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Test Infrastructure and Accelerator Research Area

Status Report

Technical Design Report on the Superconducting Cavity test Cryostat

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TEST INFRASTRUCTURE AND ACCELERATOR RESEARCH AREA

WP 9 – TIHPAC

Test Infrastructure for High Power Accelerator Components

Deliverable 9.2:

Technical Design Report on the Superconducting (SC) Cavity test Cryostat

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GLOSSARY

LHe: Liquid Helium

LN2: Liquid Nitrogen

SC: Superconducting.

UHV: Ultra High Vacuum

HV: High vacuum

MLI: Multi Layer Insulation

RF: Radio Frequency

This document reports on the engineering design of a test cryostat for low beta superconducting cavity RF tests at cryogenic temperature This cryostat is a key test-infrastructure required for the development on low beta superconducting cavities as they are envisaged or under development for European projects such as SPIRAL2, ESS, IFMIF, EURISOL, MYRRHA, HiE-ISOLDE…

This document first recall the main user specifications and requirements, as they were reported in MS35 and then present all the content of the engineering detailed study of this test cryostat.

1. SCIENTIFIC AND TECHNICAL CONTEXT

1.1. Recall of the TIARA-PP context and objectives

The realization of current and planned state-of-the-art accelerator-based research infrastructures, such as LHC, XFEL, FAIR, SPIRAL2, ESS, IFMIF, EURISOL serving the needs of a vast range of research communities, is only made possible by continuous progress in accelerator science and technology supported by strong and sustainable R&D activities. It is thus not surprising that strengthening Europe‘s capability in accelerator R&D has been identified as a very high priority issue within many of the communities using accelerator-based research infrastructures. This is, in particular, the case for Particle Physics, for which the CERN Council has ranked accelerator R&D as a top priority in its European Strategy document, and also applies to a large number of projects included in the ESFRI roadmap. To carry out a viable and state-of-the-art accelerator R&D programme requires the use of a wide variety of R&D infrastructures, ranging in scale from high-tech equipment and large size accelerator component test stands up to state-of-the-art test accelerator infrastructures costing several tens of millions of Euros.

The main objective of the TIARA Preparatory Phase is to study the possible framework, objectives and requirements for the integration of national and international accelerator R&D infrastructures into a single distributed European accelerator R&D facility.

TIARA will enable full exploitation of the complementary features and expertise of the individual member infrastructures and will maximize the benefits for both the member infrastructures and the users. This includes the agreement and implementation of organizational structures and methods that will enable integration of existing individual infrastructures, their efficient operation and upgrades, and the construction of new infrastructures as part of the TIARA facility, thus ensuring the competitiveness and sustainability of accelerator R&D in Europe. Such a unique distributed facility will enable Europe to establish its leadership in accelerator science and technology through the development of an integrated R&D program embracing the needs of many different fields, as well as medical and industrial sectors both for technical and human resource aspects.

1.2. TIARA-PP WP9 objectives

The TIARA WP9 is specially concentrating on the specialized required infrastructures for accelerators developments for nuclear physics, typically like the EURISOL future facility.

EURISOL would be the next generation of a facility aiming at the production of radioactive ion beams (RIB) using the ISOL (Isotope Separation On Line) technique. This facility would provide unique world-class research opportunities in nuclear physics, nuclear astrophysics and material sciences, and supply new radiopharmaceutical radioisotopes. The facility is based on a 5 MW driver accelerator, capable to accelerate protons up to 1 GeV, and also some other species like deuterons and He3 (2+) to respectively 250 MeV and 2 GeV, at a reduced current. The beam is then directed to one multi-MW target and several low power target stations for the neutron conversion and the RIB production. The produced RIBs are then prepared and sent to the post-accelerator, which can accelerate up to 150 MeV/u, depending on the physics case requirements.

Achieving the required performances on the EURISOL facility necessitates an important R&D on several key components to assess the technological choices. Several components are today at the technological limit, and the difficulties will be overcome only with an intense R&D effort which includes an important test and qualification program. The opportunity to test these components in conditions a close as possible to the final operation on the machine is mandatory to achieve a reliable design to meet the specifications.

