogenic cooling cost of cryostat. (Parma 2015, 15.)

4.1.5 Multilayer insulation

The effective way of reducing the heat load and increasing the effectiveness of the thermal shield is to apply MLI between warm and cold surfaces. Multilayer insulation is done by packing the reflecting and insulating layers next to each other and so creating a blanket. The reflecting layers reflect radiation and the insulators prevent thermal conduction. Those layers are aluminized polyethylene films and the insulating layer is made of polyester, paper or glass fiber. The efficiency of the insulation depends on the assembly of the MLI blankets. The density of the layers should be kept the same. If the blanket is compressed or loose the effectiveness can be compromised. To avoid solid thermal conduction, there should be left enough space between the warm surface and MLI. (Parma 2015, 17.)

4.2 Mechanical design

As the cryostat is basically a container, its shape and size is designed for the instrument or substance needed to contain. At CERN the cryostats are mostly housing magnets and RF cavities. There are usually four main components in the cryostat: cryogenic vessel, vacuum vessel, thermal shield and support structure. (Parma 2015, 27.)

The materials used in the cryostats have to be capable to handle extremely low temperatures. Usually cryogenic and vacuum vessels are made of austenitic stainless steel, the most common grade used is 304-type stainless steel: preferably a low carbon version 304L as it is corrosion resistant and ductile in welded structures. Austenite is also non-magnetic. The vessels are usually made of sheet metal and the thickness of the material ranges from 1mm to 15mm. (Parma 2015, 28.)

The thermal shield has to be made of a high thermal conductive material, usually copper or aluminium alloys. Series 6000 aluminium (Al-Mg-Si) is commonly used in accelerator cryostats as it has good manufacturability, weldability and thermal conductivity. It is also cheaper than copper, which is usually used in smaller cryostats. Pure copper is only used when very high thermal conductivity is needed to ensure temperature homogeneity. (Parma 2015, 28.)

The support structure design and material vary by the design of the cryostat and where it is placed. The support rods for the cryogenic vessels are usually made of fiber reinforced plastic materials as they have low thermal conductivity. (Parma 2015, 28.)

Important part of mechanical design of the cryostat is manufacturability. The requirements for that varies depending on the production volume. At CERN the production quantities vary from one cryostat made for one experiment, like the

HEL test station, to over 1000 cryostats, like the LHC main dipoles. Another important aspect is safety. The cryostats are pressure vessels and they have to fulfill relevant safety regulations. (Parma 2015, 28.)

4.3 Cryogenics

When the operating temperature of the cryostat is aimed to be below 10K, liquid helium is the only suitable cryogenic fluid. In atmospheric pressure cryogenic liquids boil at a certain fixed temperature. The temperature of helium bath can be adjusted by pressurizing or evacuating the gas space. The boiling point of ^4He in atmospheric pressure is 4,230K. Lowering pressure lowers the boiling point and that way the bath temperature, and increasing pressure increases the boiling point and temperature. ^4He is the most common liquid coolant used in cryogenics in temperatures under 10K. Other option is a lighter isotope of helium, ^3He, which is rarely used as it is very expensive if compared to ^4He. ^3He is used to achieve temperatures under 1K. Other cryogenic coolants that can be used to achieve temperatures above 10K are for example Hydrogen, Neon and Nitrogen. (Ekin 2006, 39.)

4.4 Vacuum

In cryostats vacuum is used for multiple purposes. As explained in previous chapter, vacuum pumping can be used to lower the temperature of cryogenic liquids. Probably the most important is the insulation vacuum. A good insulation vacuum is necessary in order to achieve extremely low temperatures. Different vacuum levels and applications are shown in figure 9. (Ekin 2006, 153.)

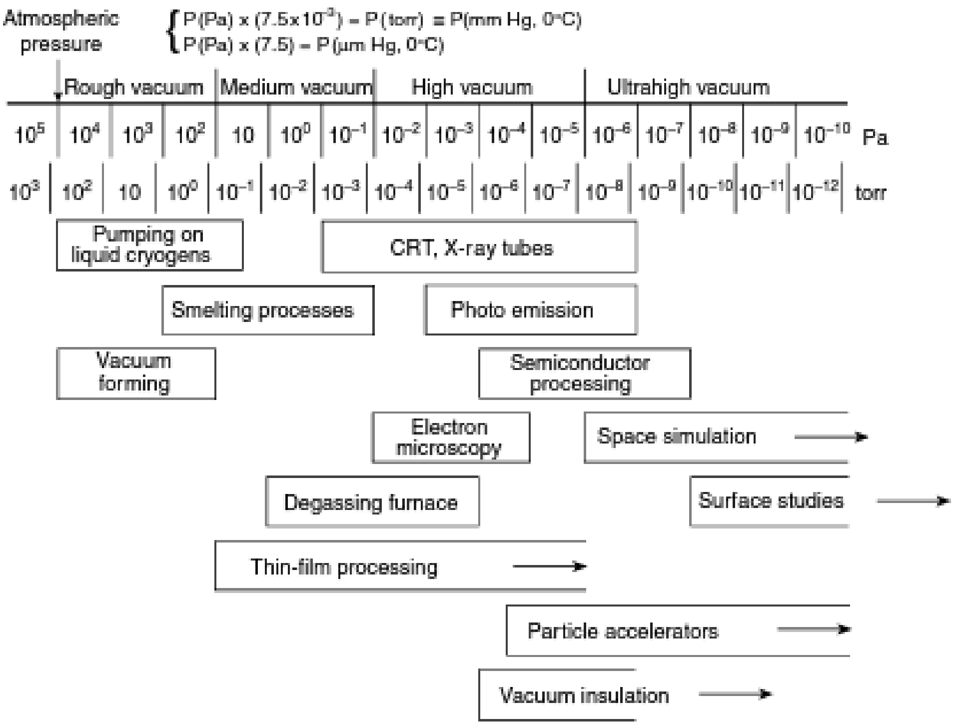

Fig. 9. Table of vacuum applications (Ekin 2006, 153.)

The level of vacuum needed sets requirements for the vacuum space and equipment. To achieve a good insulation vacuum the vacuum space has to be evacuated and backfilled with dry nitrogen gas several times to eliminate all residual helium and water vapor from the vacuum space. After cooling the cryostat with liquid helium all remaining gas residues, other than helium, will condensate on cooled surfaces and that provides an action called “cryopumping” which lowers the partial pressure of gases. (Ekin 2006, 154.)

The vacuum vessel has to be equipped with a safety valve such as a pressure-release valve or burst valve. In case of slow leak in the vessel cryopumping can condensate a fair amount of gases to the vacuum chamber and when the vessel is warmed back to room temperature those gases will rapidly evaporate and overpressure the vessel. That may cause the vessel to explode if necessary safety valves are not installed properly. (Ekin 2006, 154.)

4.5 Superconductivity

Superconductors are metals and alloys that completely lose their resistance in certain temperature. For most superconductors that happens in extremely cold temperatures and researches are nowadays studying new materials to find room temperature superconductors (RTS).

Superconductivity was first discovered in 1911 by the Dutch physicist H. Kamerlingh-Onnes when he was measuring the electric resistance of mercury at very low temperatures. He found out that the resistance of purified mercury disappeared in temperatures below 4,15K. (Ginzburg & Andryushin 2004, 1.)

The electric resistance R is measured in Ohms and it represents how strong “friction” electric current encounters in material.

Electric current can be compared to the flow of gas or liquid. Larger the diameter and shorter the length of the pipe is, the easier the flow is. (Ginzburg & Andryushin 2004, 4.)

Copper is a common conductor. It has resistivity of $1{,}75 \times 10^{-6}$ Ohm * cm in room temperature. As temperature decreases to cryogenic temperatures the resistivity of copper lowers to 10^{-9} Ohm * cm. It does not reach zero, as copper is not superconductor. Aluminium, lead and mercury can reach a superconductive state in cryogenic temperatures. Superconductors have resistivity under 10^{-23} Ohm * cm which is a hundred trillion times less than copper has. (Ginzburg & Andryushin 2004, 4.)

Superconductors have the critical temperature T_c. Below that temperature the resistivity of superconductors drops to zero. T_c varies depending on material. Niobium has the highest T_c, 9,3K, of chemical elements. Superconductive alloys can though reach a higher T_c. The main reason for using high temperature superconductors is that some of the HTS alloys have T_c above 77K which is the boiling point of liquid nitrogen which is much cheaper cryogenic liquid than liquid helium. Room temperature superconductors have not yet been discovered. (Ginzburg & Andryushin 2004, 7.)

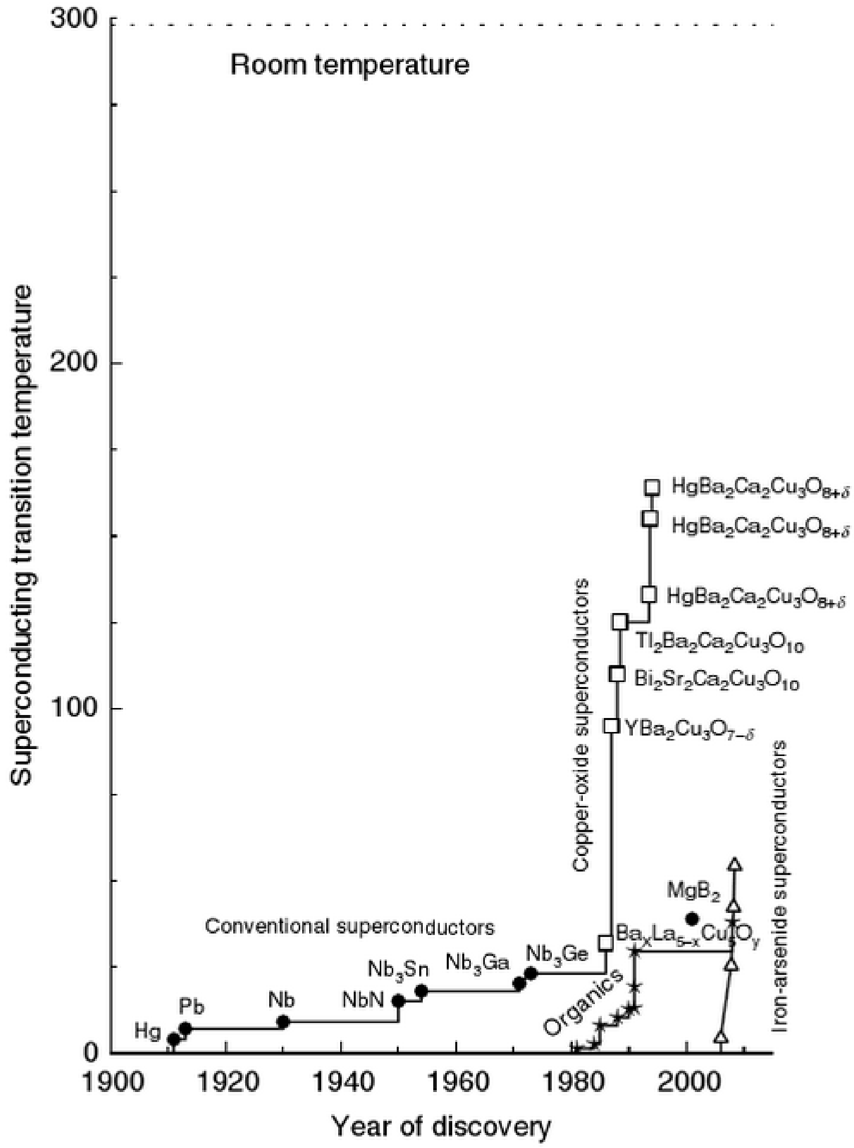

Fig. 10 Transition temperatures for different superconductors (Blundell & Stephen 2009, 111.)

Some superconductors T_c temperatures since the discovery of superconductors are shown in figure 10. As seen in the figure, recently many HTS copper-oxide compounds have been discovered. Those compounds are difficult and expensive to manufacture as they require a technique called chemical doping. It is done to destroy magnetism and make the material superconductive. That is achieved by substituting charged atoms next to each other in layers between the copper oxygen planes. (Blundell & Stephen 2009, 110.)

4.5.1 Magnets

The strength of a magnetic field is proportional to the current and number of windings in the electromagnet. As regular copper windings produce a lot of heat with high currents due to their resistance in room temperature, making that extremely strong magnets require cooling and there is a limit how strong a magnetic field can be achieved with normal conductors. Superconductive magnets use a fraction of the electrical power needed for normal conductive copper magnets and they do not produce heat nearly at all. (Ginzburg & Andryushin 2004, 68.)

Manufacturing superconductive wires for magnets is not easy nor cheap. There is a field of metallurgy and metal science that is specialized in manufacturing superconductive wires for magnets. The most common superconductive alloy for magnets is niobium-titanium alloy. More complicated wires are commonly manufactured from triniobium-tin (Nb3Sn). It can withstand 10^3 A/mm^2 where normal copper wire cannot take more than 1-2 A/mm^2. Superconductive wires are manufactured so that superconductive veins are positioned in a copper matrix. The superconductive veins are less than 0,1mm in diameter. The wires are made that way as they have to withstand extreme stress caused by the magnetic field. (Ginzburg & Andryushin 2004, 71.)

The superconductive magnet has to be cooled down to cryogenic temperatures. The temperature depends on the alloy used but usually in science applications superconductive magnets are cooled below 10K. That means magnet has to be in a helium path. One risk in operating superconductive magnet is the situation called *quench*. When a quench occurs part of the superconductive coil loses its superconductivity and enters the normal state. High current circulating in coil turns into heat and that increase in heat warms the entire coil and that causes the cryogenic liquid to vaporize. That causes a sudden increase in pressure which may cause danger. The quench may also damage the windings as the sudden increase in heat may burn the wires. To detect the quench and avoid damage to the coil, the voltage in the current leads has to be monitored. When the magnet is functioning correctly the voltage is zero and if the quench occurs the voltage will increase and at that point the current has to be directed out of the coil. This quench detection and coil protection system is usually automatic and works in milliseconds. (Perini 2015.)

5 HEL – HOLLOW ELECTRON LENS

The Hollow Electron Lens (HEL) (Fig. 11, Appendices 1–6) is an instrument designed to clean the proton beam that is circulating in the accelerator. It will be installed on the LHC during LS3, the long shutdown 3, which starts somewhere around 2020. The aim of the HEL is to remove unstable particles from the proton beam. This is done in order to prevent unstable particles from hitting the beam pipe and causing damage. The powerful magnets in the electron lens create a hollow electron beam. The electron beam is created with an electron gun that is assembled next to the cryostat. The proton beam passes through the electron beam and everything that is out of the centerline of the beams will be pulled out with the hollow electron beam. In the centerline of the electron and proton beams there is a neutral, uncharged, space, but right out of the centerline there is a strong electric charge that will draw out all the particles that are out of the centerline and that way clean the beam. This happens because the electrons have a negative charge and protons have a positive charge. The particles that are drawn from the beam will go to a particle collector with the electron beam. The particle collector is an instrument that slows down and spreads the beam so the energy of beam does not concentrate on one spot. The collector has a copper pot where the particles are “collected”. The copper pot is cooled with a water circulation to prevent it from melting. (Perini 2015.)

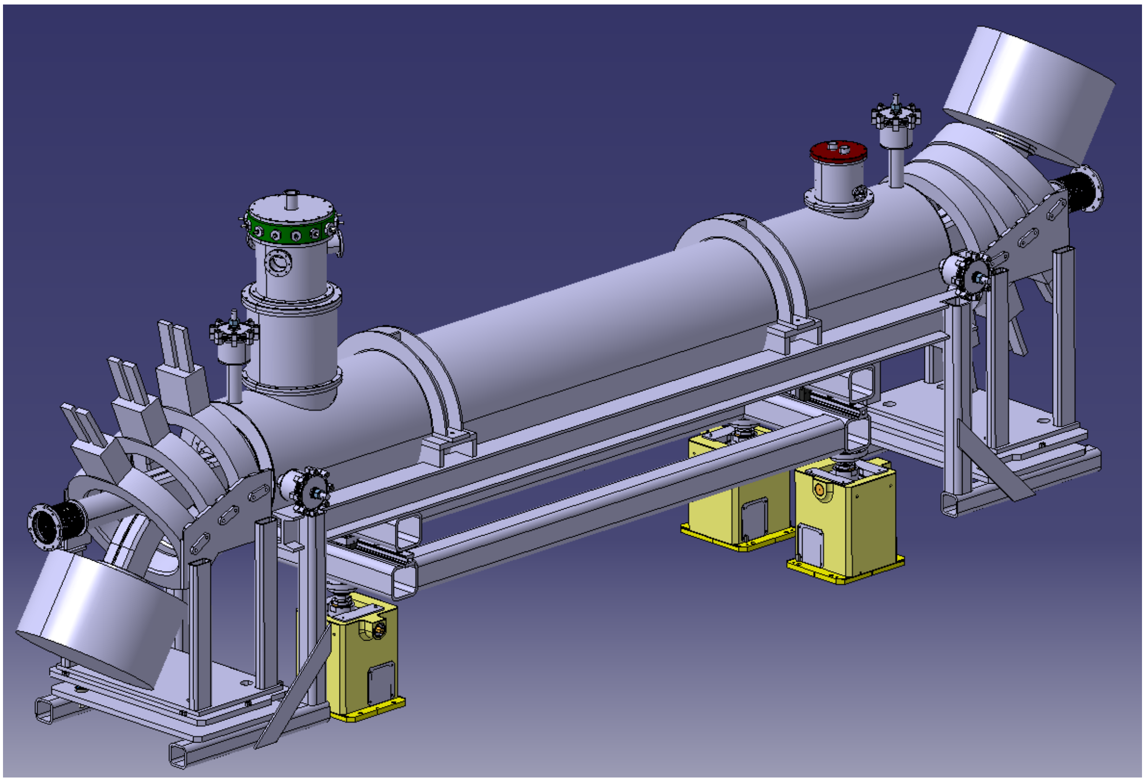

Fig. 11 Pre-model of HEL (Riekki 2014.)

The electron lens is designed to replace the mechanical cleaning technique that is now in use. Now the beam is cleaned with collimators by drawing the unstable particles out of the beam centerline and colliding them with physical objects that are put near the beamline. The drawback in the collimators is that they lower the intensity of the beam and the collision causes radioactive radiation. Using the HEL instead of the collimators would profit in higher beam intensity and less side effects. (Perini 2015.)

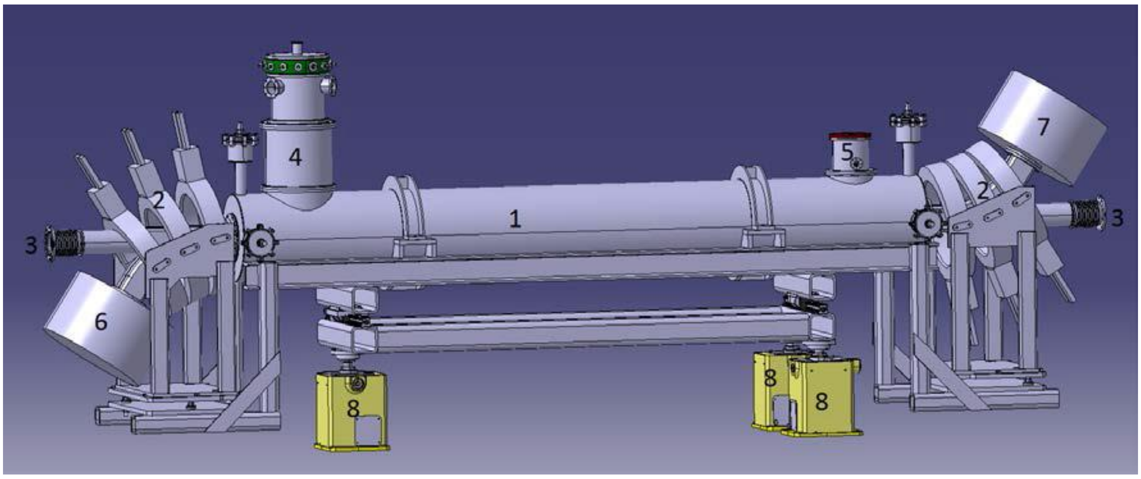

Fig. 12 Pre-model of HEL (Riekki 2014, 20.)

Parts of the Hollow electron lens shown in figure 12 are:

1. **Solenoid magnet** used to create the hollow electron beam
2. **Toroid magnets** used to turn the electron beam
3. **Proton beam tube**, LHC beam travels in this tube
4. **Current lead chimney**
5. **Helium chimney** used for helium supply and circulation
6. **Electron gun** used to create the electron beam
7. **Collector**, used to collect unstable particles
8. **Jack**, used for alignment

5.1 Future of Hollow Electron Lens project

By the time this thesis work is ready the Hollow Electron Lens will be officially added to the HL – LHC baseline, the development plan of LHC, but many things are still open. While the design work of the test station (Appendices 7–12.) is going on, the budget for building it is still under discussions. The decision will probably be made in January 2016. Meanwhile the first prototype of the electron gun is being built at CERN and it will be sent to Fermilab in the USA to be tested in their test station. The aim with the electron gun design is to study different cathodes in order to increase the current from 5A, which is the maximum at the moment, to 10A. (Perini 2015.)

6 CHALLENGES AND SOLUTIONS

In this chapter the whole design is dealt with and the challenges of each sector explained and how these challenges were solved. The main focus and the most difficult part of design was the cryocooler chimney.

6.1 Input data and requirements

There was not much input data in the beginning. The dimensions of the test station would be same or almost the same as in the HEL, but only 1/3 of the length. The length of the 5T superconductive magnet would be 1000mm and the outer diameter 300mm. It is exactly the same as in the HEL, but in the HEL there are three of these magnets in a row. The temperature of the helium path has to be below 4,2K and the thermal loads have to be minimized so that the cryocooler works properly and there should be an option to cool with a constant helium circulation. (Perini 2015.)

The requirements for the instrumentation were still under discussions while the pre-design was done. Most of the instrumentation wiring for the coil monitoring can be done through the helium outlet. There has to be the instrumentation to monitor the coil superconductivity, temperature, pressure etc. (Dudarev 2015.)

The instrumentation for the beam monitoring has to be designed and included in the test station, but that will be defined later and it is not part of this thesis and pre-design.