Two major domains of EURISOL are concerned: the high power target and the low beta superconducting accelerating structures. The objective of this WP is to coordinate the design of two test benches: an irradiation test facility for the high power target developments and a cryogenic test cryostat for testing fully equipped low beta superconducting cavities (SC). These equipments are key infrastructures towards the accomplishment of the R&D plan to be able to construct EURISOL, but they are also relevant for other projects like ESS or the ADS (Accelerator Driven Systems) developments (MYRRHA project).

1.3. The TIARA-PP WP9 sub-task on the design of a low beta cavities test cryostat

The Eurisol accelerators (driver and post-accelerator) are mainly based on the superconducting technology for accelerating the different beams. Several types of superconducting cavities are foreseen, covering a wide range of particle velocities. While the classical elliptical cavities are used in the driver at high energy, the low and intermediate energy of the driver, as well as all the post-accelerator structures are composed of low beta SC cavities of different shapes. Other accelerators like ESS, HIE-ISOLDE, ADS, IFMIF, are also based on low beta SC cavities. Contrary to elliptical cavities, operating experience on these accelerating structures is today much more limited, even not existing for some of them like the promising single or multi-gap spoke cavities. It is then mandatory to test them in an accelerator-like configuration to definitively validate them for beam acceleration.

To perform these tests, a specific test cryostat is required, capable to host these cavities, fully equipped with their ancillary systems (power coupler, cold tuning system). The only solution developed today by the various project to be able to perform these tests is, for each project, to develop a test cryostat specific for each cavity type (see fig. 1 for the Eurisol case) [1]. This is obviously possible only in an advanced phase of the project, when available financial resources are sufficient to afford such equipment. The real need of the projects is to perform these tests well before in the project development plan, in an upstream R&D phase. The difficulty is that the available resources at this stage are usually too low to afford a dedicated equipment.

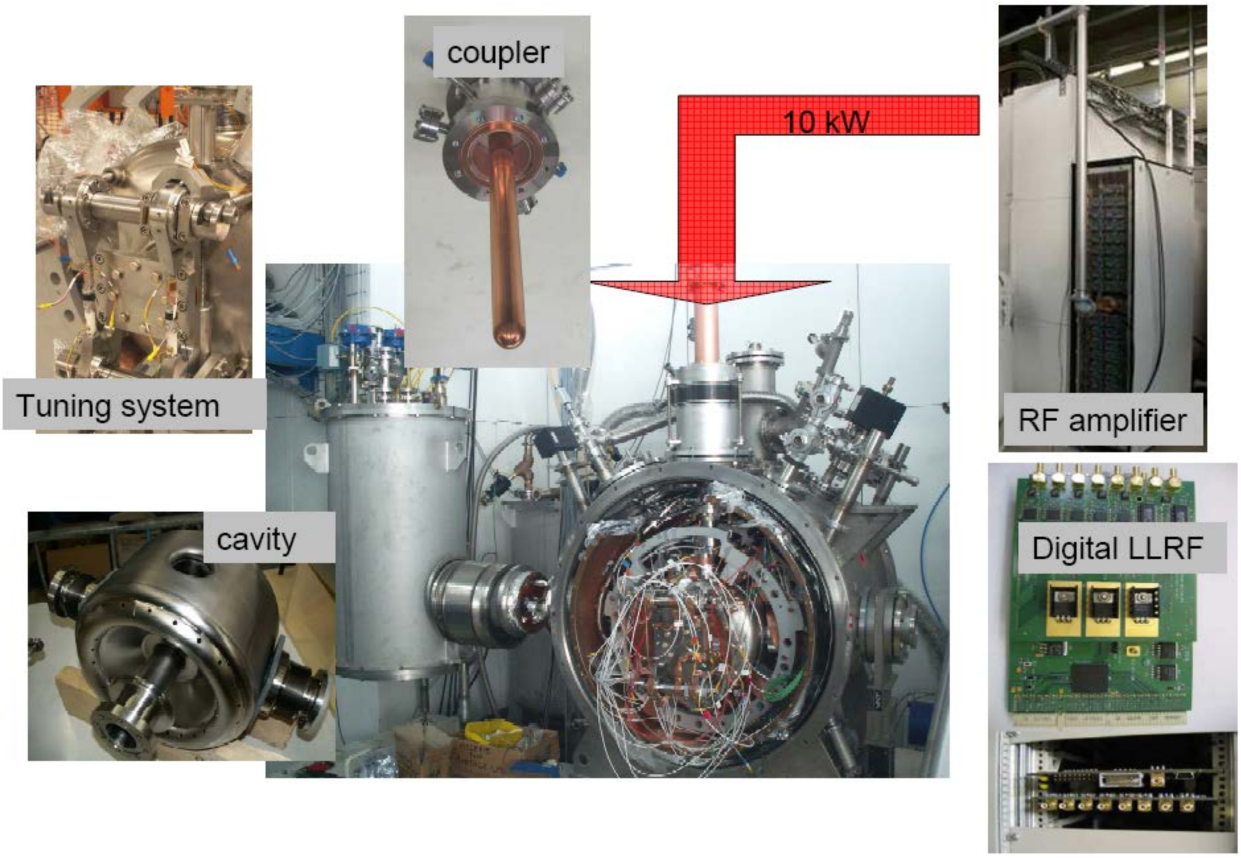


Fig. 1: A typical set-up for SC cavity testing: example of Eurisol for one type of spoke cavity

The main idea to overcome this difficulty is to develop a test cryostat for low beta SC cavities, not specific for one cavity type, but versatile enough to accommodate several cavity types, and make this equipment available to any user or project. This equipment would be complementary to the few ones available in Europe, dedicated and fully used for elliptical cavities tests.

The aim of the sub-task 9.2 of the TIARA-PP WP9 is to design a versatile test cryostat adapted to the test of low beta cavities of various shape and geometries, as they are being developed for several accelerator projects in Europe.

2. REQUIREMENTS FOR THE LOW BETA SC CAVITIES TEST CRYOSTAT

As defined in the WP9 work plan, the first task consists in studying and defining the user requirements for this low beta cavity test cryostat. These requirements will then be used to define the specifications for the test cryostat. This chapter summarizes the different type of requirements.

A survey on the on-going research and developments on low beta superconducting cavities in Europe has been done in order to collect information and establish a requirement list that is integrating the widest possible range of applications for such a test cryostat.

In summary, four main categories of requirements have been identified:

a. Geometric dimension (cavity type and physical capacity)
b. Integration of couplers and cold tuning system
c. Cryogenic requirements
d. Assembly requirements
e. Specific test requirements

2.1. Requirements on the cryostat geometric dimensions

Many different cavity geometries are under development (or envisaged) for the already listed accelerator projects in Europe. This low beta cavity "bestiary" is corresponding to the accelerating solution which could specific for each project, but having the same basis. These different geometries are corresponding to several cavity type, a range of different beta (giving the range of particle velocity that a cavity can efficiently accelerate), and several resonant frequencies.

The main different cavity types are (Fig. 2 and 3):

- Half-wave resonators [5, 6]
- Quarter wave resonators [4]
- Spoke cavities (single, double or triple spoke) [2, 3]
- Others: re-entrant, CH,…
- Special cavities designed not for acceleration, but for beam deflection (like the crab cavities for instance)

Moreover, the vertical or horizontal positioning for some of these cavities (half-wave resonators for instance) has to be to be envisaged to define the cryostat geometry (Fig. 4). Indeed, one of the requirements is to test the SC cavities in the same disposition as the one in the final cryomodule.

The range of cavity beta is typically ranging from 0.05 to 0.5. To each beta is corresponding a different cavity length.

The range of frequencies is from 60 MHz to 400 MHz. The cavity size in varying with the inverse of the frequency: for a given cavity type, the lower the resonant frequency is, the bigger is the cavity.

The number of accelerating cells is also another parameter which impacts on the cavity length: the low beta cavities type concerned are mainly the CH structures and the spoke cavities.