6.2 Helium vessel

The helium vessel consists of an inner tube, outer tube, end flanges, cryocooler chimney bellows and cryocooler heatsink. Everything else but the heatsink is made of 304-type stainless steel. The surface of helium vessel can be polished in order to reduce emissivity and heat load caused by radiation. The heatsink is made of copper as it has to have good thermal conductivity. The helium vessel is housing the superconductive magnet. The coil is wound directly to the inner tube. At first a composite coil support was designed between the inner tube and windings, but in order to reduce the coil diameter the coil will be wound directly on the inner tube. The end flanges have to be welded on the inner tube before winding, as there will be insulator plates on each end of the coil and they are glued on the end flanges. After the end flanges are welded the whole assembly will be machined to obtain a good surface for the windings. Between the inner tube and windings there will be only a thin layer of the insulation film, so the surface quality of the inner tube determines the quality of the winding. All instrumentation and current lead supports have to be assembled before welding the outer tube, as the vessel will be closed and accessible only through the chimney hole on top of the vessel. The current leads coming from the coil, will be attached on the insulation plate on the chimney side of the cryostat. As the position where winding ends cannot be determined beforehand, the copper connectors for the current leads will be assembled after winding. From those connectors current leads will be continued on the surface of the support rod all the way to the chimney opening on the top of the helium vessel. That has to be done to be able to solder high temperature superconductive current leads on the coil when assembling the cryostat. The chimney hole is not in the middle of the cryostat, to reduce the length of current leads. (Perini 2015.)

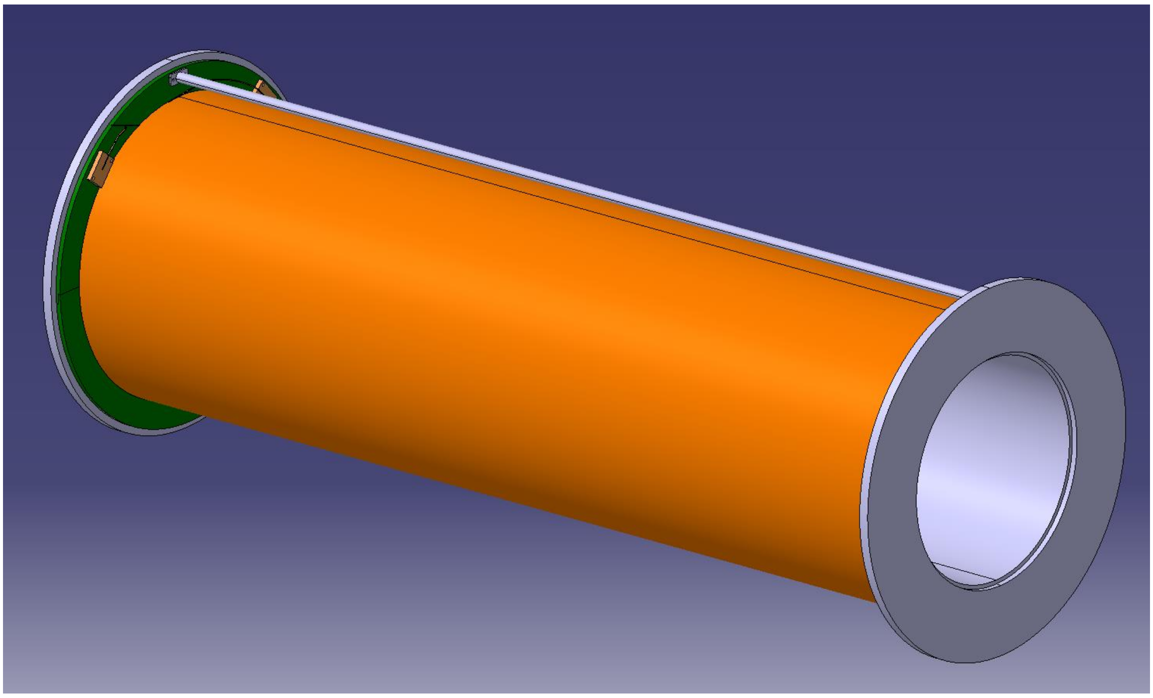

Fig. 13 Coil and helium vessel inner tube

The inner tube, end flanges, insulation flanges (green), windings (orange) and current lead support are shown in figure 13.

The cryocooler will be connected to the heatsink that is partly inside the helium vessel. The heatsink is braced to stainless steel bellows on the top of the helium vessel, together they form a smaller chimney, from now on called the lower chimney. The bellows are used to reduce forces caused by thermal contraction. The bellows have to be hydro formed as there are no standard bellows suitable for this situation. The bracing has to be done before the lower chimney is assembled, but the lower chimney cannot be welded on the helium vessel before assembling the thermal screen and vacuum chamber as they have to slide on their places over the helium vessel. So there has to be enough space to do assembly welding between the bellows and the helium vessel.

To reduce the solid heat transfer to the helium vessel, the vessel has to be supported with a material that has low thermal conductivity. In this case Permaglass composite rods will be used to hold the vessel in its place. All together two M10 and four M6 threaded rods will be used, three on each end: one M10 rod facing up and two M6 rods facing down (Fig.14). The lower rods are angled inside, so the vessel is locked in all directions. As stated earlier reducing the cross-section and increasing the length of the rods, the heat load can be reduced.

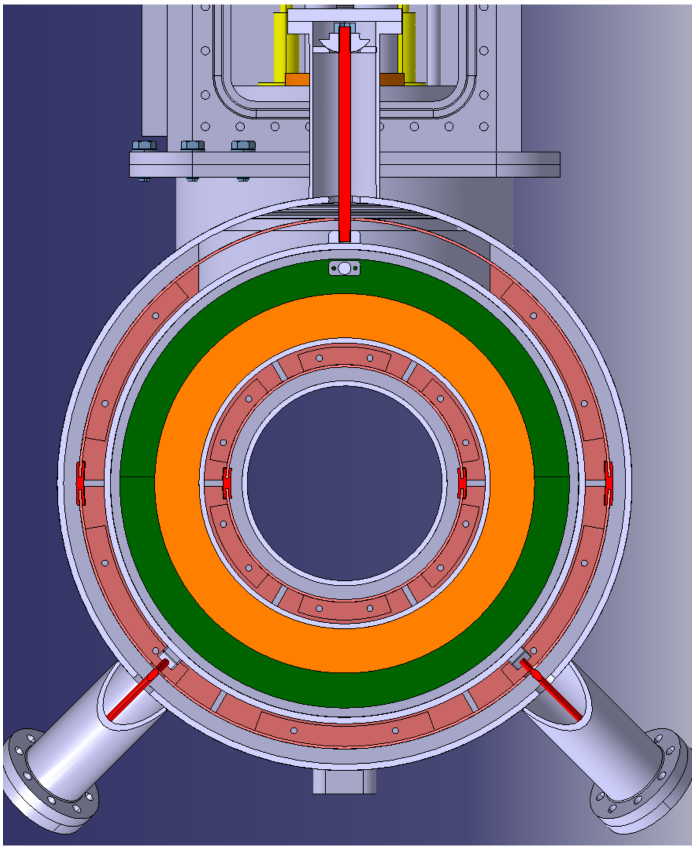

Fig. 14 Section view of cryostat

The first idea was to use four rods on each end; one facing up, one down and one on each side. That support system would not have locked the helium vessel on the beam direction and that direction has to be locked for the transport. If that system was used there would have been a need to use rods to support the vessel from the end flanges of vacuum chamber and there is no space on that direction as there will be the instrumentation on both ends of the test station. To reduce solid heat conduction it was decided to use less rods. The strength of rods is not an issue, so one on top and two on bottom is enough to hold the weight of the helium vessel. The lower rods were angled so they lock the vessel in the beam direction. All rods have ball-joint on top so the heat contraction of the helium vessel will not cause flexure to rods (Fig. 14). The support rod columns are shown in figure 15. There is also shown the lower part of shielding which was designed at CERN by another student, Jarkko Harjuniemi. (Perini 2015.)

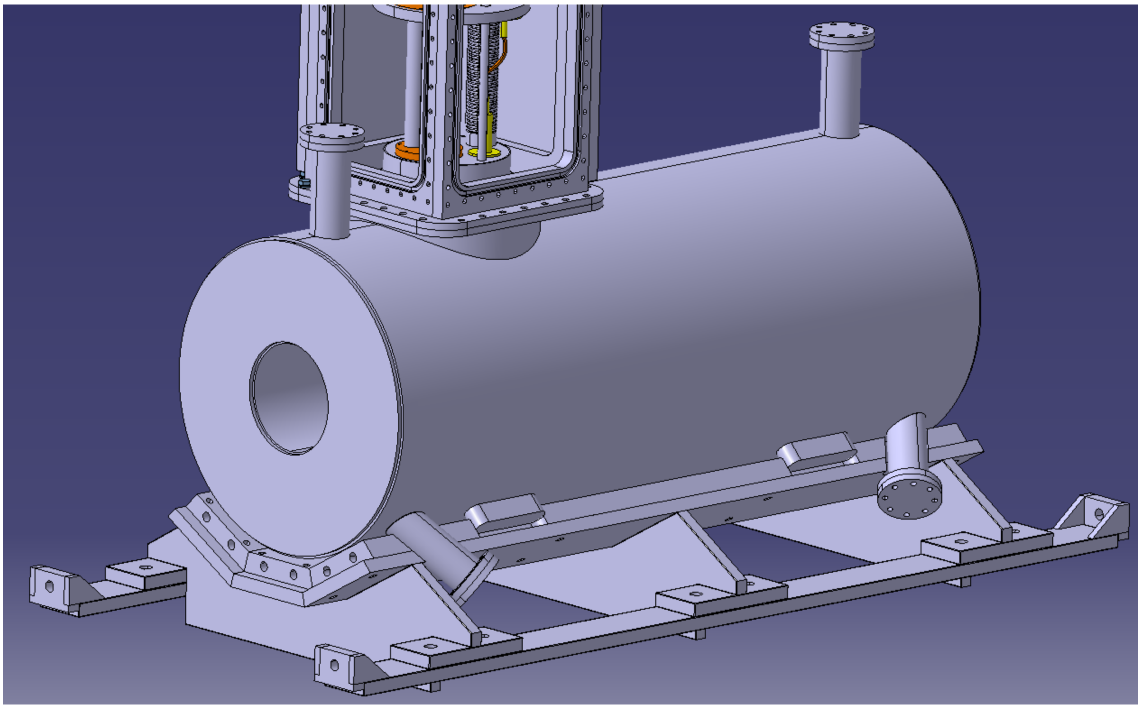

Fig. 15 Closed cryostat on shielding bed

The alignment of the magnetic field is critical and that is done by aligning the helium vessel. For the test station, the need for references outside the vacuum chamber are being considered as the helium vessel can be aligned before closing the vacuum chamber and fine tuning can be done with the beam tube that is going through the test station. (Perini 2015.)

If it is considered that references are necessary, they have to be done by machining measurement points on the end flanges of helium vessel after the magnet is wound and measure the distance from those reference to the centerline of magnet. Then when the helium vessel is assembled and aligned there has to be reference points outside the cryostat and the distance between those points and the references on the helium vessel have to be measured and that way the beam tube can be aligned to the magnetic field by using references outside the vacuum chamber. (Kolehmainen 2015.)

6.3 Thermal screen

The intermediate copper screen (Fig. 16) between the helium vessel and the vacuum chamber is crucial in order to manage heat loads. It is made of two tubes, inner and outer, which are cut in half lengthwise. The halves are bolted together with insulators between them. That is done to avoid the magnetic field from crushing the tube. One problem was that the end plates would connect the halves together. To avoid that the end plates were made from 6 sectors that are bolted on the inner and outer tube halves.

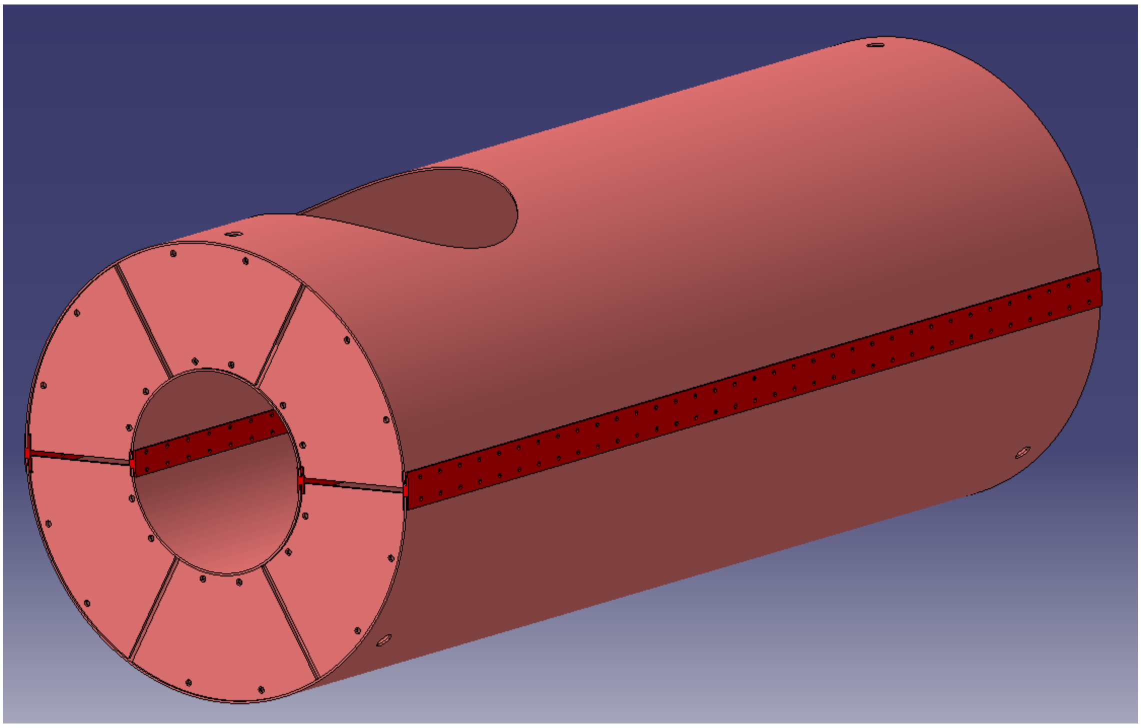

Fig. 16 Thermal screen

6.4 Vacuum chamber

The vacuum chamber consists of an inner tube, outermost tube, chimney flange and end flanges. The chamber is welded together after the helium vessel and the thermal screen are assembled inside it. The helium vessel supports are attached to small columns which are welded on the outermost tube of the vacuum chamber. To avoid air pockets and slow leaks, all welds have to be on the vacuum side of the seam. That makes welding flanges difficult. The welding groove has to be machined so that the weld penetrates all the way to the vacuum side. These welds were discussed with the CERN welding group.

Section view of the vacuum chamber with the thermal screen and helium vessel inside it is shown in figure 17. Also the helium vessel top supports can be seen in the figure.

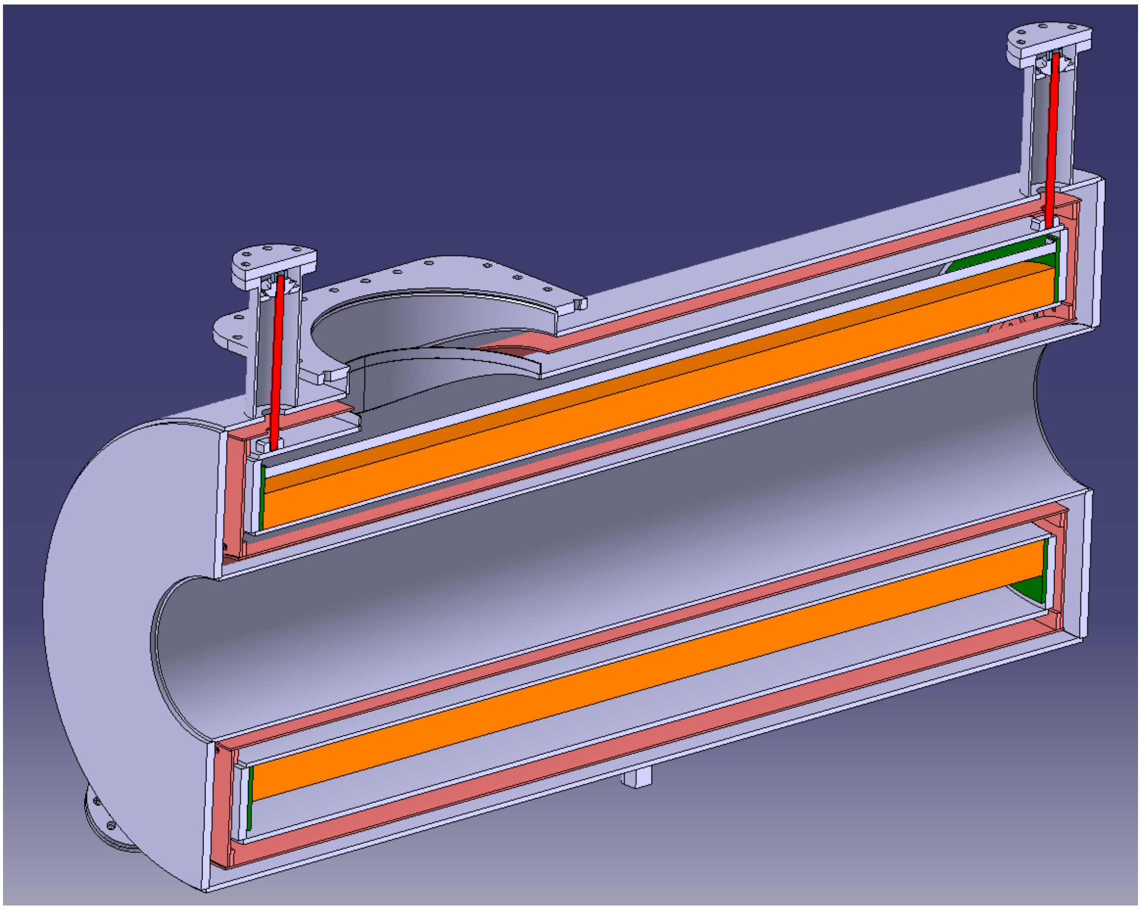

Fig. 17 Section view of cryostat

6.5 Cryocooler chimney

The most complicated part of the design was the cryocooler assembly. The cryocooler that will be used in the test station is a Cryomech PT405 two-stage pulse tube cryocooler. It has a cooling capacity of 1,5W in temperature of 4,2K and 40W at 45K. It has to be assembled on the top of the cryostat. The first stage of the cryocooler will be used to cool down current leads, instrumentation wiring and thermal screen. So there has to be an intermediate copper heatsink attached to the 1st stage and the 2nd stage has to be attached to the copper heatsink that is in the helium vessel. As the cryocooler cannot be disassembled to make the assembly easier the chimney has to be designed in such a manner that the assembly is possible. In case the helium circulation is available the cooler can be replaced with flanges that close the vacuum. In that case nitrogen cooling has to be added to the 1st stage heatsink to provide thermalisation for the wiring, thermal shield and helium pipes.

6.5.1 Round chimney

First design for the chimney was pretty similar to original HEL current lead chimney. The early version was a tube welded directly to the outermost tube of cryostat. It was quickly recognized that it would not work as it was impossible to assemble. There was multiple different flanges and seams closing at same time and there was no access to them. After some discussions and iteration windows were added to gain access to those connectors, welds and flanges.

6.5.2 Round chimney with windows

As the chimney is in room temperature, adding flanges or windows is fairly a straight forward task as a regular rubber O-ring sealing can be used. The first idea was to use round holes on the opposite sides of the chimney, as that way standard vacuum flanges could have been used. After sketching those round windows and talking with Diego Perini and Antti Kolehmainen it was decided that the windows have to be square shaped and be as wide as possible to get enough room for the assembly. Those square windows are shown in figure 18.

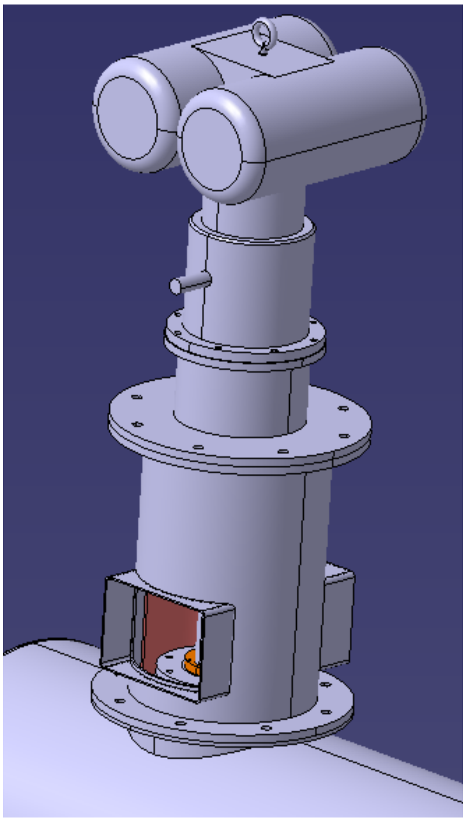

Fig. 18 Round chimney with square opening

To reduce the complexity of the chimney there was an idea to add another smaller chimney for the helium filling pipe, safety valves, current leads and instrumentation wiring and dedicating the bigger chimney just for the cryocooler (Fig. 19). The problem in the 2^{nd} chimney was that it would increase the heat load and thermalisation of wiring and piping would be difficult and inefficient as the thermal contact between them and the 1^{st} stage of the cryocooler would be too long. Therefore the 2^{nd} chimney was discarded.