In any case, the assumption is taken that the cavity to be tested is equipped with its helium tank, which is the only possible test configuration when the ancillary components (power coupler, cold tuner) are also mounted on the cavity.

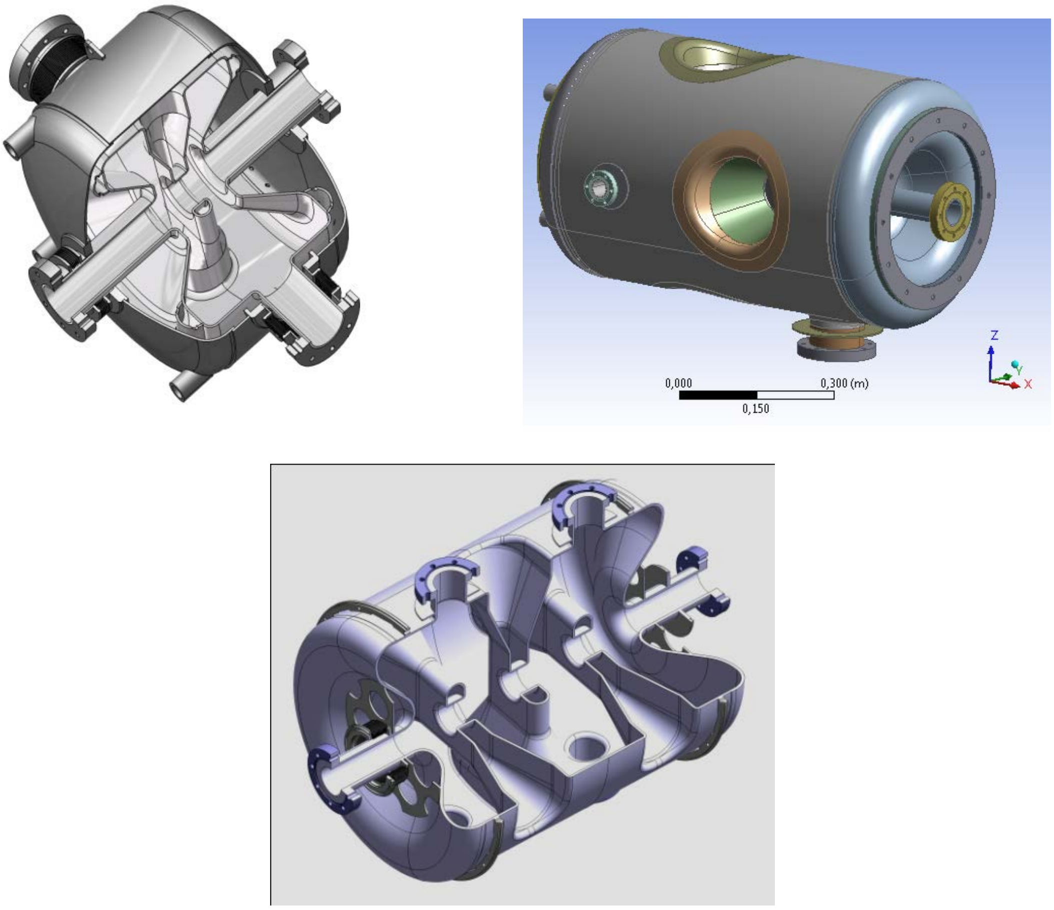


Fig. 2: Different geometries of spoke cavities, from single spoke (left) to triple spoke (right) [2, 3]

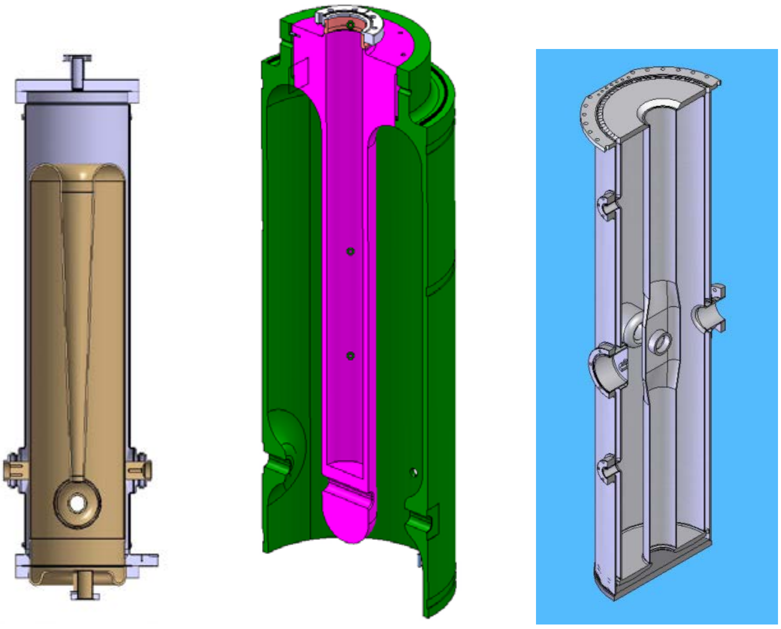


Fig. 3: Other low beta cavity types: quarter-wave resonators (2 examples on the left) and half-wave resonator (right) [2, 4]

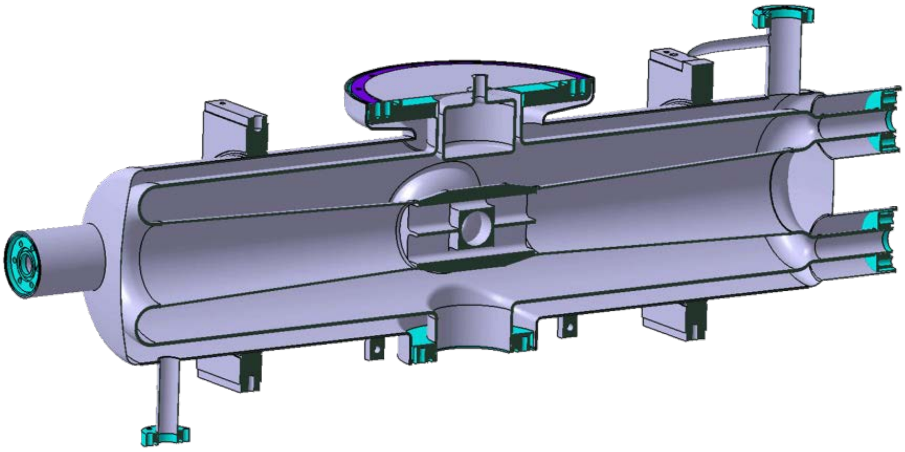


Fig. 4: A half-wave resonator to be used in the horizontal position (IFMIF case) [5, 6]

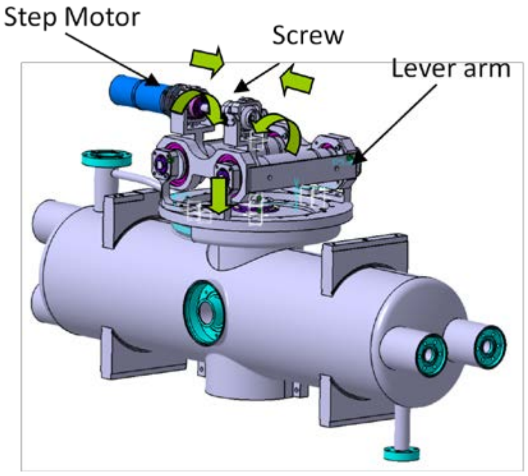
The overall dimensions of these cavity types will be taken into account to size the cryostat. The maximum cavity volume that will accommodate the cryostat is a cylinder of 700 mm diameter and 1600 mm long, to be used either horizontally or vertically.

2.2. Integration of power couplers and tuners

Integrating couplers and tuners for different geometries is the main concern for this versatile cryostat

- **Power couplers:** For all cavity type, geometries are very different: the cryostat should have the possibility to have couplers located on the bottom or on the side of the module (power coupler located on top: option discarded, too difficult to implement while keeping the cryostat versatility). A power coupler design example is shown in Figure 5 (right side)
- **Cold tuning system**: Also very different from one to each other: tuning by deformation, volume insertion, integration of piezo actuators; using cold or warm motors . A cold tuning system design example is shown in Figure 5 (left side)

Only a cryostat with high flexibility (many openings & access) can solve this issue.