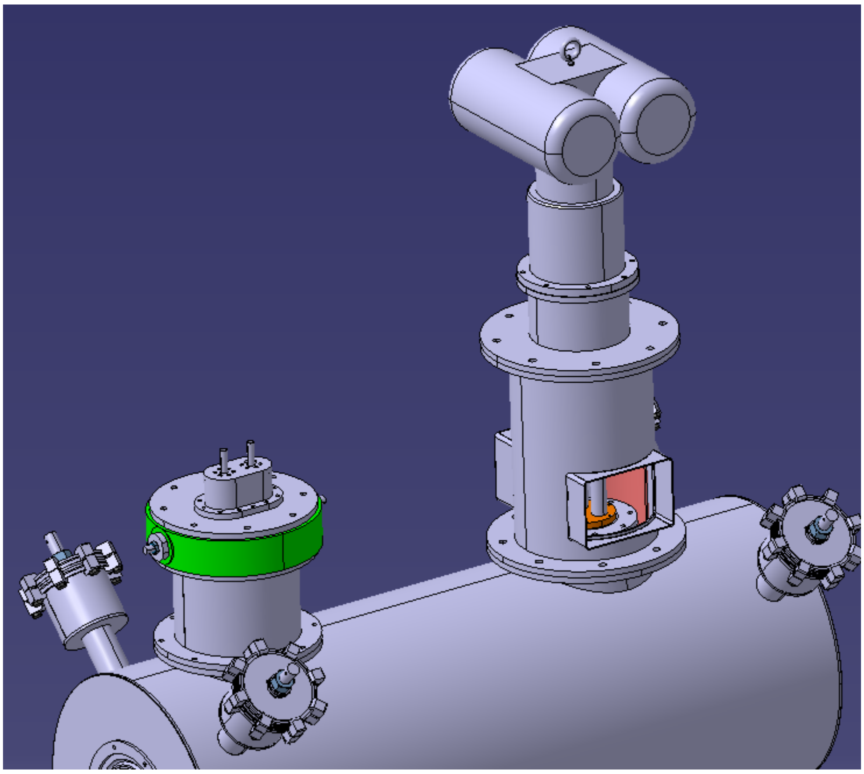

Fig. 19 Cryostat with two chimneys

The thermalisation of the thermal screen was a problem as the 1st stage of the cryocooler is fairly high in the chimney and there has to be copper claws coming from the screen to the 1st stage (Fig. 20). At this point those claws had been changed from eight small claws to two bigger ones. The problem with the copper claws was the assembly. They could not be brazed to the thermal screen before assembling the outermost tube of the vacuum chamber and there is no room to braze or bolt them afterwards. This problem could be avoided by using flexible copper braids instead of solid copper plates. The braids could be brazed on the thermal screen before the assembly and they could lay down on the screen during the assembly and then be pulled up from the chimney hole.

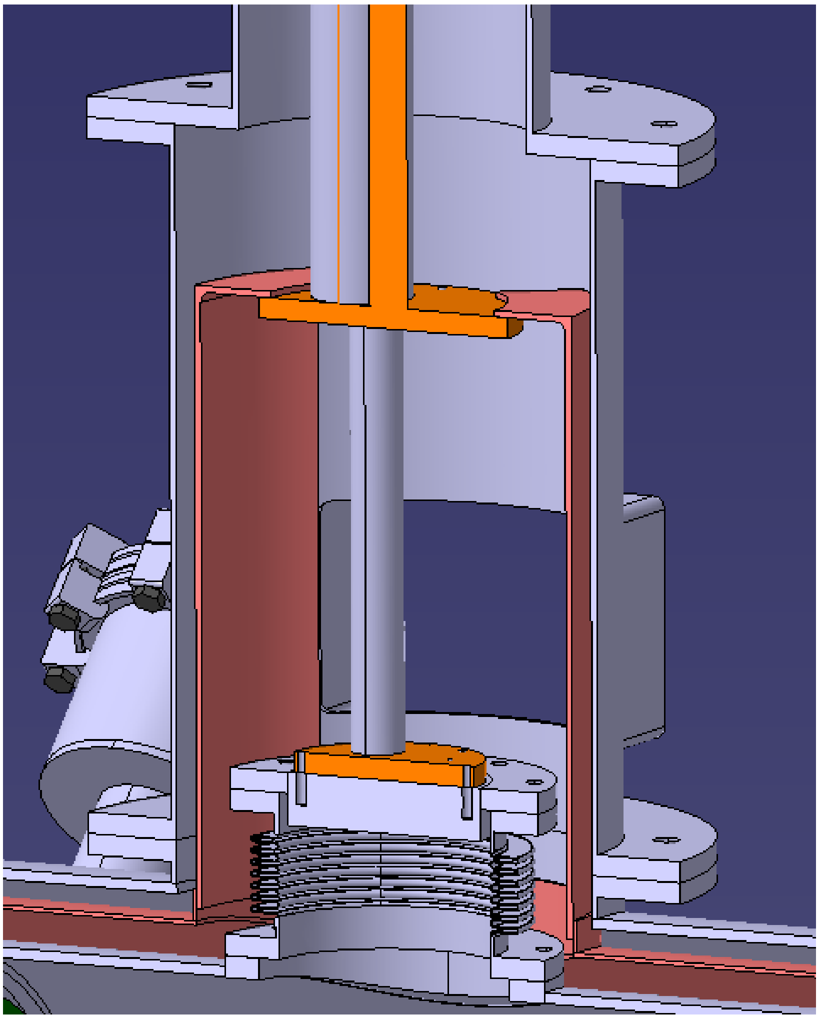

Fig. 20 Thermalisation claws of thermal screen

After solving the thermalisation of the screen, there was still not enough space for soldering the current leads nor welding the lower chimney. Increasing the diameter of the chimney would profit more space for the assembly, but it would also increase the vacuum space, prolong the pumping time and increase the heat load. To maximize the assembly space and still keep the chimney dimensions as small as possible, the round chimney had to be substituted with a square chimney. The square chimney would also be easier to shield, as the cryostat has to be shielded with a thick iron shield to contain the magnetic field.

6.5.3 Square chimney

The idea of the square chimney was to maximize the size of the windows without making the chimney itself bigger. The diameter of the hole on the top of the cry-ostat is the same as it was with the round chimney.

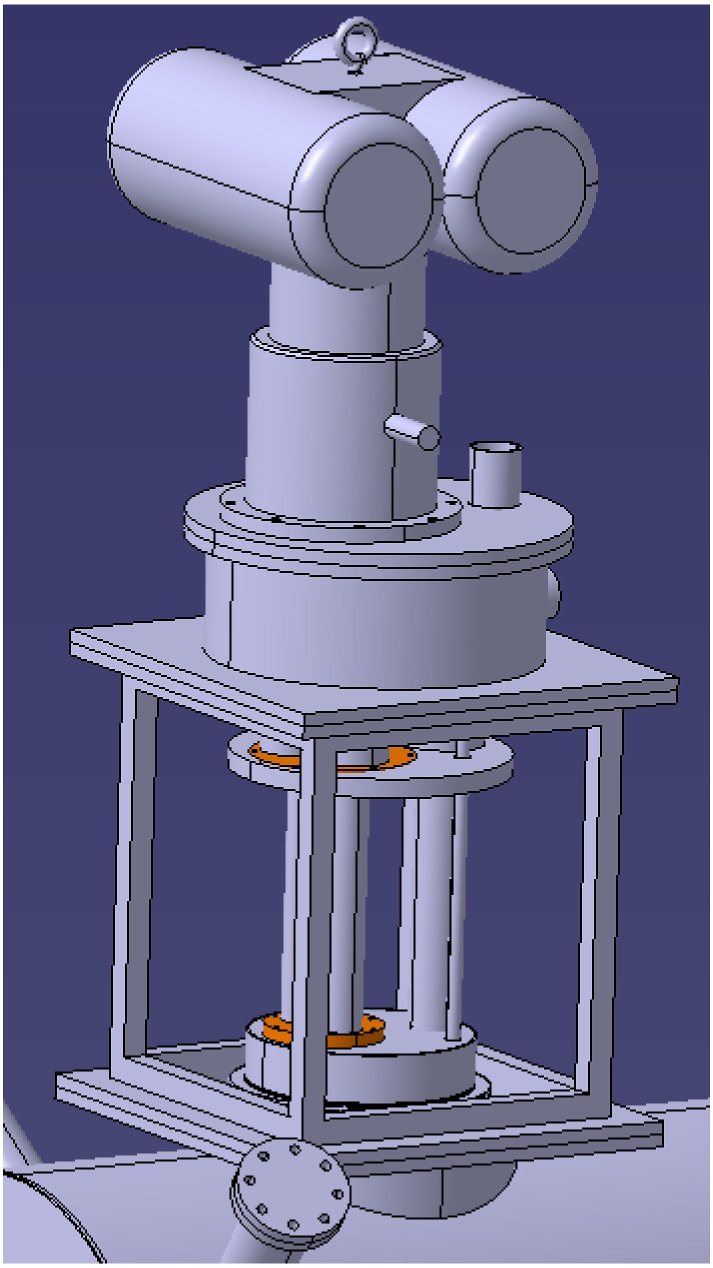

Fig. 21 Early version of square chimney

In figure 21 there is an early version of the square chimney with a short round chimney on the top flange. The idea was to reduce vacuum space by making the round part on the top. As there was not enough space for the instrumentation on the top flange, an insulation flange was added between the top flange and the chimney (fig. 22). Current lead feedthroughs were designed to be assembled to this insulation flange. The short round chimney was quickly noticed to be unnecessary and complicated and it was discarded at this point. The cryocooler would be installed directly on the top flange.

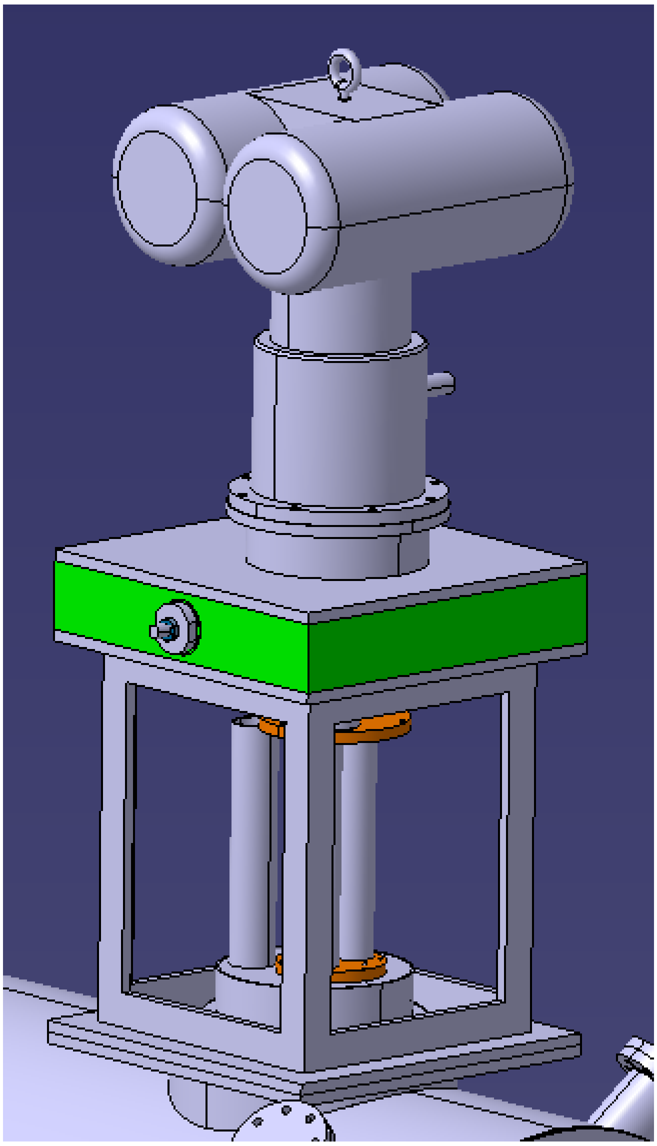

Fig. 22 Chimney with insulation flange

Without the short round chimney on the top of the square chimney, the height of the cryocooler governs the height of the column.

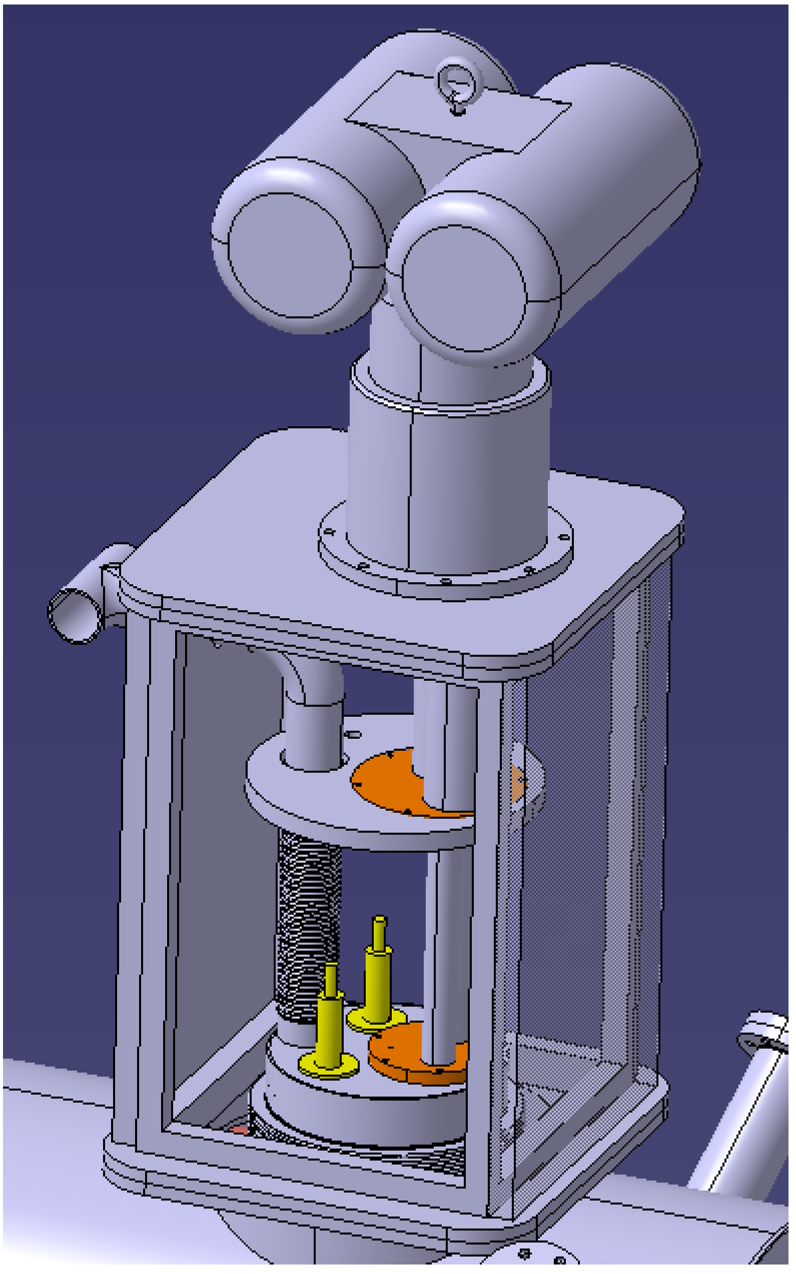

Fig. 23 Cryocooler chimney without short round chimney

In figure 23 the short round chimney has been removed. That provides enough space for the assembly and welding. The cryocooler cannot be attached in the middle of the heatsink on the helium vessel as there has to be space for feed-throughs and helium pipes (Fig. 24). The yellow feedthroughs shown in figure 24 are 250A vacuum-proof feedthroughs that are braced to the copper heatsink.

There is ceramic insulation braced on the stainless steel shell and copper connector inside it. The superconductive current leads coming from the coil are soldered on these feedthroughs before the lower chimney is welded on its place and the HTS current leads are soldered on the feedthroughs afterwards.

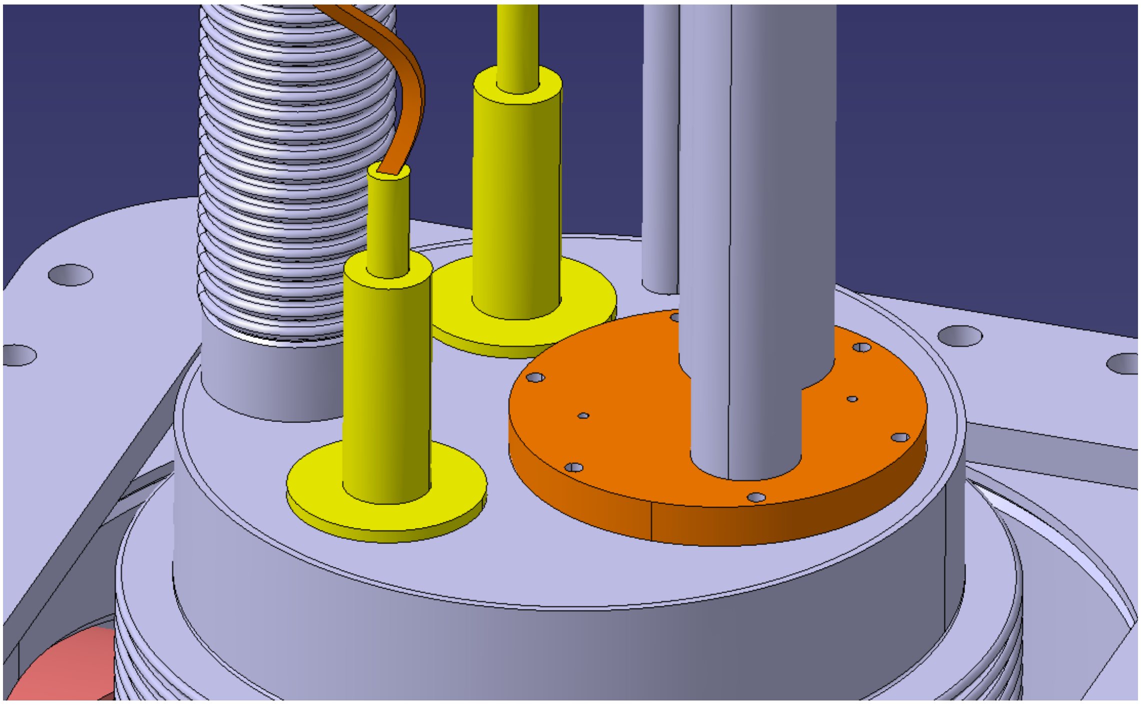

Fig. 24 Cryocooler 2nd stage heatsink and connections

As the thermalisation of wiring and piping is needed to lower the heat load caused by solid conduction every pipe and wire has to be attached to the 1st stage of the cryocooler. There is not enough space in the 1st stage itself to attach everything to it. To gain space for thermalisation a copper heatsink is attached to the 1st stage. That heatsink is shown in figure 25.

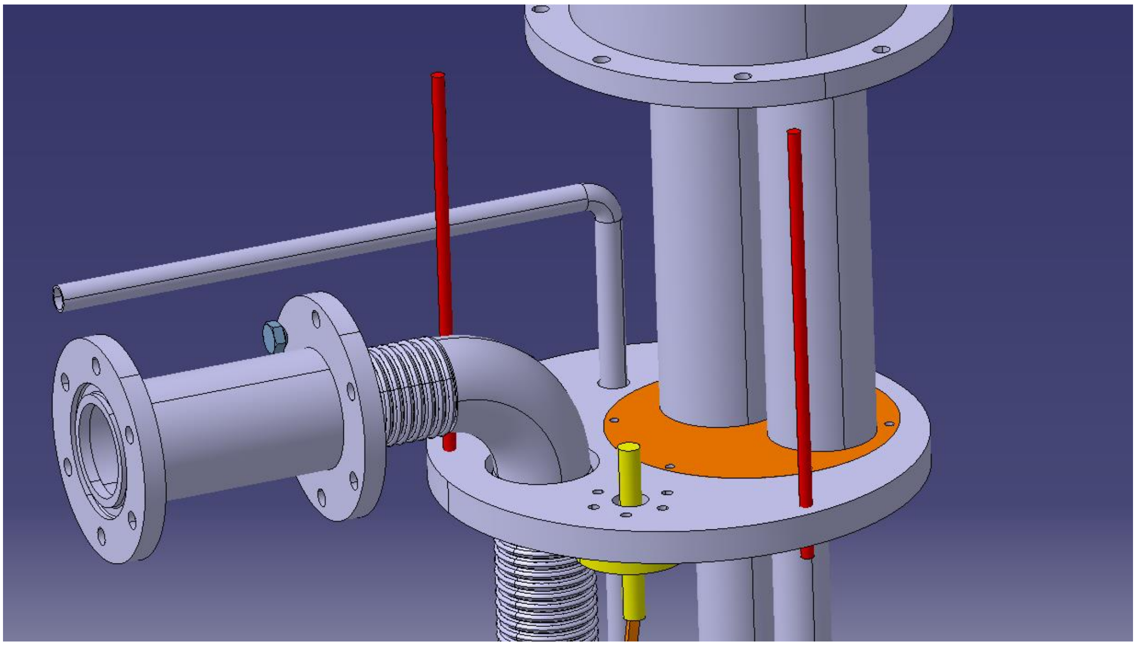

Fig. 25 Cryocooler 1st stage heatsink and connections

The red rods shown in figure 25 are made of the same Permaglass that is used in the helium vessel support rods. They are used to support the heatsink in order to avoid forces from bending the cryocooler.

There are two helium pipes in the test station. One for filling and another one for a safety valve. There is no helium vapor evacuation as it is a closed circulation and vapor is condensed back to liquid helium with the cryocooler. A helium out pipe is also used for the instrumentation cables, vaporized helium provides cooling to these cables. That is why there is a T-branch at the end of the helium out pipe (Fig. 26). The filling tube is number 1 in figure 26 and the helium out pipe is number 2.

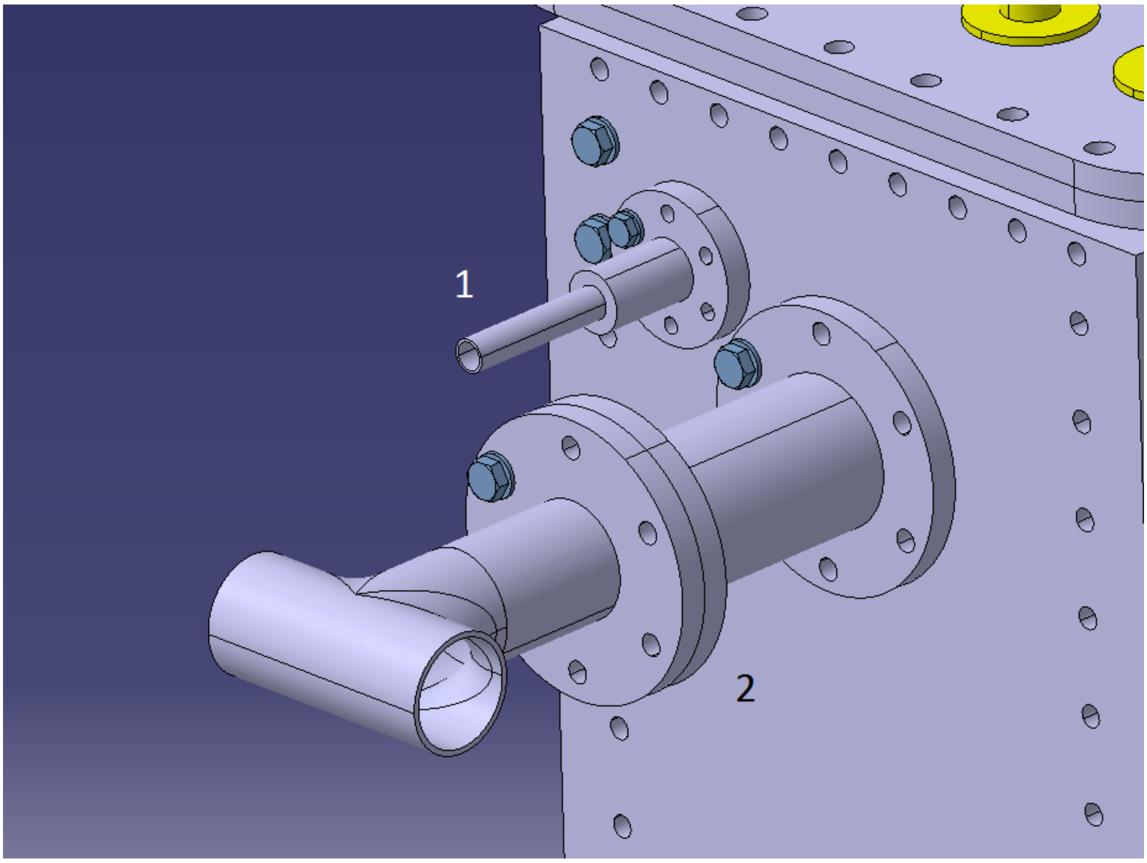

Fig. 26 Helium pipes

Long bellows in the helium out pipe has two purposes; it will reduce stress caused by thermal contraction and it also increases length and that way, as stated in equation 2, decreases thermal conduction.

As the chimney side flanges are 20mm thick iron to shield the surroundings from the magnetic field, the stainless steel pipes cannot be directly welded to the flange. Also if the flange has to be opened it is better to have pipes bolted to the flange. To gain a vacuum tight sealing between the pipes and the flange a secondary stainless steel flange is used between them. The structure is shown in figure 27 where the weld between the helium out pipe and flange is illustrated with red.

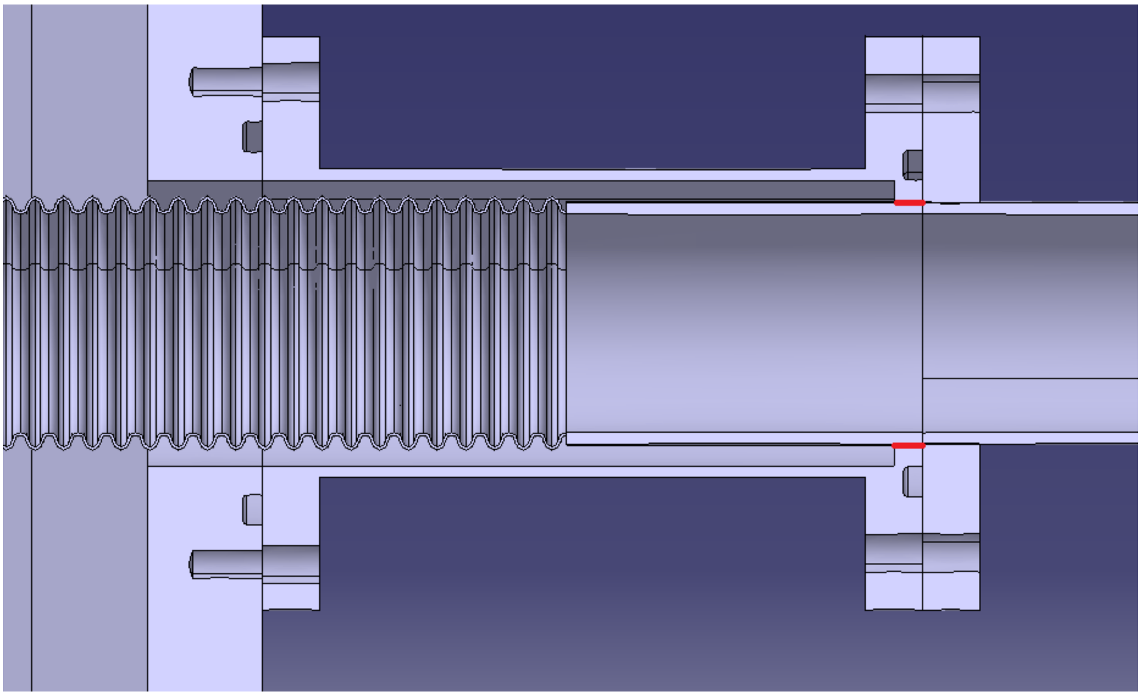

Fig. 27 Helium out pipe connection to flange

The stainless steel flange is bolted to the iron flange and sealed with an O-ring. The helium out pipe is welded to the other end of that pipe and T-branch is bolted to this flange and sealed with an O-ring. The helium in pipe has a similar structure but in a smaller scale as there is no need for the second flange as the filling tube is attached only when the helium vessel is filled and it is closed after that. For filling and closing there are specific devices. Both helium pipes are brazed to the cryocooler 2nd stage heatsink (Fig. 24) and both are attached to the 1st stage for thermalisation (Fig. 25).

6.6 Assembly

Assembly of the test station is relatively complicated and has multiple steps and sub-assemblies. In this chapter all the steps will be explained. It may be necessary to use temporary covers to make sure that no bolts, nuts or tools is dropped inside the vacuum chamber as they could be difficult, or even impossible to remove from there without opening the vessels.

6.6.1 Helium vessel assembly

As the inner tube of the helium vessel is also the coil support and it acts as the spool for winding, it has to be prepared first. The inner tube is made of a 6mm thick 304 stainless steel tube, the outer diameter of the tube is 234mm and the length is 1018mm. Before the flanges can be welded on the inner tube, a 2mm deep groove (Fig. 28) has to be machined on both ends of tube.

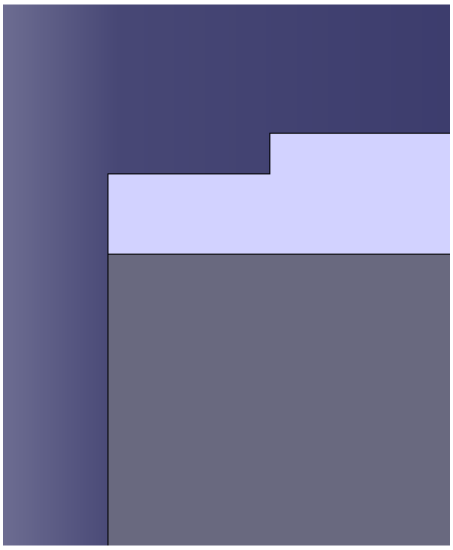

Fig. 28 Helium vessel inner tube machining before welding end flange

After machining the grooves, 12mm thick 304 stainless steel end flanges are fitted on their place and welded as shown in figure 29. The red area number 1 is the weld. A fillet weld is used instead of a flat weld to ensure good vacuum tight welding. Yellow surfaces in the figure 29 are machined after welding. That is done in order to eliminate possible deformation caused by a heat input. The surface quality and cylindricality of the tube and perpendicularity of end flanges are crucial aspects for a good winding quality.

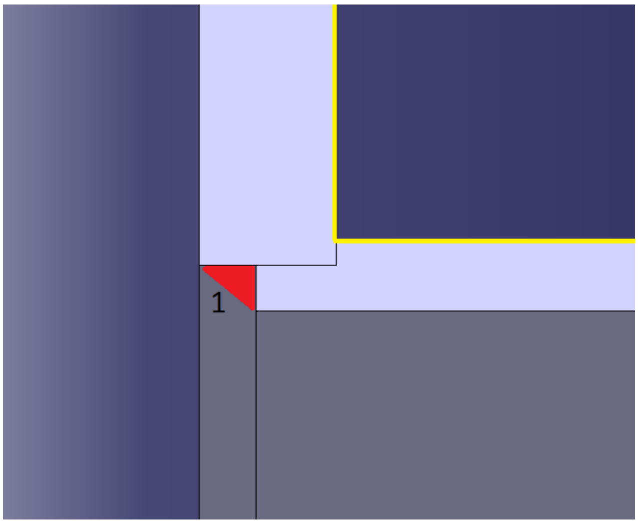

Fig. 29 Helium vessel inner tube and end flange after welding

After machining (Fig. 30) the thickness of the tube is 4mm and the flange is 10mm. Next step is winding the coil. After that is done the current lead support rod can be assembled and the current leads prepared for soldering before the vessel is closed (Fig. 31).

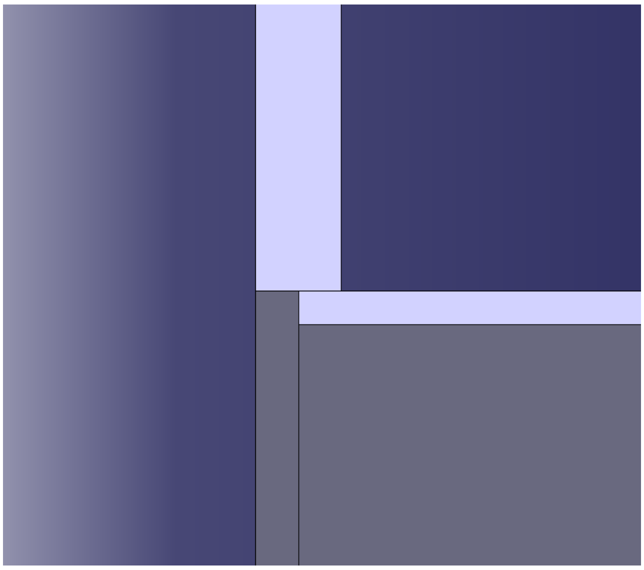

Fig. 30 Helium vessel inner tube and end flange after machining

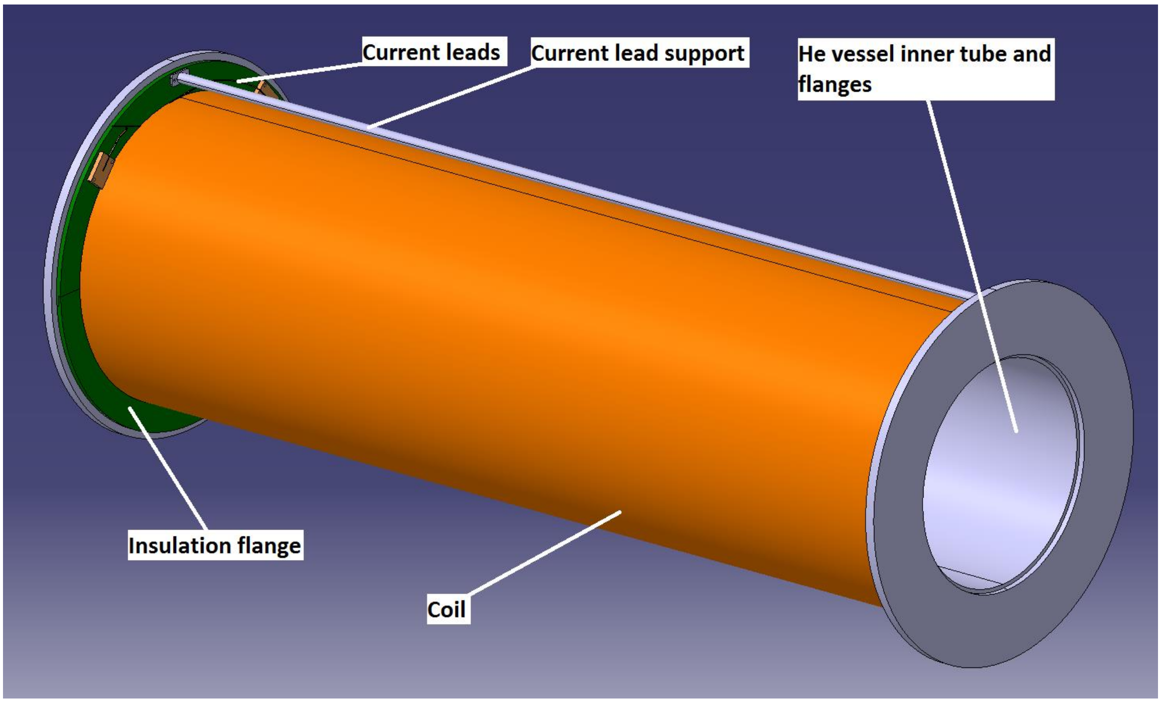

Fig. 31 Coil before helium vessel is closed

After the current leads are prepared the outer tube of the helium vessel is slid on its place and welded, leaving the hole on the top of the helium vessel the only access inside (Fig. 32).

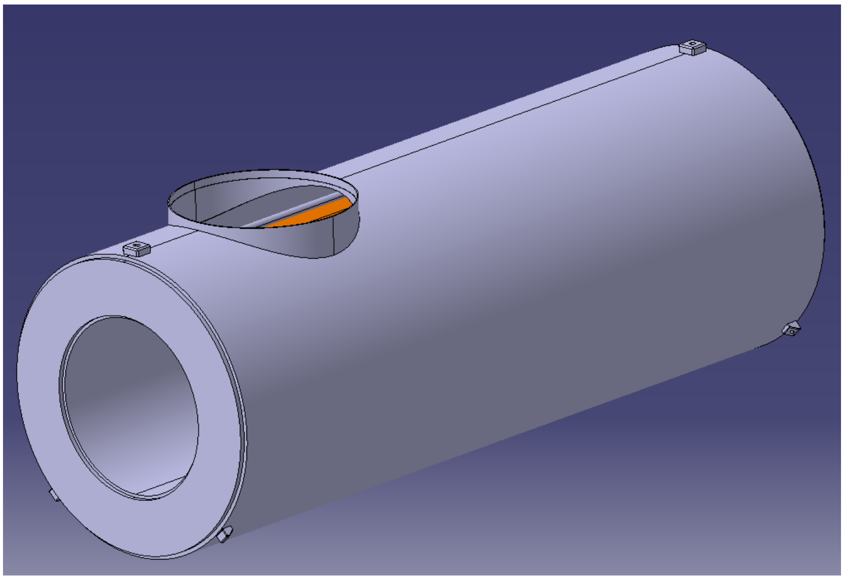

Fig. 32 Closed helium vessel

The short tube on the top of helium vessel (Fig.32) is welded on its place before assembling the outer tube as if it was welded after assembling the outer tube there would be a risk that a spark flies inside the vessel and damages the coil. Also threaded mounting blocks for support rods are welded on the outer tube before assembly.

6.6.2 Thermal screen assembly

The outer halves of thermal screen have to be assembled around the helium vessel before the vessel can be assembled to the vacuum chamber, as the support rods pass through the screen and support the screen as well as the helium vessel. The screen is locked on its place with nuts. The inner halves of screen cannot be assembled before the helium vessel is supported with the rods as it has to be supported from the inner tube while being assembled to the vacuum chamber. After the helium vessel is on its place in the vacuum chamber, the inner halves are bolted together with the insulators and slid into the helium vessel inner tube and then the end plates are bolted in place. The end plates hold the inner tube of thermal screen on place. The section view of thermal screen assembly is shown in figure 33. Originally the end plates were made of two halves but with smaller end plate sectors the assembly is easier as now the inner tube can be supported with one or two end plate sectors on each end and the adjustments can be done e.g. on a multilayer insulation.

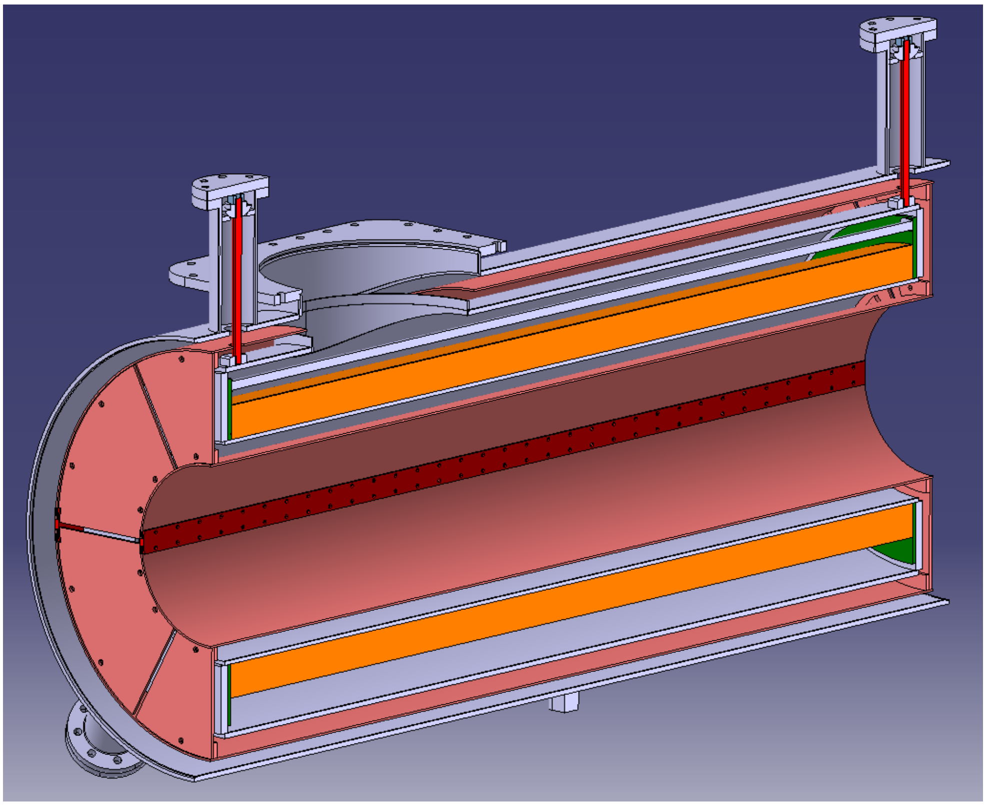

Fig. 33 Thermal screen assembly

6.6.3 Vacuum chamber

The outer tube of the vacuum chamber has to be prepared before the helium vessel and the thermal screen can be assembled inside it. The columns for the support rods have to be assembled and welded to the outer tube and the cryocooler chimney flange has to be welded. After they are assembled, the helium vessel and thermal screen can be assembled inside the vacuum chamber. The helium vessel has to be aligned at this point and references have to be done outside the vacuum chamber, if they are considered necessary for the test station, as the alignment can be fine-tuned afterwards with the alignment of the beam tube. In the HEL those references are necessary as it has to be aligned to the LHC beamline. The closed vacuum chamber is shown in figure 34.

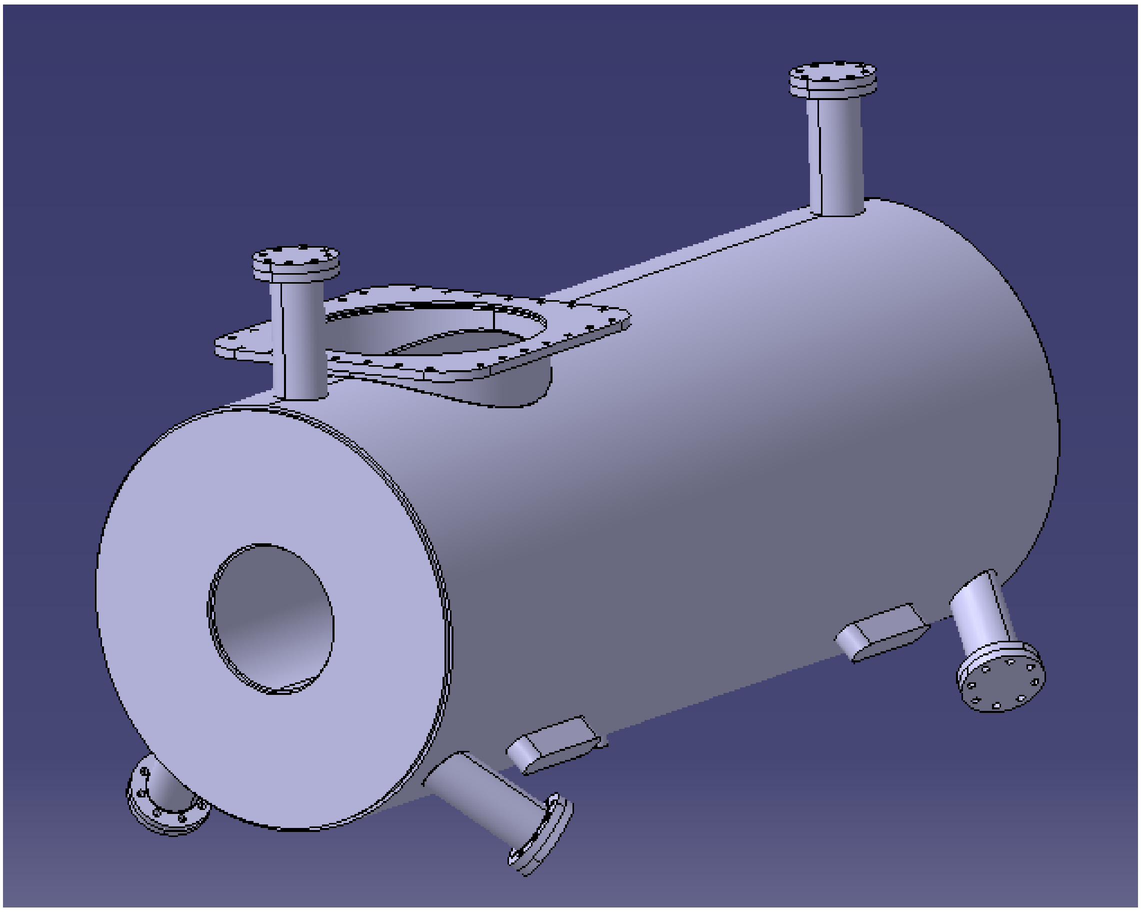

Fig. 34 Vacuum chamber assembly

When everything inside the vacuum chamber is assembled and aligned, the inner tube and end flanges are welded in place and the vacuum chamber is closed. Also the multilayer insulation has to be added before closing the vacuum chamber. As the welds have to be on the vacuum side of the structure and some of them cannot be done from inside, there are some special requirements for all welds. (Brachet, Claret, Favre, Perini & Kolehmainen 2015.)

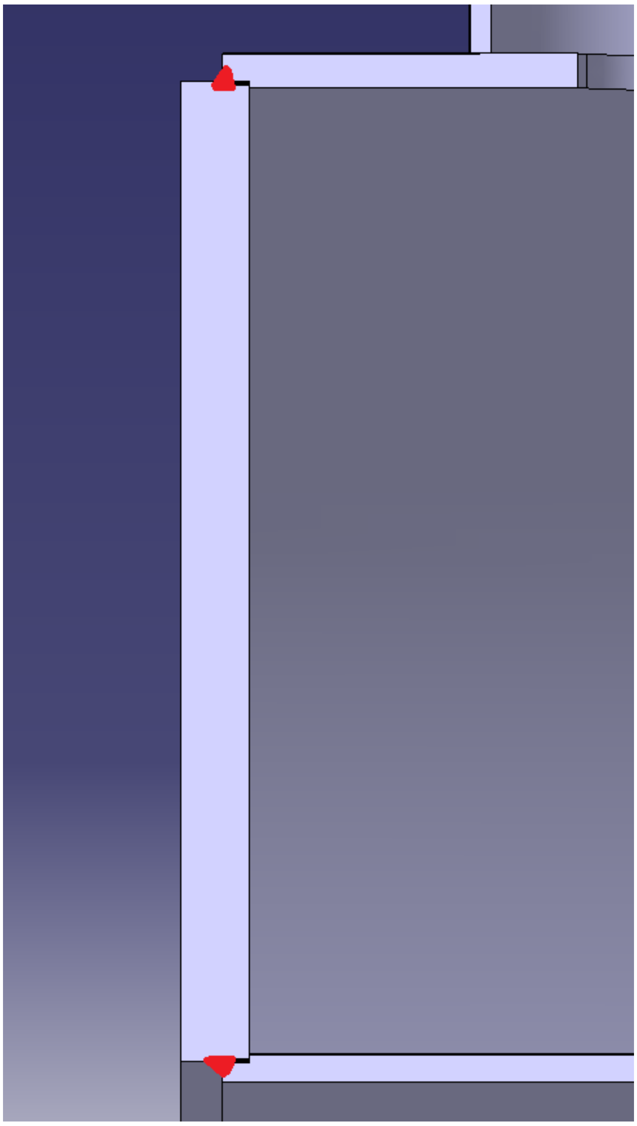

Fig. 35 Vacuum chamber end flange welds

In figure 35 the red areas show the end flange welds. To avoid tight gaps forming air pockets or slow leaks there has to be a large enough airgap between the flange and vacuum chamber tubes. That way the bead can penetrate deep enough to reach the vacuum side. (Brachet et al 2015.)

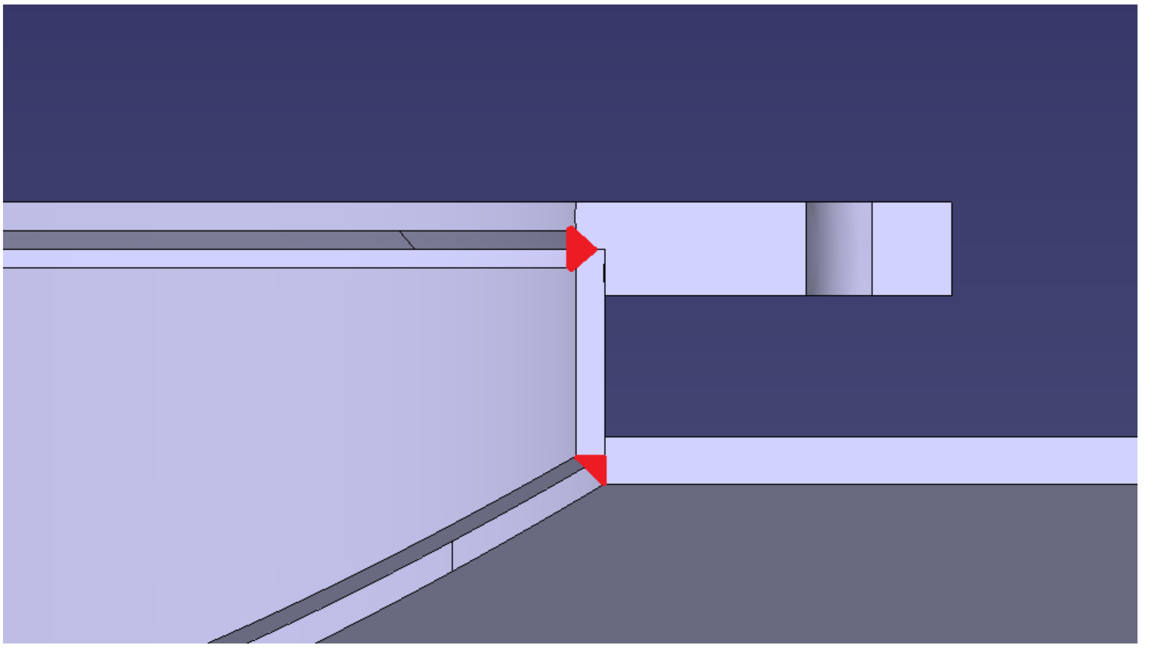

Fig. 36 Vacuum chamber top flange welds

In figure 36 the structure and welding of lower flange of the cryocooler chimney is shown. As it is welded before assembling the helium vessel or thermal screen, the welds can be done from inside. The red areas in figure 36 illustrate the welds. (Brachet et al 2015.)

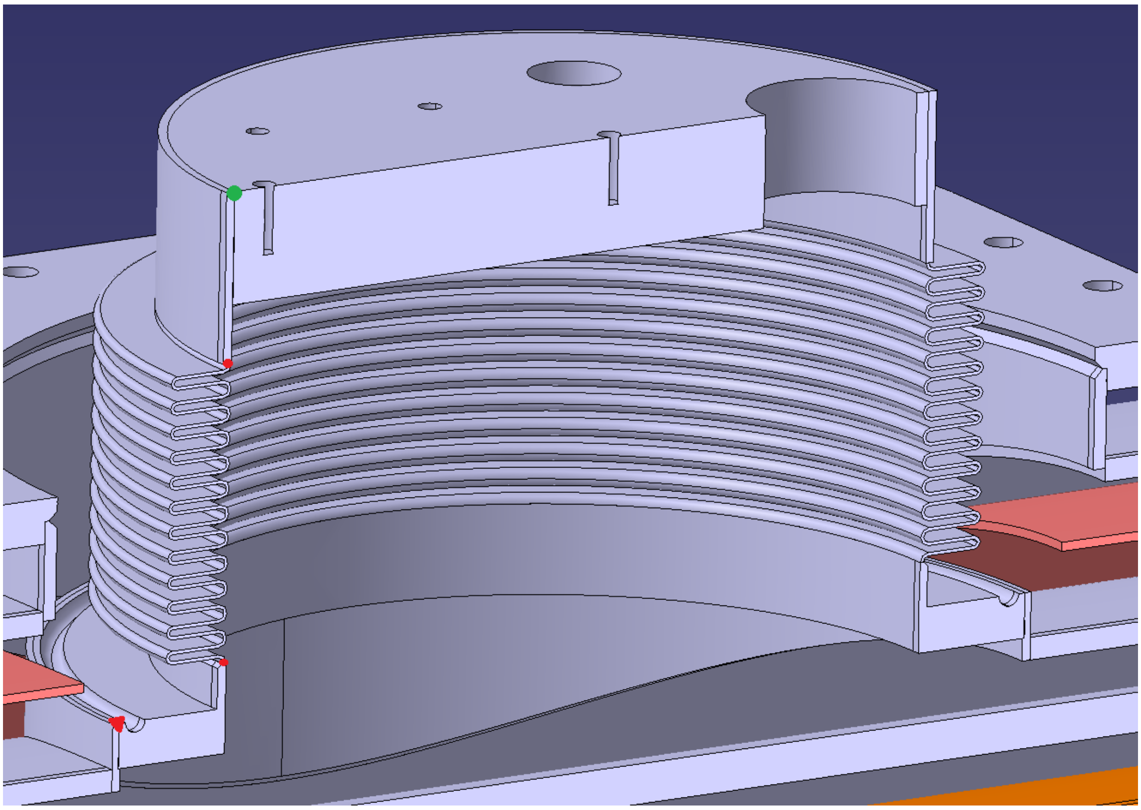

Fig. 37 Lower chimney welds

The lower chimney has to be assembled at this point when the helium vessel is inside the vacuum chamber. Bracing between the copper heatsink and stainless steel bellows, green in figure 37, is done before assembling the lower chimney. Bellow welds are also done beforehand. Welding the lower chimney on the helium vessel is difficult and it requires TIG welding with a special long electrode and electrode holder. As there is no space for applying a welding wire the shape of the groove is done such way that there is enough material to melt (Fig. 38).

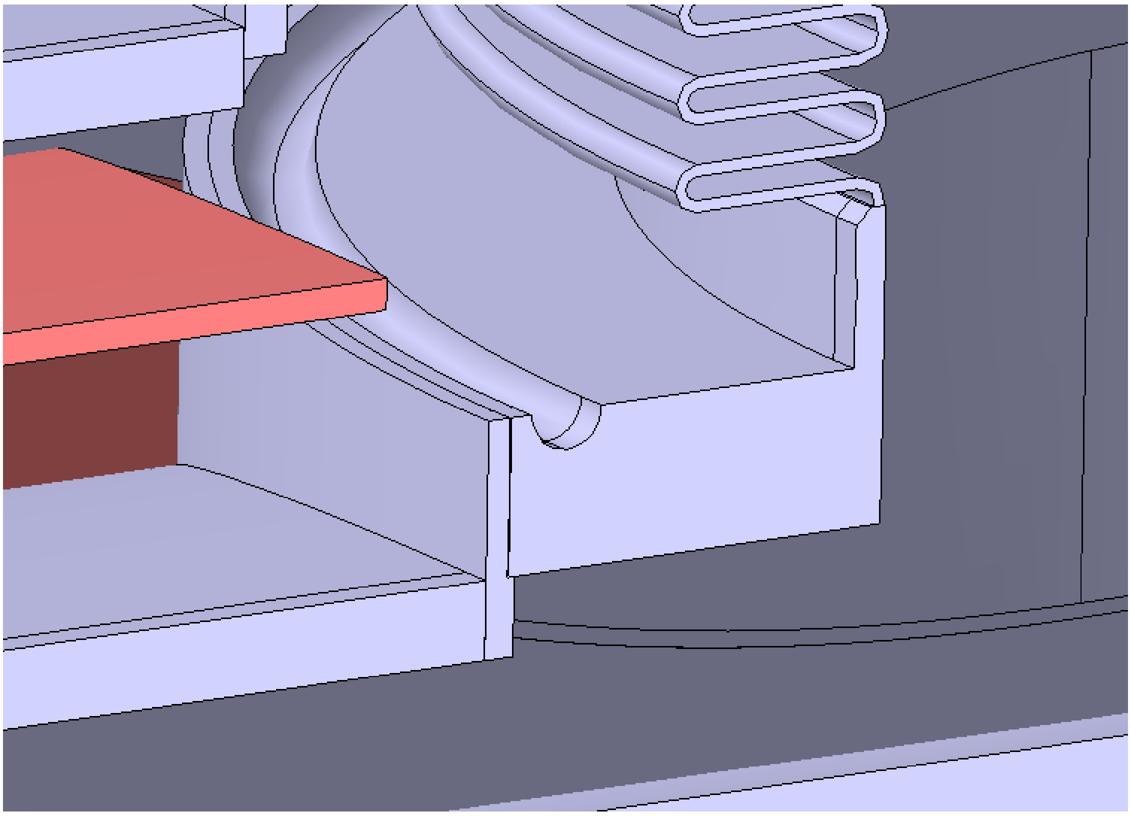

Fig. 38 Lower chimney welding groove

6.6.4 Cooler chimney

The cryocooler chimney consists of the chimney itself and all the instrumentation and so the assembly has multiple steps. First the chimneys parts have to be manufactured and welded together. The top and bottom flanges are identical. Sidewalls have two bigger sides and two smaller sides. As they have to be welded and there cannot be 45 degree fillets on the sides because the bolt holes would penetrate through the fillets and each other. To avoid that, two sides are narrower than the other two. That way there is enough room for bolt holes and sealing grooves (Fig. 39). The side flanges are made of 20mm thick steel. Sealing surfaces have to be machined to obtain good sealing. After machining the sealing grooves and hole patterns and threading the holes, the side walls are ready to be welded together with the top and bottom flanges. All welds can be done from inside and they are on the vacuum side. As the chimney is in room temperature regular O-ring sealing can be used and the side flanges can be opened and closed multiple times if necessary.

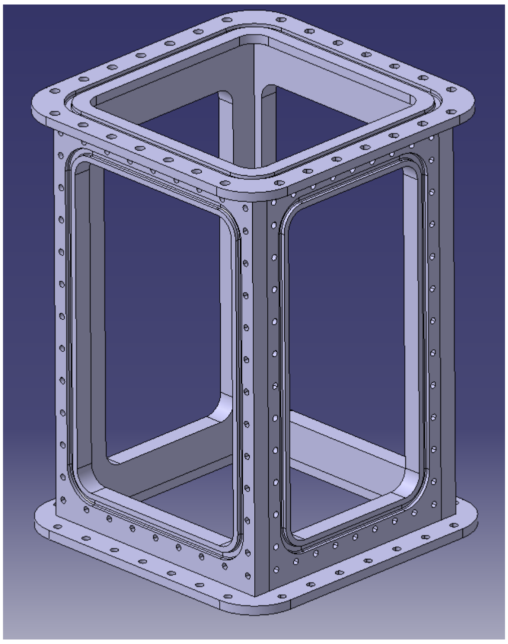

Fig. 39 Chimney structure welded together

When the chimney “cage” is welded together it can be bolted on the vacuum chamber and the instrumentation can be assembled. First the helium pipes have to be fitted through the 1st stage heatsink and brazed to the 2nd stage heatsink (Fig. 40).

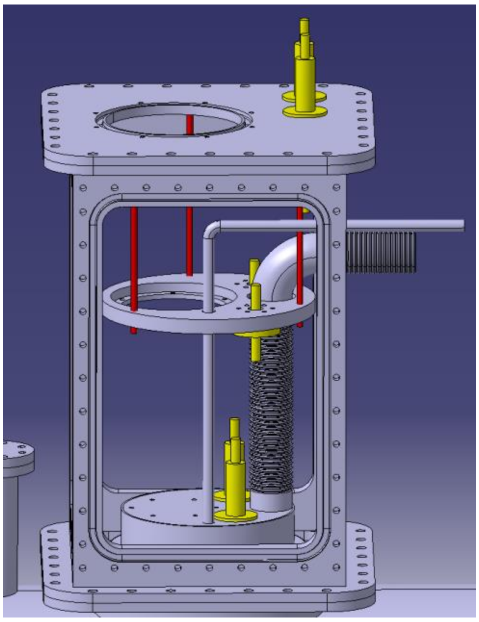

Fig. 40 Chimney assembly before cryocooler assembly

Before the cryocooler is lowered down to its place and attached to the heatsinks, the side flange on helium pipes side of chimney has to be closed and the helium pipes have to be welded on the flange as described earlier. The thermalisation of the helium pipes cannot be done before the cryocooler has been assembled, as the 1st stage heatsink has to be adjusted correctly to ensure thermal contact between the 1st stage and heatsink. HTS current leads can be soldered on the feed-throughs before that because there will be some extra wire to compensate thermal contraction and at the same time to lower the heat load as longer the wires are lower the solid conduction.

The cryocooler is lowered on its place and sealed to top flange with an O-ring. Both stages are bolted to their heatsinks and good thermal contact is ensured (Fig. 41).

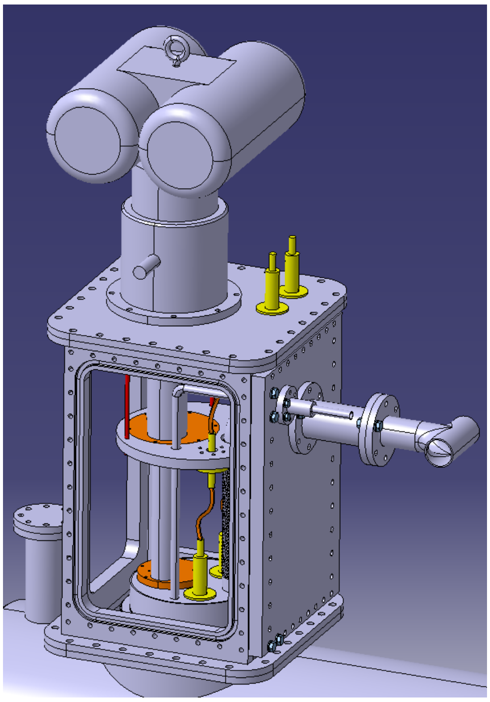

Fig. 41 Cryocooler chimney assembly

At this point possible covers are removed, all connections are checked, and MLI is added. After that the remaining flanges are closed and vacuum can be pumped. At this point the design is still missing connections for the vacuum pumps as the final design determines where those connectors will be positioned.

7 DESIGN

All the design work was carried out with the CATIA V5 and file management with Smarteam. Both are products of Dassault Systèmes. CATIA is used at CERN to make all the official models and drawings and for that reason not everybody has access to it. All official models and drawings are saved through the Smarteam file management. In some departments Autodesk software is used to make models, drawings and simulations that are not final and cannot be saved on the Smarteam. As Autodesk has no access to the file management system, it does not require privileges from the user and it is easier to access for users who do not need it on a daily basis.

7.1 CATIA

The name CATIA comes from French words Conceptio Assistée Tridimensionelle Interactive. It was originally designed by a French aircraft manufacturer Avions Marcel Dassault to be used in-house for aircraft designing. In 1981 Dassault Systèmes was created to design 3D designing software and in the same year CATIA was launched. Since then CATIA has been the cornerstone of the Dassault Systèmes products. The fifth version of CATIA, CATIA V5, was initially launched in 1999 and it is still widely used, even though the V6 has been on market since 2008. Alongside with the CATIA Dassault Systèmes has a wide range of other software for modelling, simulation, file management etc. and together they form a platform called 3DEXPERIENCE. (Dassault Systèmes 2015.)

7.1.1 CATIA V5 User Interface

CATIA has multiple different workbenches which all have their own use. In this work mostly sketcher, part design and product design workbenches were used. Altogether there are almost 100 different workbenches, e.g. weld design, mold design, machining workbench, simulations etc. CERN has its own version of The

CATIA UI that has some differences if compared to the normal CATIA V5 UI. In figure 42 the original CATIA V5 part design workbench is shown and in figure 43 is the CERN version of the same workbench. There are some minor differences in the layout but all tools and functions are the same. The CERN version has the planes and coordinates hidden by default as the CERN modelling rules say that there should be no planes nor coordinates visible in the final models or products. (Dassault Systèmes 2015.)

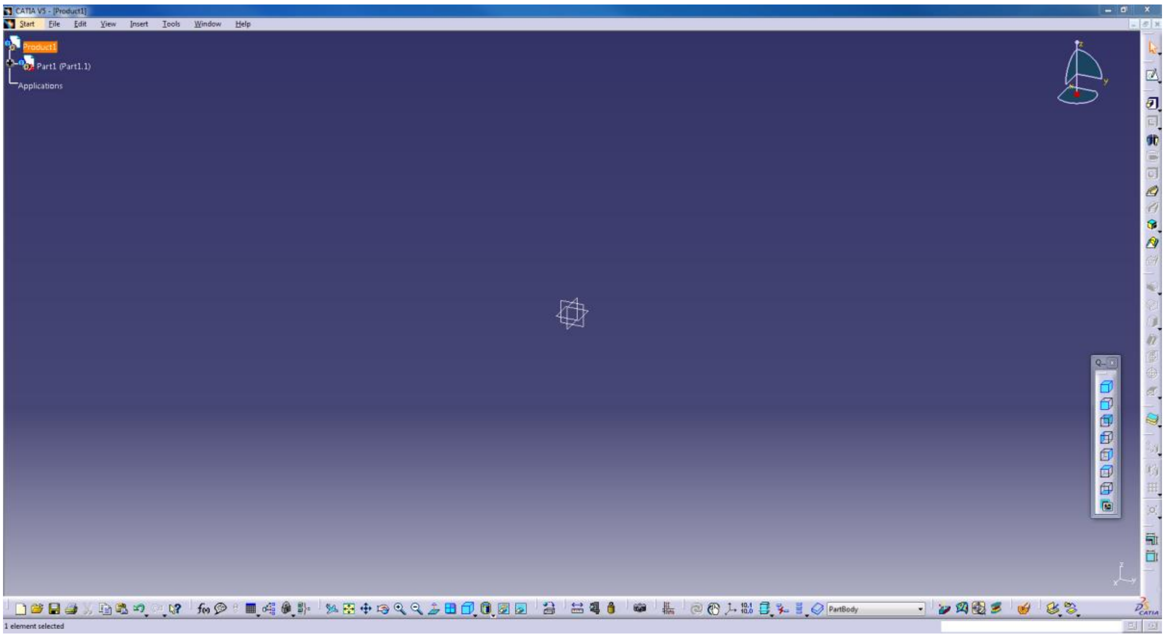

Fig. 42. CATIA V5 original part design workbench

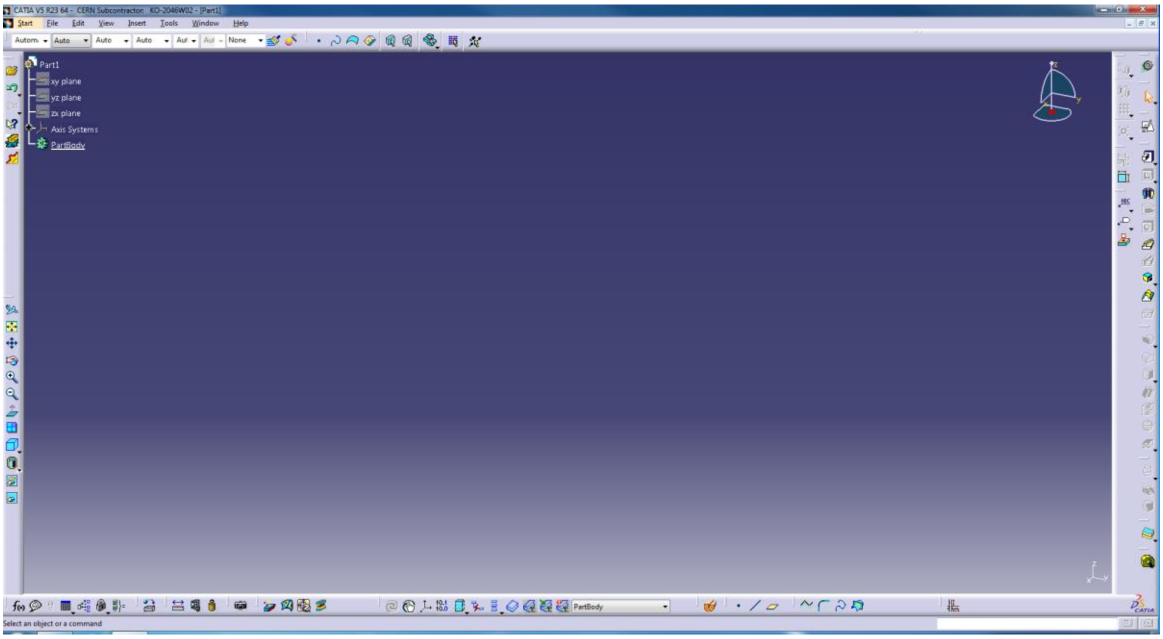

Fig. 43 CATIA V5 CERN part design workbench

7.1.2 Part design

In part design workbench a new part body is created by first creating a 2D sketch in a sketcher workbench and then extruding the 3D body in the part design workbench. In one part there can be multiple bodies. Those 3D bodies form one solid part.

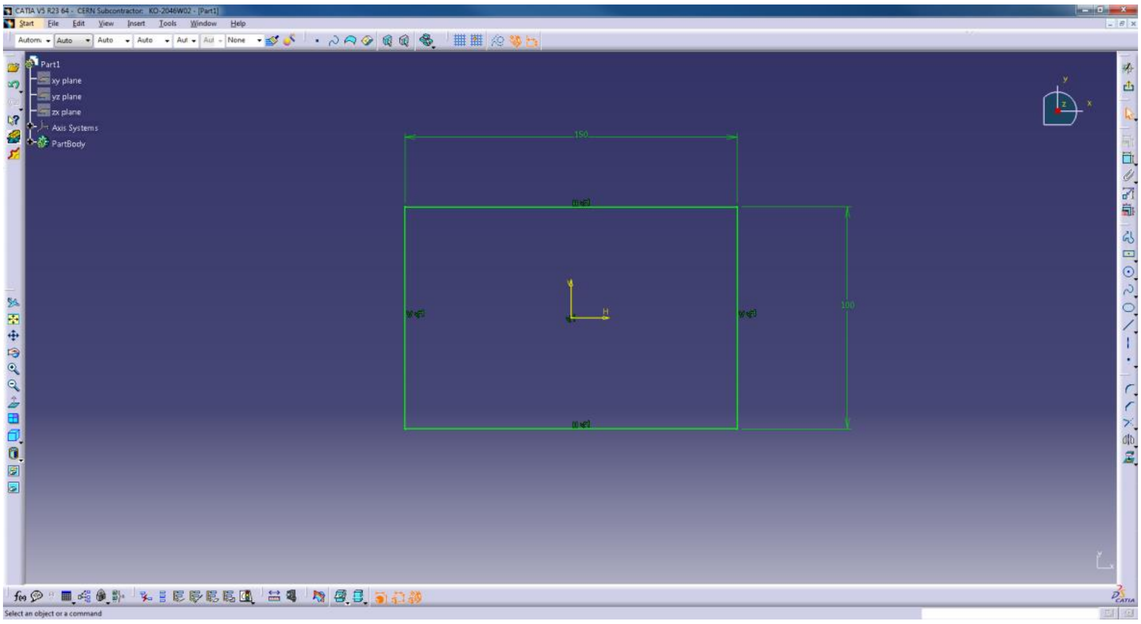

Fig. 44 CATIA Sketcher workbench

The sketcher workbench is a 2D workbench that is used to define shapes to be added or removed from the part body. The dimensions of the shape are added to the sketch but they are not be visible in the body (Fig. 44).

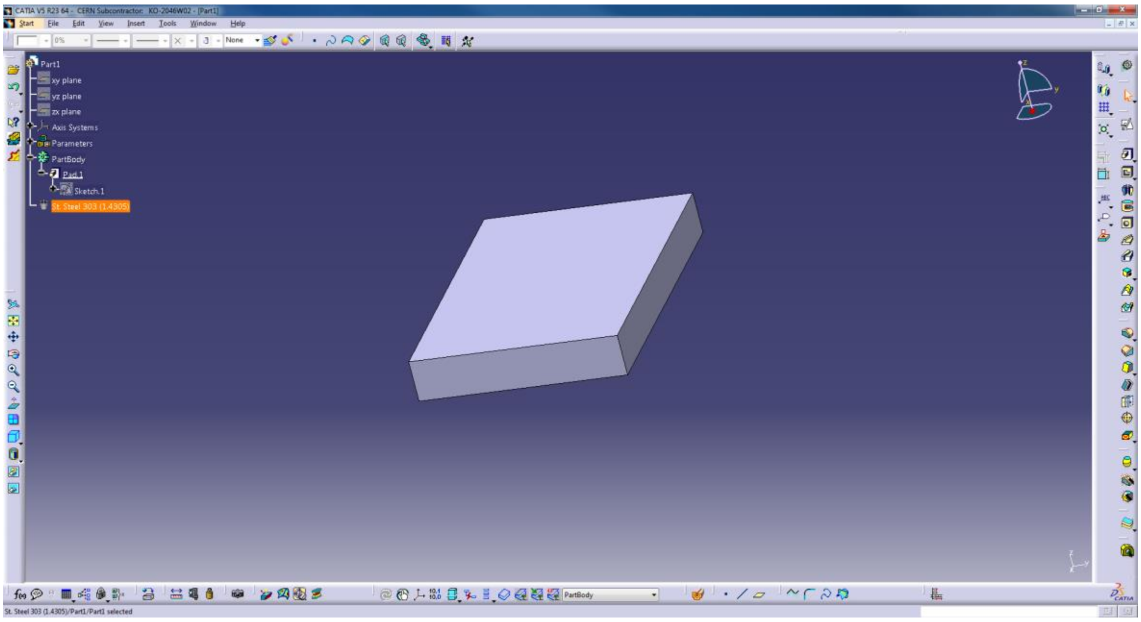

Fig. 45 CATIA part design workbench

Tools in the part design workbench use the sketch, for example a pad tool extrudes the shape and creates the part body (Fig. 45). That body is then modified and given all the necessary parameters, for example material, to achieve the part wanted.

At CERN all parts are modelled separately and no product is made from a solid body. That way accurate data can be gained from the product before manufacturing. For example the CATIA can calculate the weight of the final product and simulations can be done to assure the functionality of the product when everything is done correctly.

7.1.3 Product design

In the product design workbench parts are brought together and constrained to form a product. When everything is done correctly the product can be used for simulations, the bill of materials can be pulled together and transferred to drawings. The product design workbench is shown in figure 46.

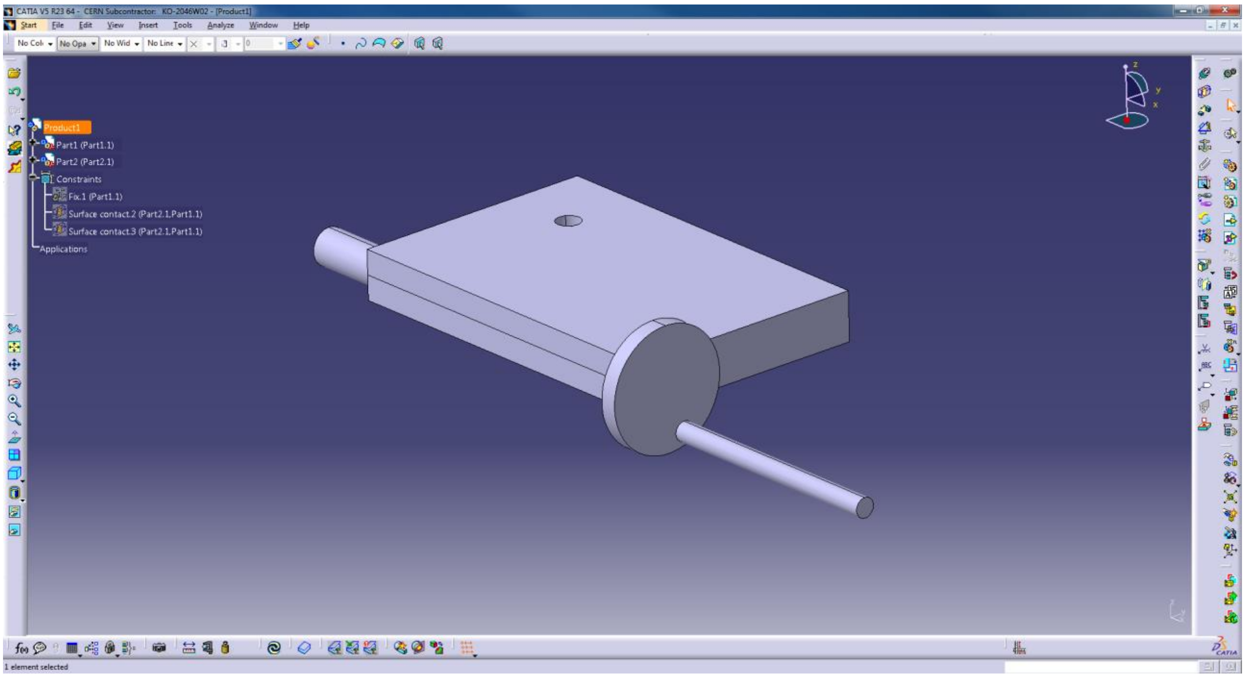

Fig. 46 CATIA Product design workbench

7.2 Smarteam

Smarteam is the file management system used at CERN. It is software made by Dassault Systèmes and it works like a cloud service where users save all the created designs. At CERN to access Smarteam the employee has to have privileges given by the CAD support.

Smarteam automatically gives new documents an ST number which is used to identify documents. When creating a new document it has to be defined who has access to it. Usually there is a team made for the particular project and in that team there are all the engineers and designers who need to have access to those particular files. If no team is defined only the person who created the file can modify it. Other people can open it in read-only state and use it as part of other products but only the authorized persons can modify it.

With Smarteam it is made sure that the file management is unified and every document is made correctly in order to maintain the high quality of design work.

8 DISCUSSION

The goal of this thesis work was to make the pre-design 3D models of the HEL test station cryostat. The focus was on making detailed models that show the structure and solve possible mechanical problems that may occur in the implementation of cryocooler.

A multitude of problems were encountered and solved and after many iterations the 3D model is in the state where it can be used to design the instrumentation and develop the test station further. The results could have been even better if co-operation between the departments would have been more frequent, but the pre-design as it is can now be designed towards the direction needed to obtain goals that are defined by the end-users of the test station. Future will show how this project will develop.

Work carried out in this thesis was very educating as it was not just 3D modelling, it contained multiple different fields of science that had to be taken into account. Modelling itself was not so challenging, but figuring out how to solve the problems in a functioning manner was sometimes difficult and required some trial and error.

As using the cryocooler in this kind of solutions is not very common, this thesis could provide information for future projects, but the lack of calculations and verified results degrade the value of this work as a sole source of information. The calculations and simulations will be done in CERN after the design is finalized. Combined with those results this thesis could be much more useful for future projects as then solutions used in this cryostat can be evaluated and possibly compared to other solutions as the design is just one of many possibilities.

This work could be continued in other theses works or projects studying the calculations, simulations. After the test station has been built the pre-design done in this thesis could be compared to the final test station which may be quite different after all necessary instrumentation has been implemented.

This thesis as part of the internship may be the beginning of ongoing co-operation with our school and CERN and one aspect of making this thesis was to provide information to other students going to work at CERN. Evaluating the usefulness of information contained in this thesis has to be done by the reader. For someone going to CERN to do internship, this thesis might not provide much information about important practical matters, but it provides knowledge about the HEL project for students who may work on the project.

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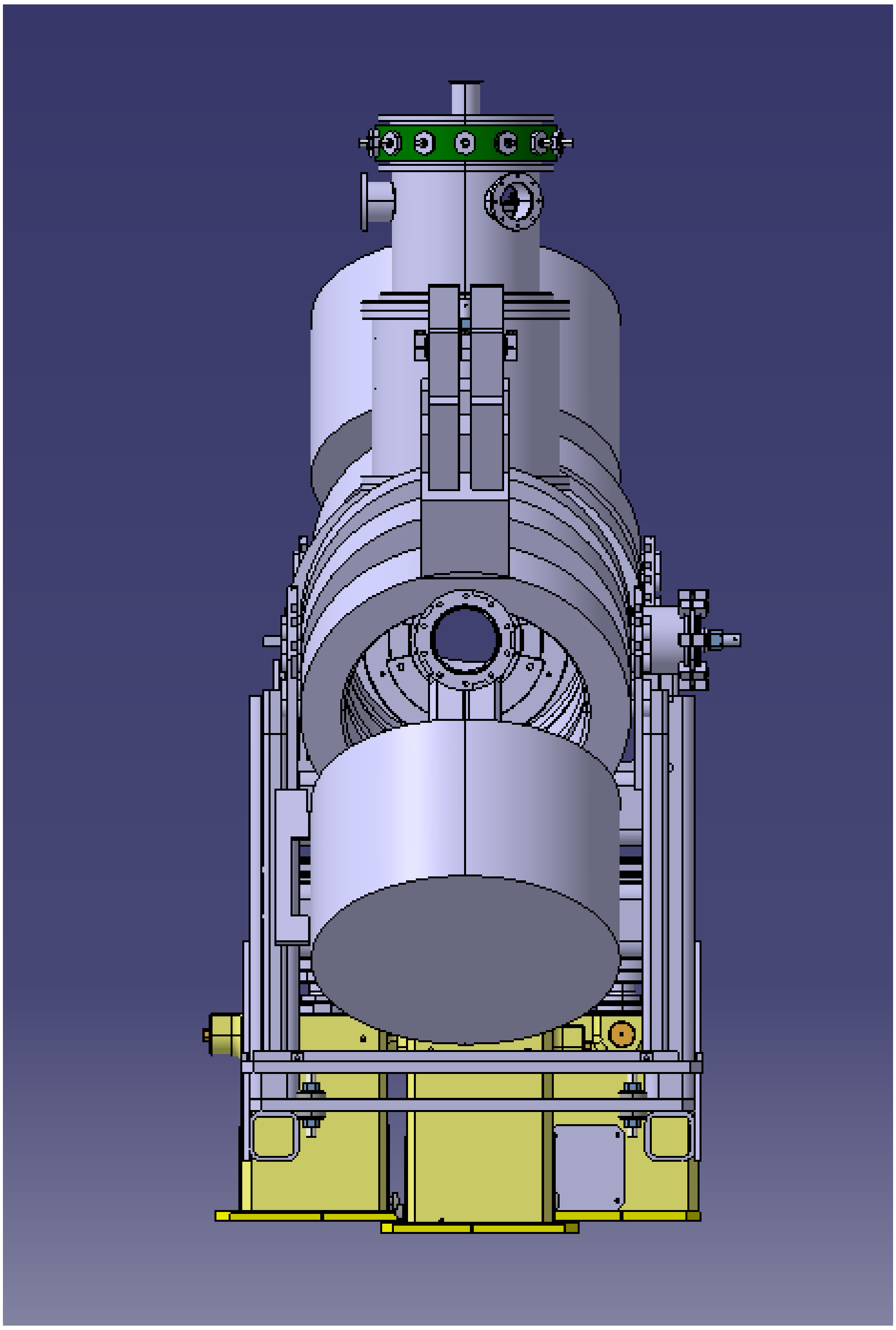
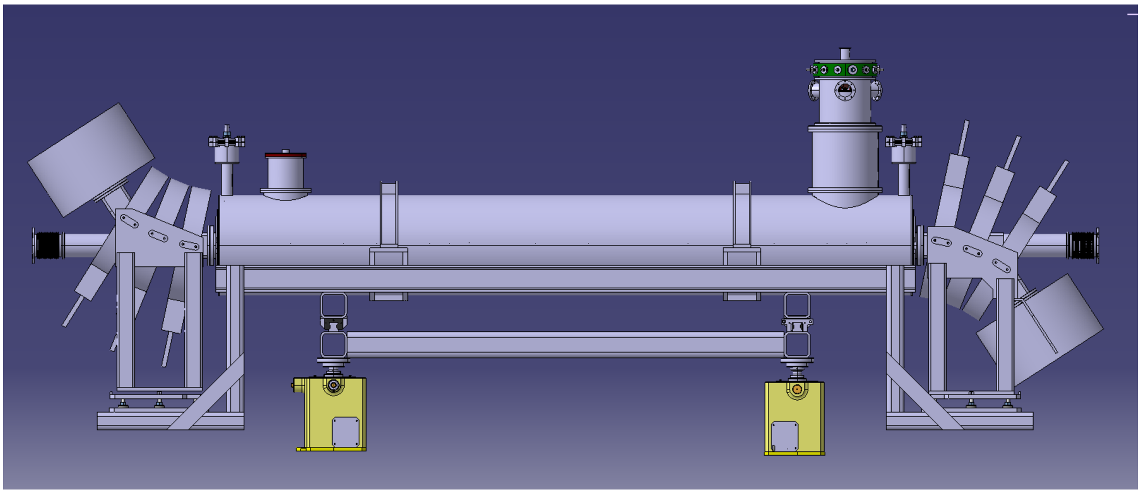
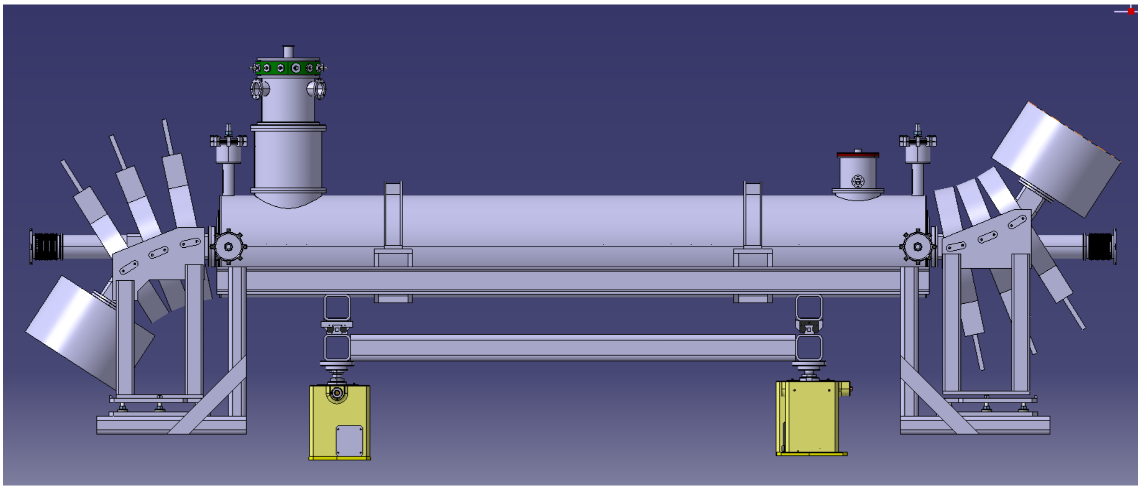
APPENDICES



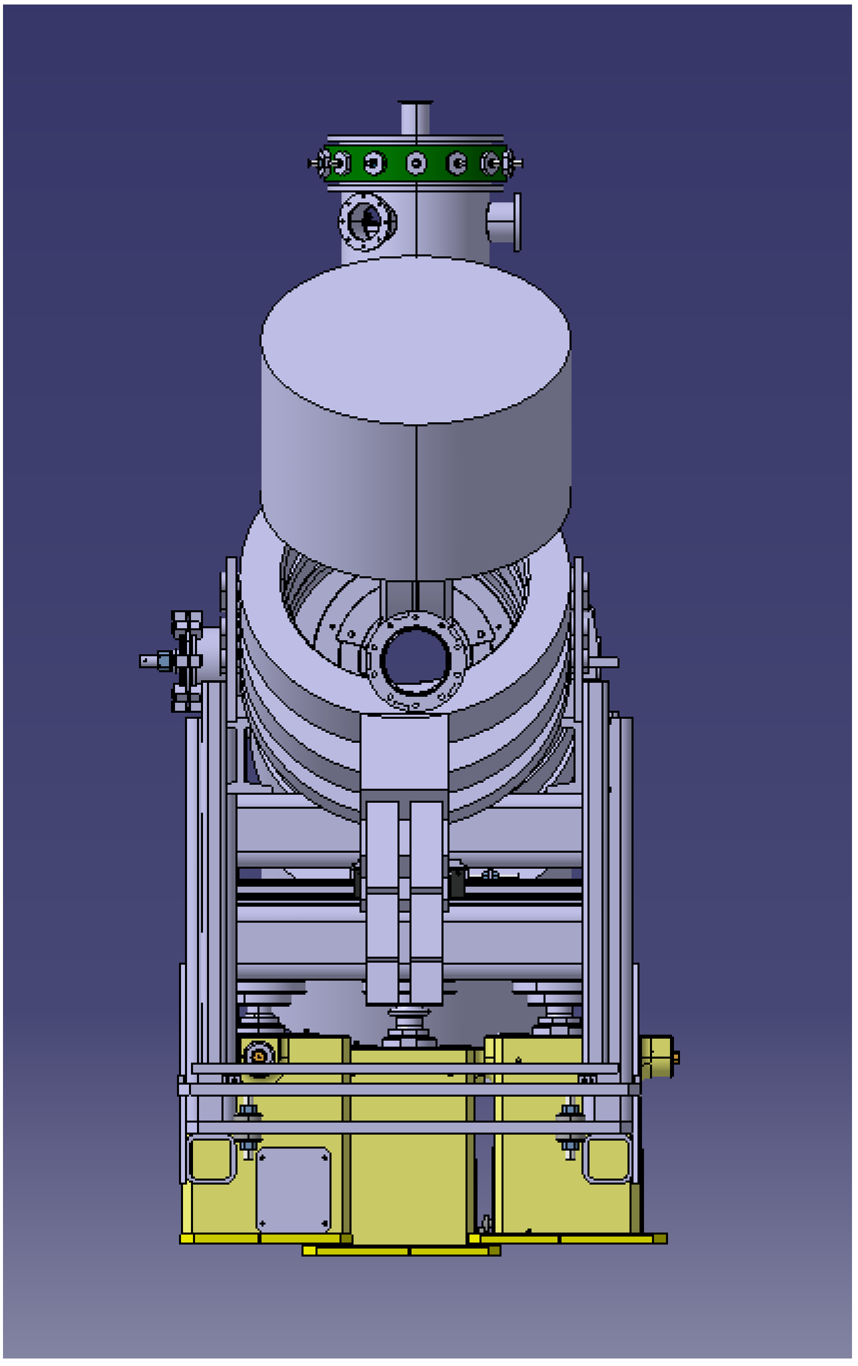
Appendix 1 Hollow Electron Lens front view



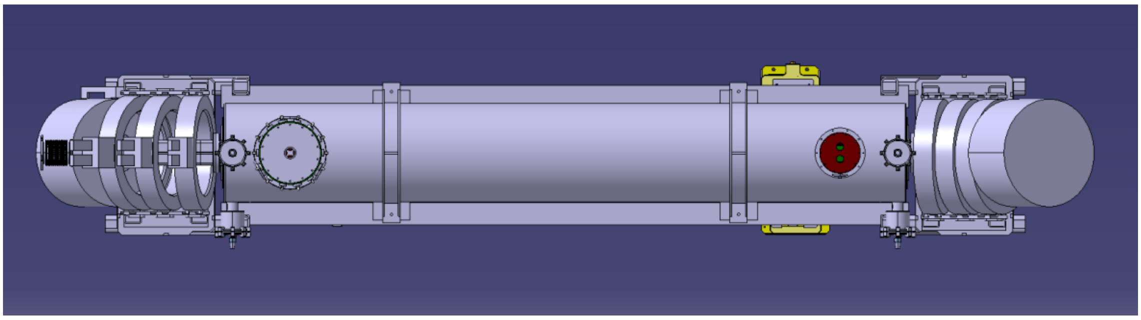
Appendix 2 Hollow Electron Lens left side view



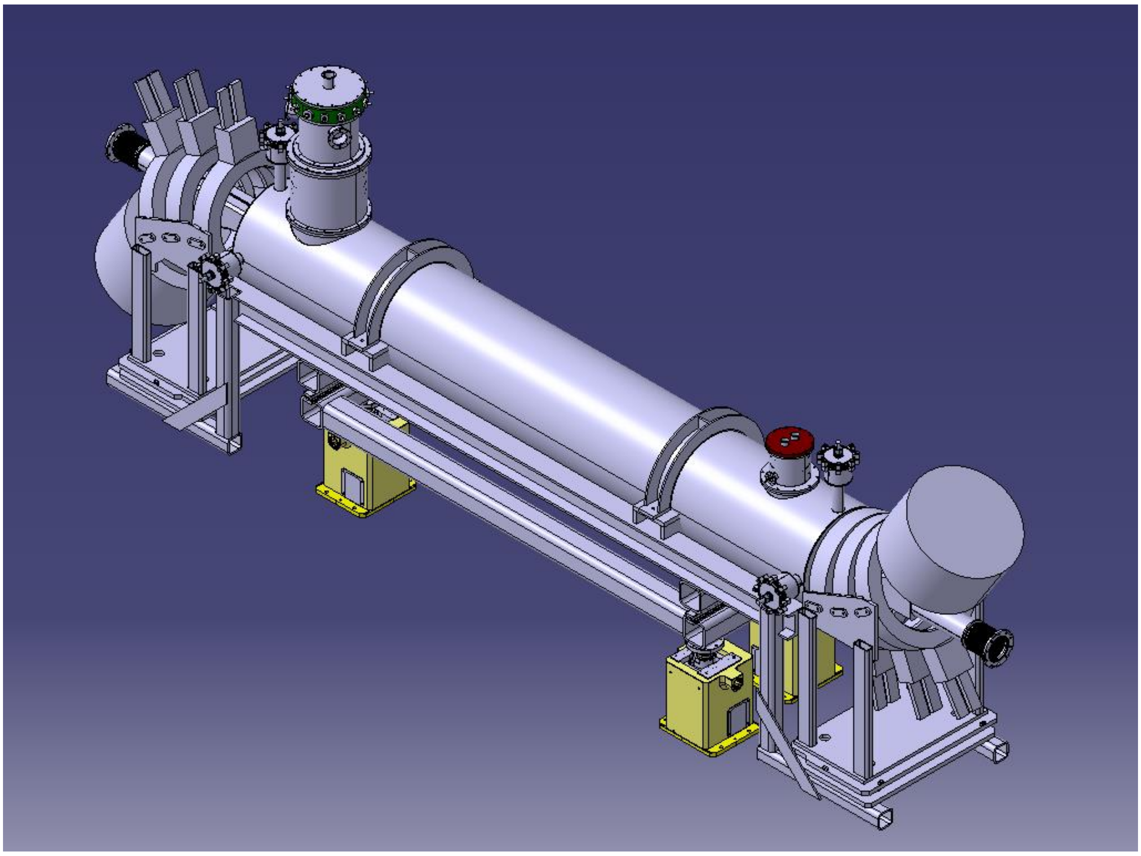
Appendix 3 Hollow Electron Lens right side view



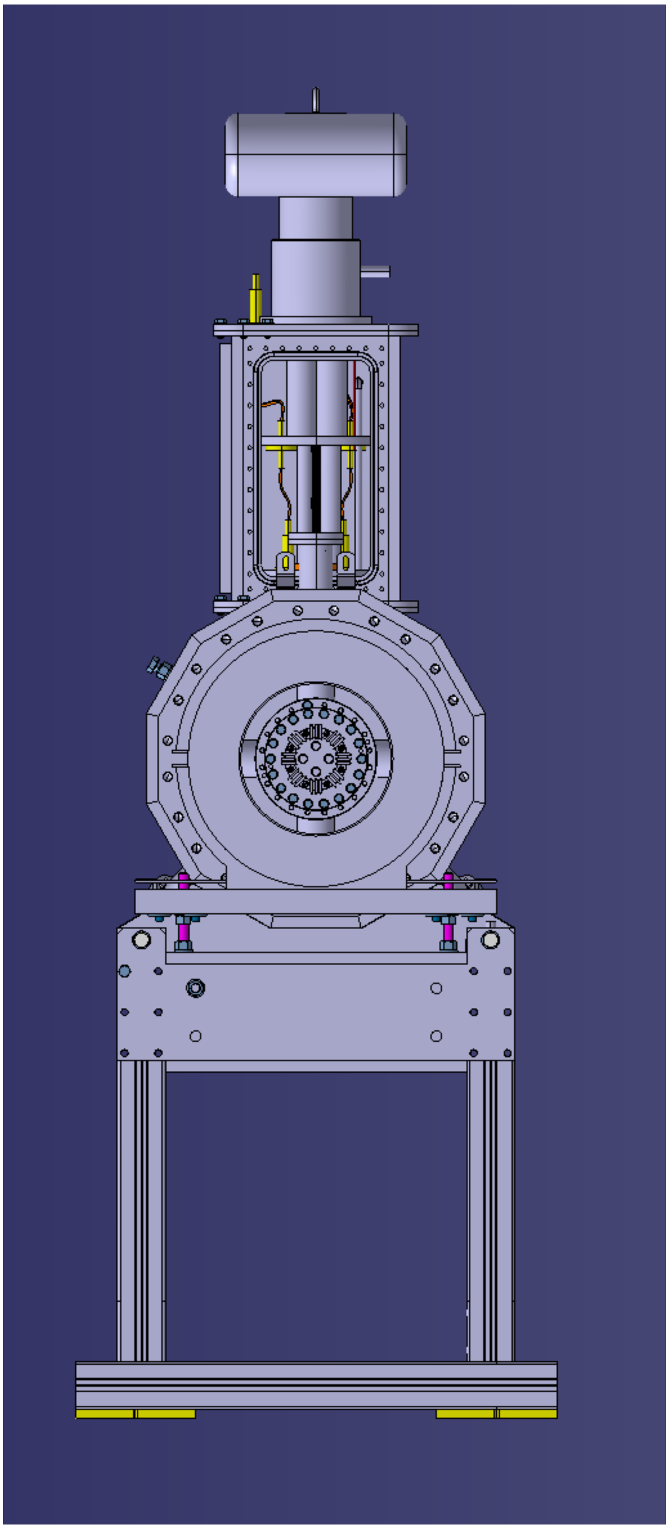
Appendix 4 Hollow Electron Lens back view



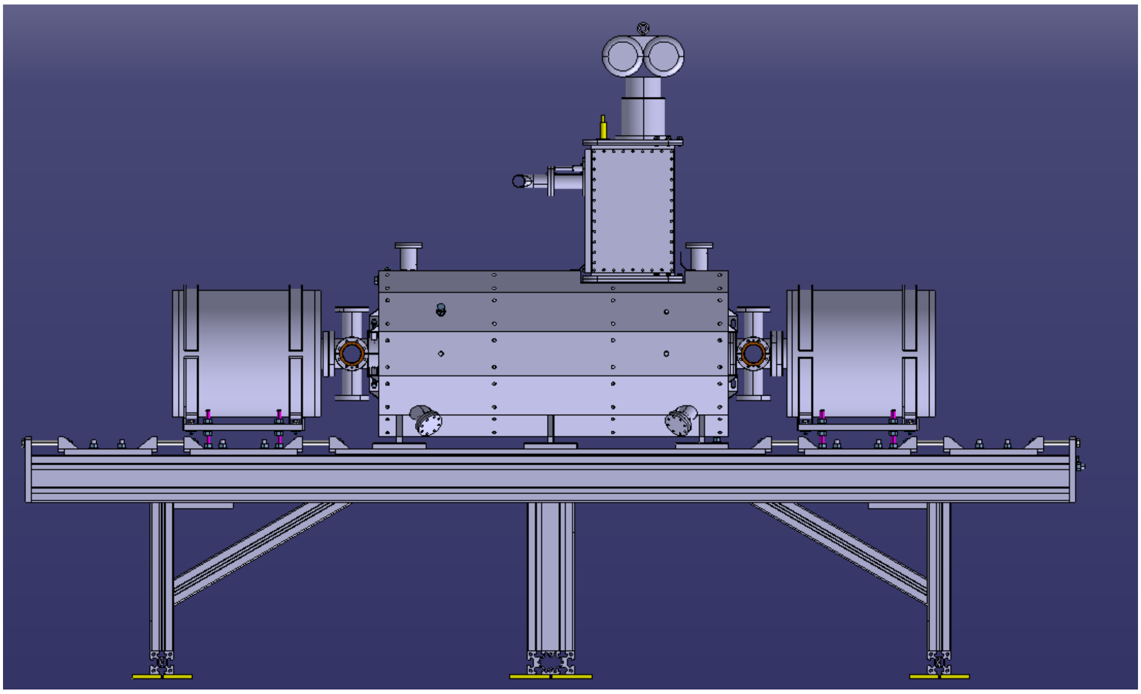
Appendix 5 Hollow Electron Lens top view



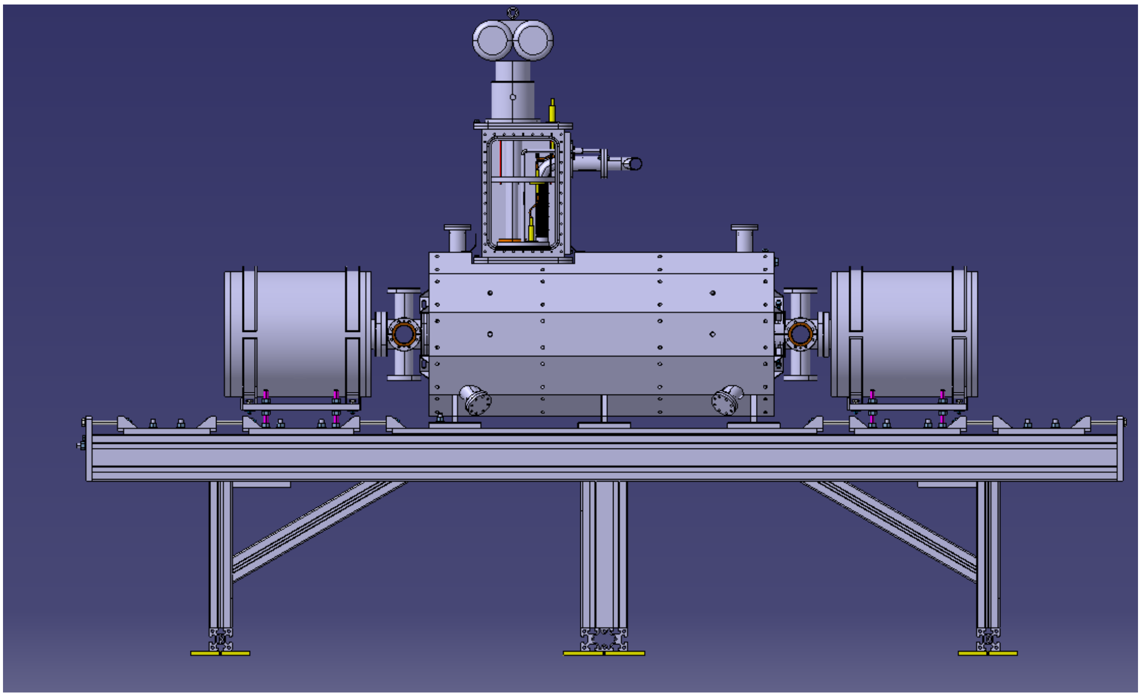
Appendix 6 Hollow Electron Lens isometric view



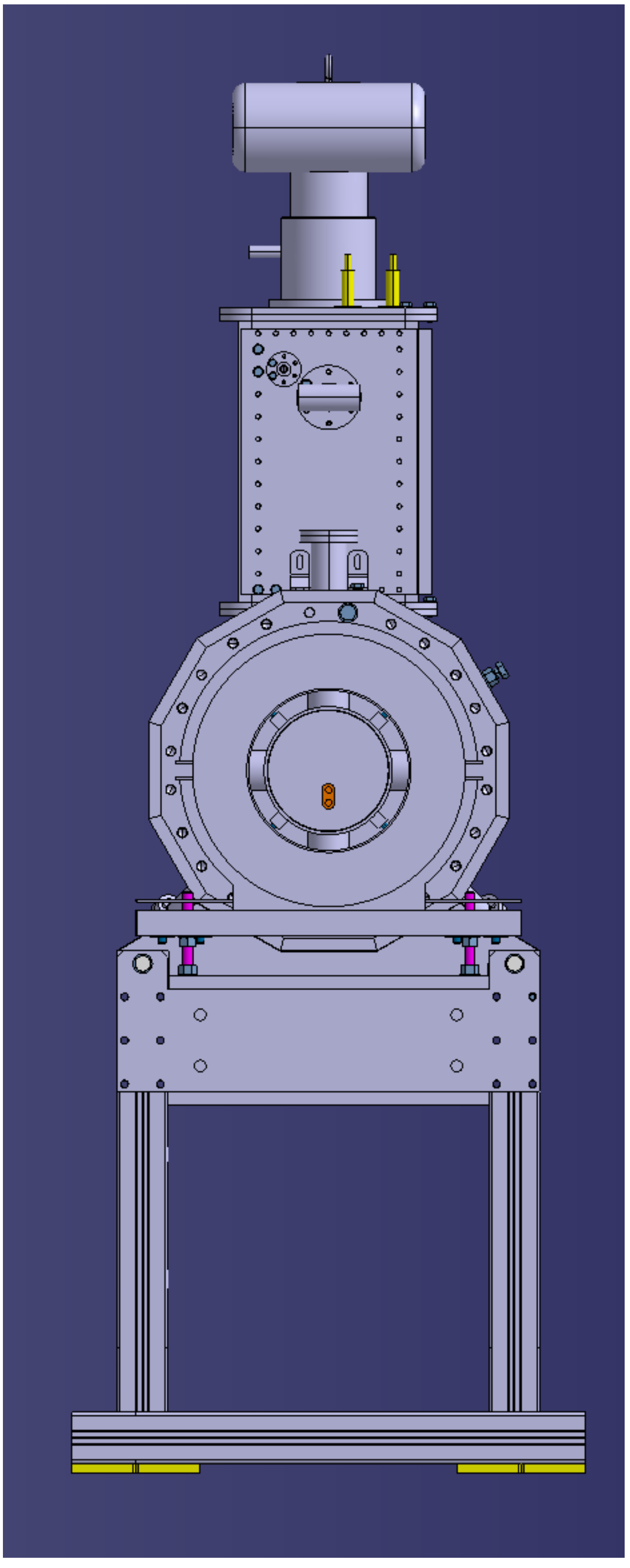
Appendix 7 Hollow Electron Lens test station front view



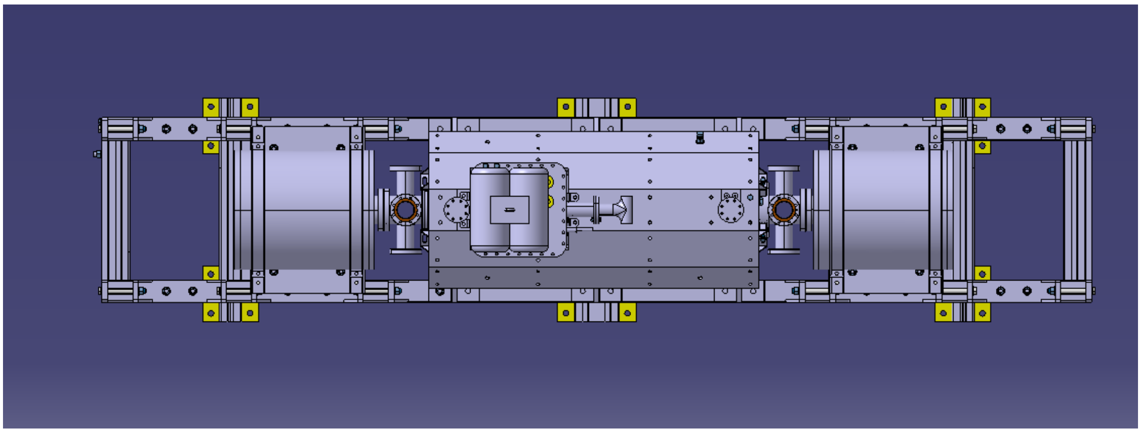
Appendix 8 Hollow Electron Lens test station left side view



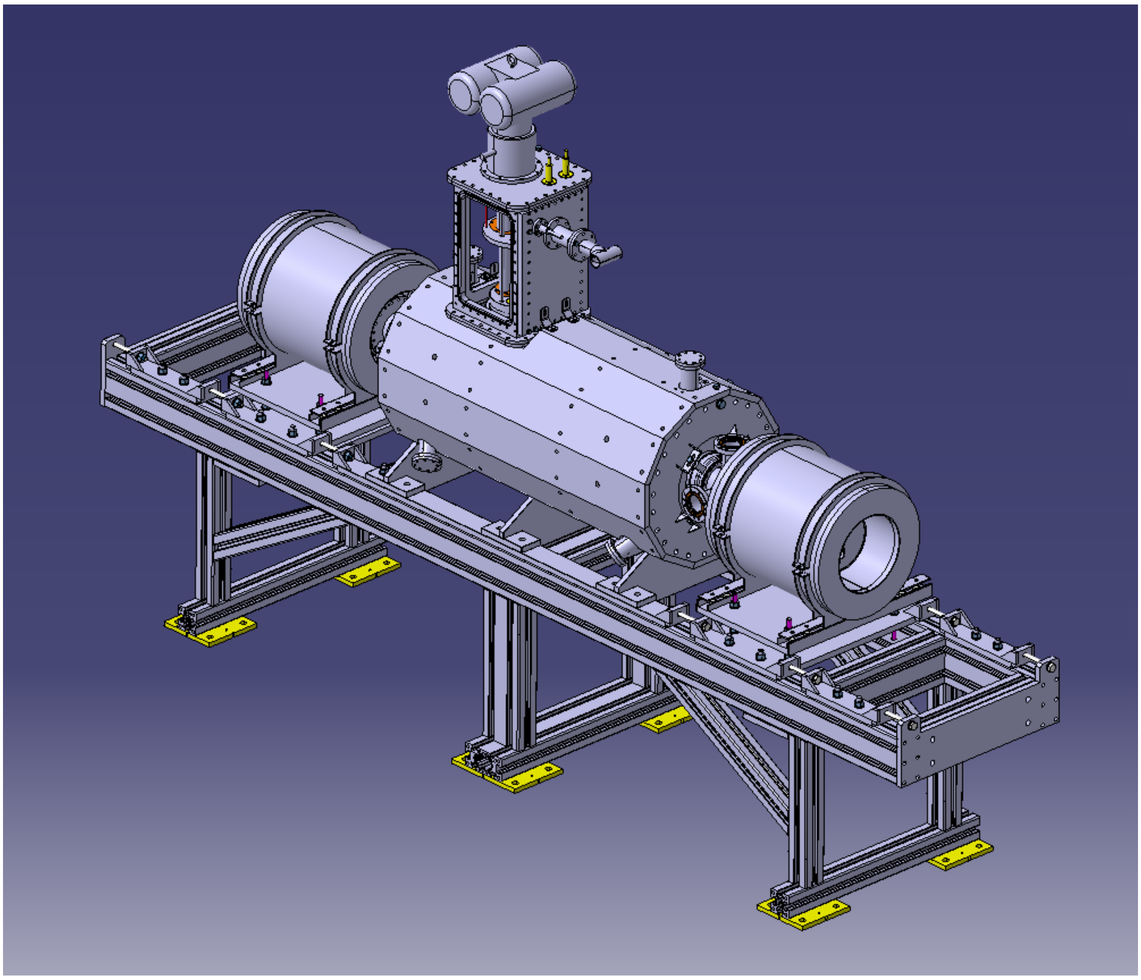
Appendix 9 Hollow Electron Lens test station right side view



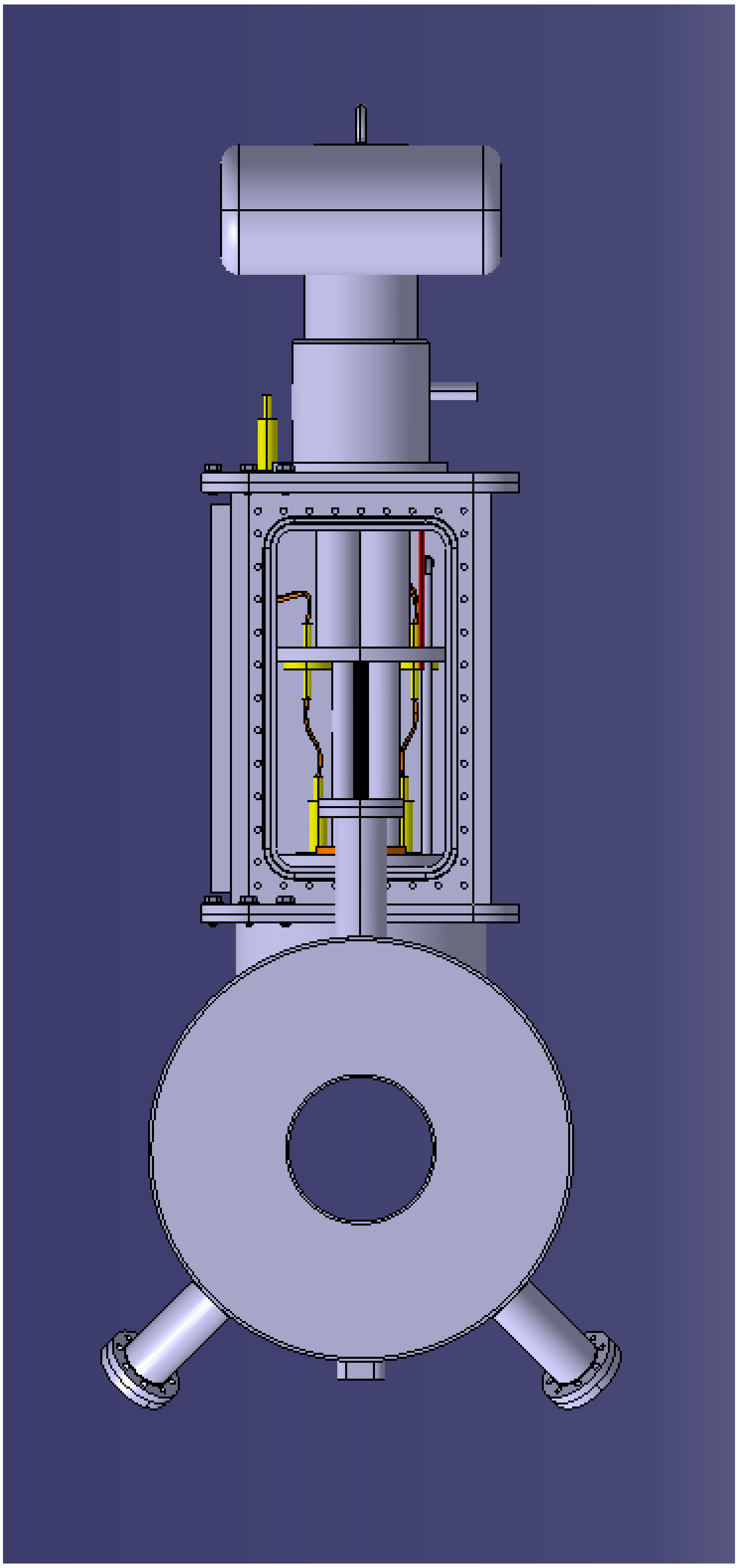
Appendix 10 Hollow Electron Lens test station back side view



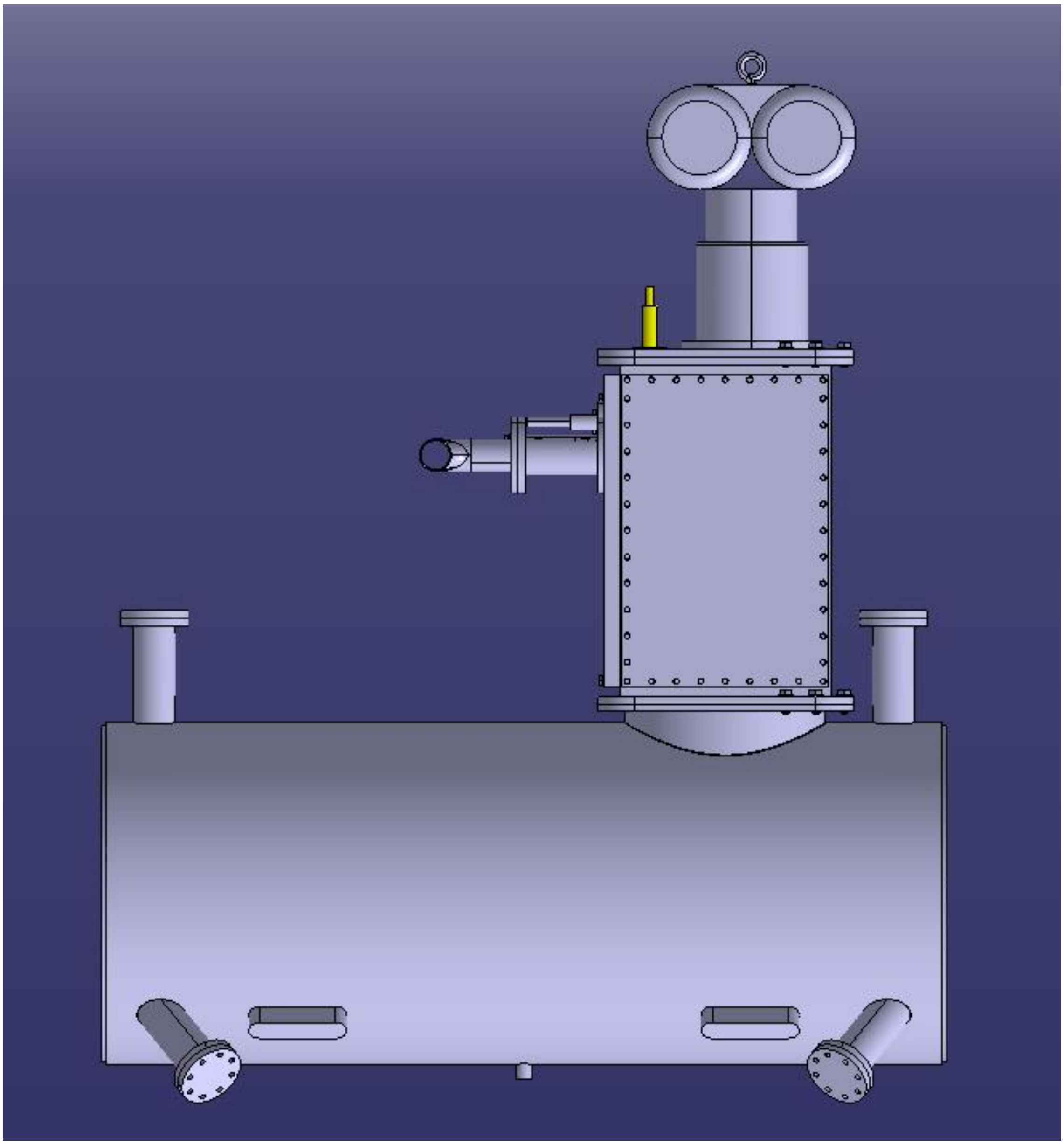
Appendix 11 Hollow Electron Lens test station top view



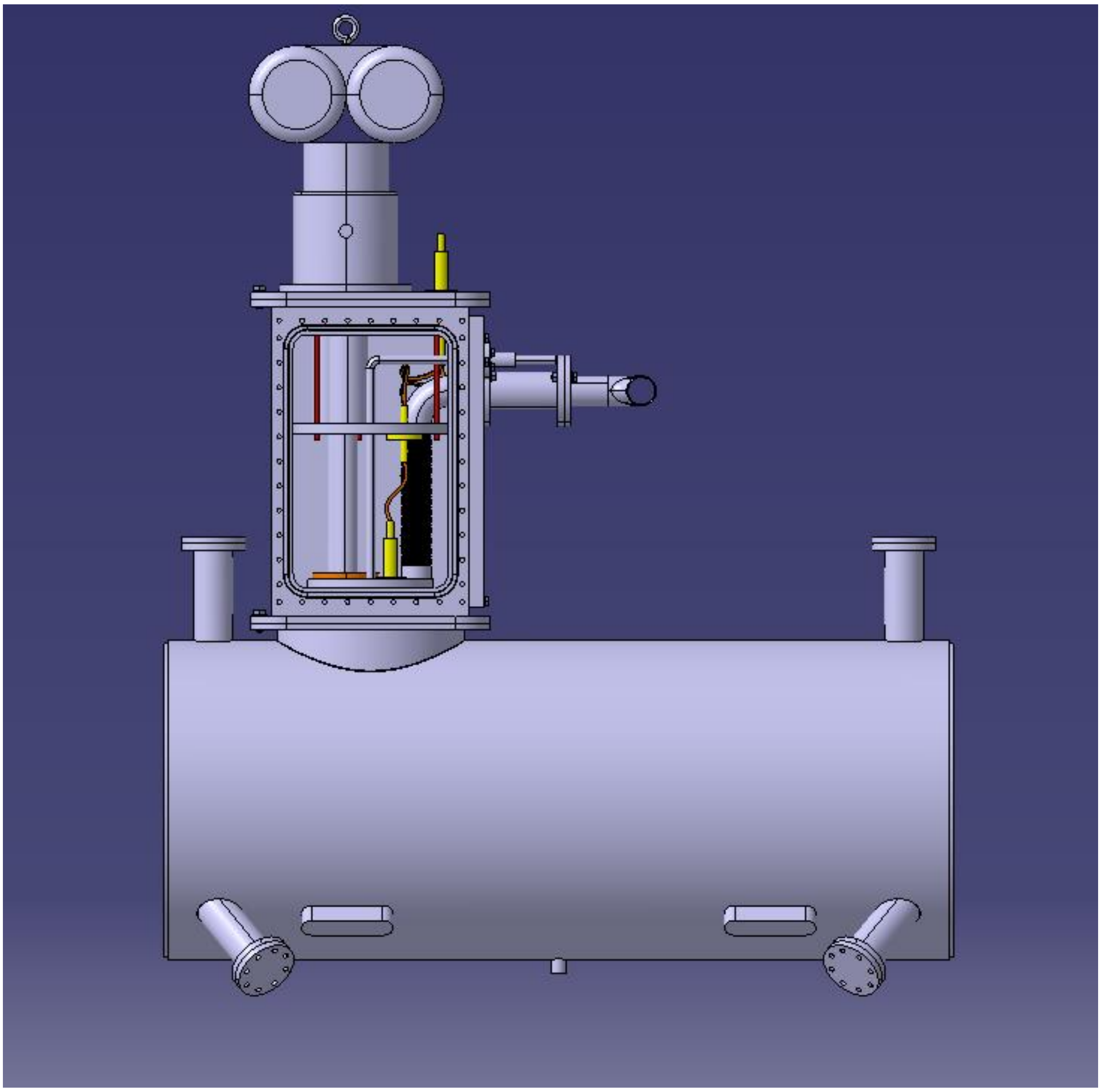
Appendix 12 Hollow Electron Lens test station isometric view



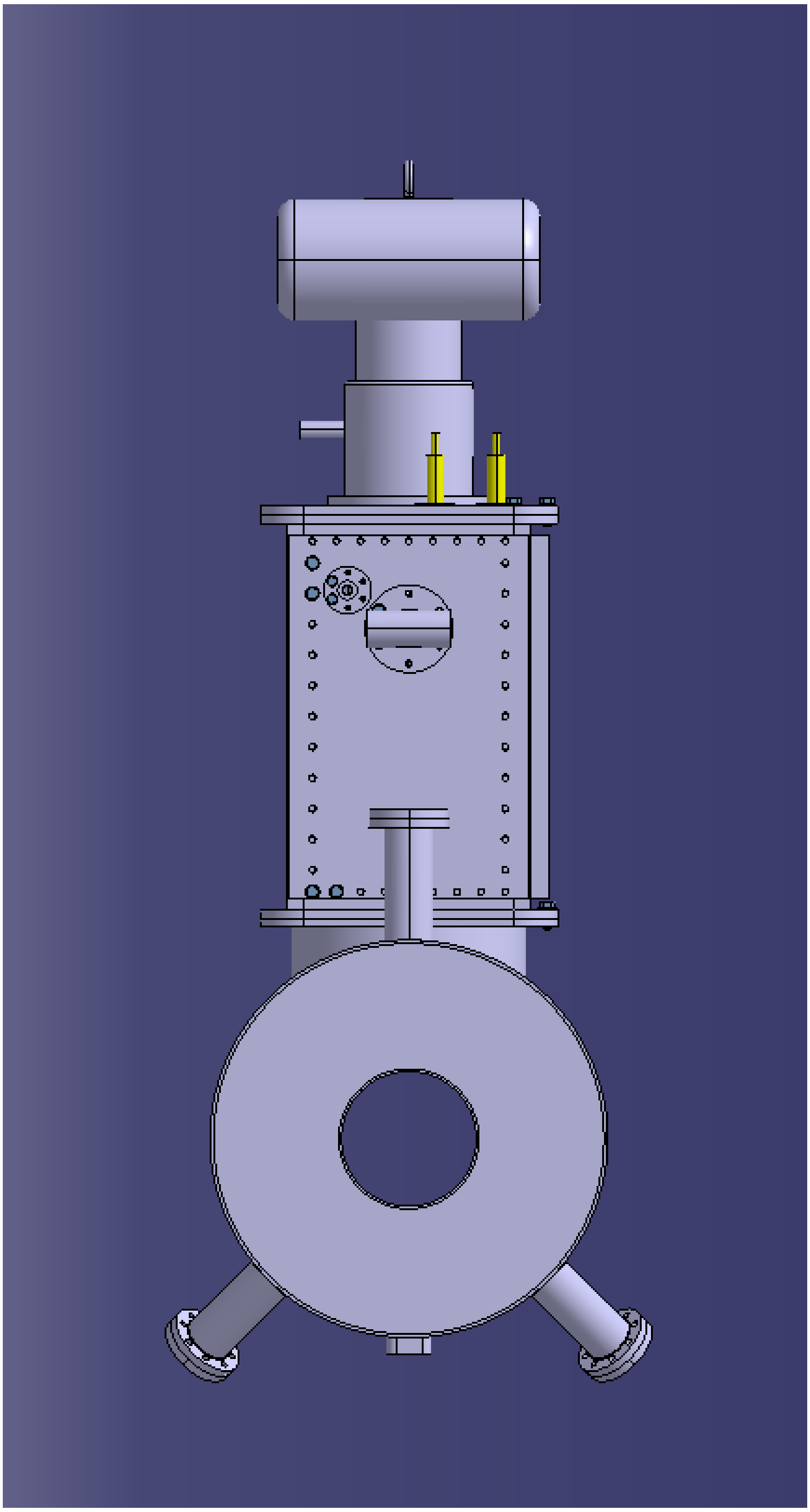
Appendix 13 HEL test station cryostat front view



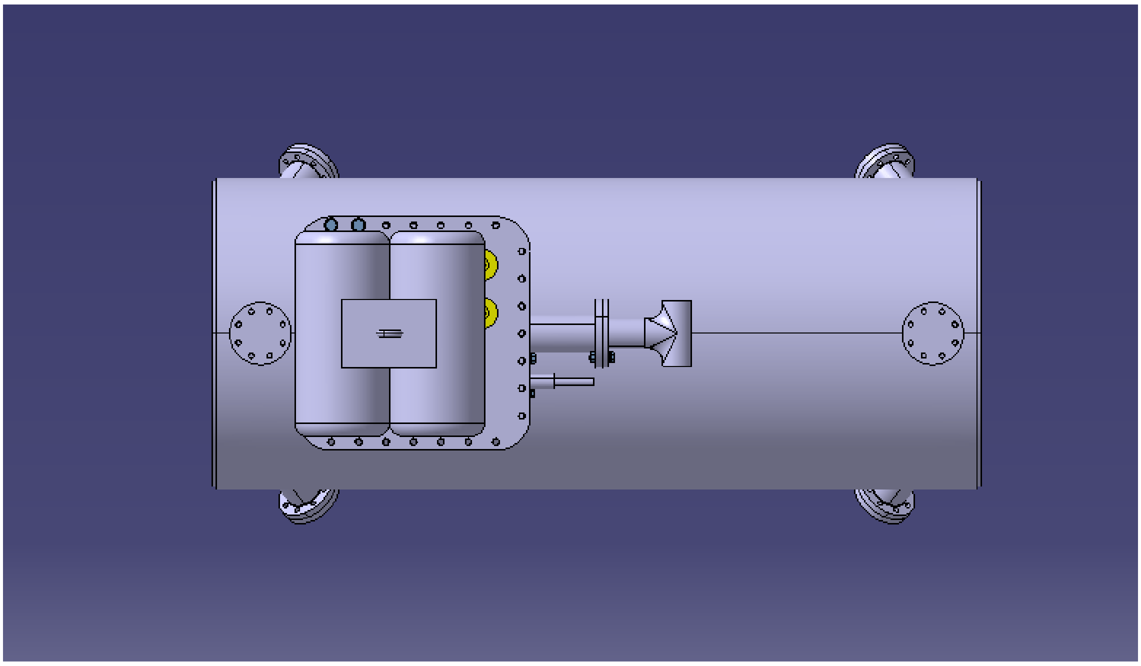
Appendix 14 HEL test station cryostat left side view



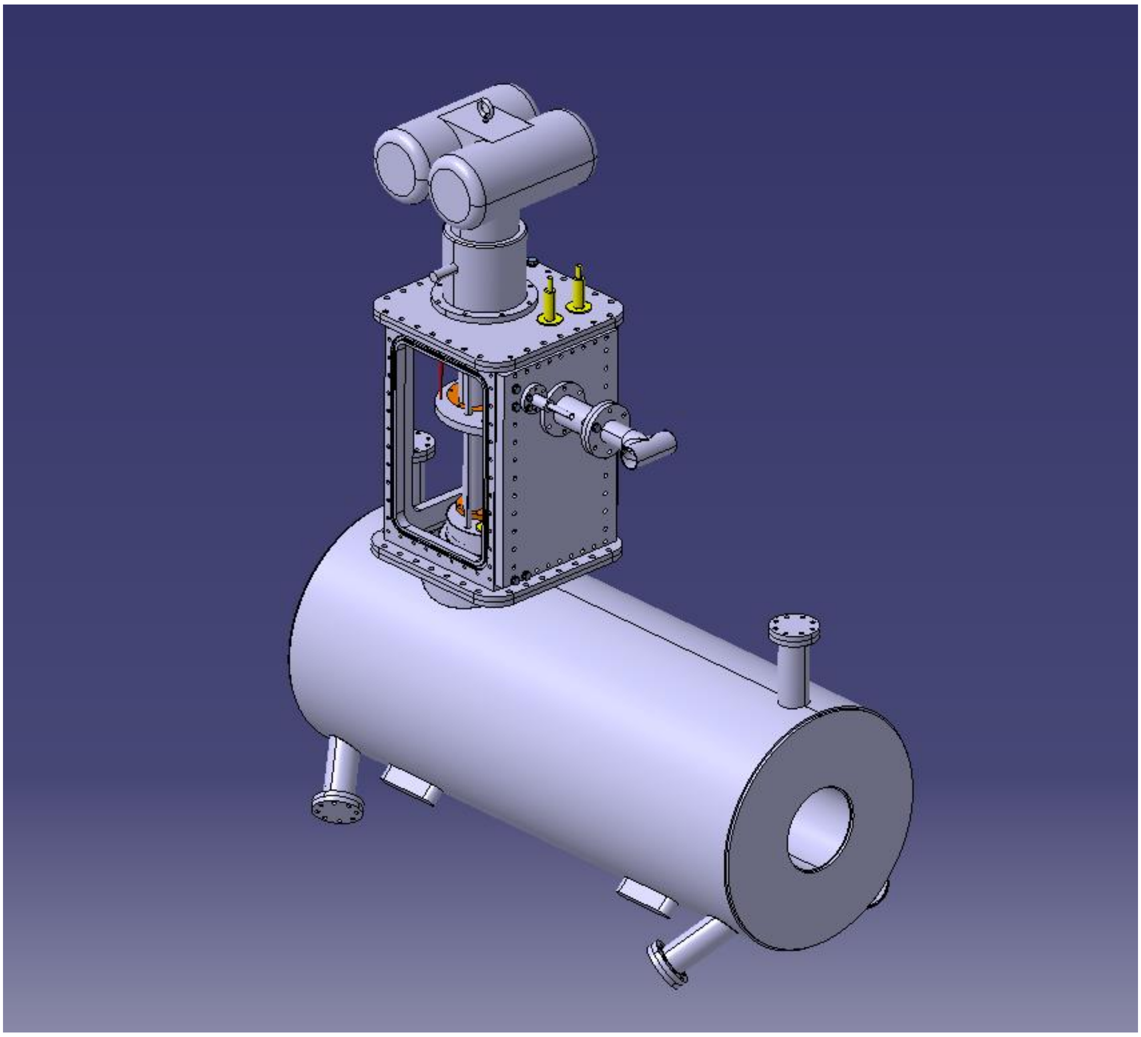
Appendix 15 HEL test station cryostat right side view



Appendix 16 HEL test station back view



Appendix 17 HEL test station top view



Appendix 18 HEL test station isometric view