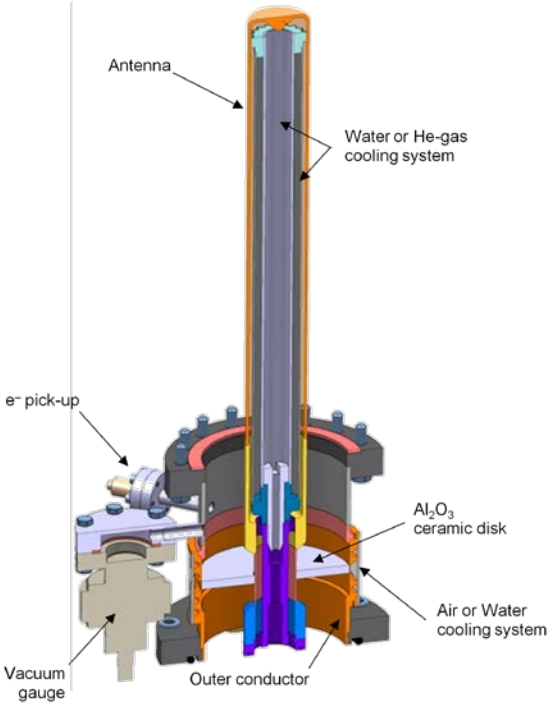


Fig. 5: The IFMIF Cold tuning system (left) on a half-wave resonator, and the ESS double spoke power coupler design (right side) [6, 3]

2.3. Cryogenic specifications

- Operating temperature: 4.2 K or depressed He bath (2 K typically)
- Cryogenic power: the cryostat cryogenic system and distribution should be able to handle about 70 watts (in average) of dissipated power at 2 K. To have margin, 80 Watt is an adapted design point for the cryogenic losses to be sustained in the cryostat.
- Cooling time: in order to avoid the ”100 K effect”, the module should be able to cool down rapidly (typically, not more than one hour between 130 K and 70 K)

2.4. Assembly requirements

- The cryostat assembly has to be feasible in a huge variety of clean rooms : height requirements not too important, as simplest as possible assembly tooling, lowest possible amount of material entering in the clean room (pollution control) => concerns with the clean air blowing direction
- No requirements on any alignment device (has only meaning in a real accelerator module)
- As the cryostat is only a test-cryostat, no beam ports are required

2.5. Specific test requirements

The only special requirement for testing is the integration of superconducting solenoids. In some projects, superconducting cavities are integrated very close to the cold focusing element in the cryomodules (IFMIF, HiE-ISOLDE…). The potential impact on the magnet on the cavity performances is often an issue and a validation of the developed solution for the magnet shielding is mandatory, thus requiring a test cryostat capable to integrate SC magnets.

The test cryostat has to take into account the space needed for integrating such a device, with the necessary current lead, instrumentation, and dedicated cryogenic lines for its proper cooling-down and warming-up..

3. SC CAVITY TEST CRYOSTAT DESIGN OVERVIEW

3.1. Cryostat design

Superconducting cavities operate at cryogenic temperature, typically at 4.2 K (Liquid HELIUM boiling temperature at atmospheric pressure) or below 2.1 K (Superfluid Helium at sub-atmospheric pressure, below 30 mbar). Due to the very low latent heat of helium (~ 21 J/g) and the high cost to produce liquid or superfluid helium, a thermally insulated vessel, is mandatory. This special vessel, called cryostat, is designed to reduce as much as possible the thermal loads coming from the external environment. The way to decrease the thermal loads is to minimize the effect of the three different thermal exchange phenomena, solid conduction, gaseous convection and conduction, and thermal radiation. A cryostat (See Figure 6) is typically composed of a vacuum vessel, to eliminate convection and reduce gaseous conduction, a radiation thermal shield, and a light mechanical handling system made from low thermal conductivity materials.

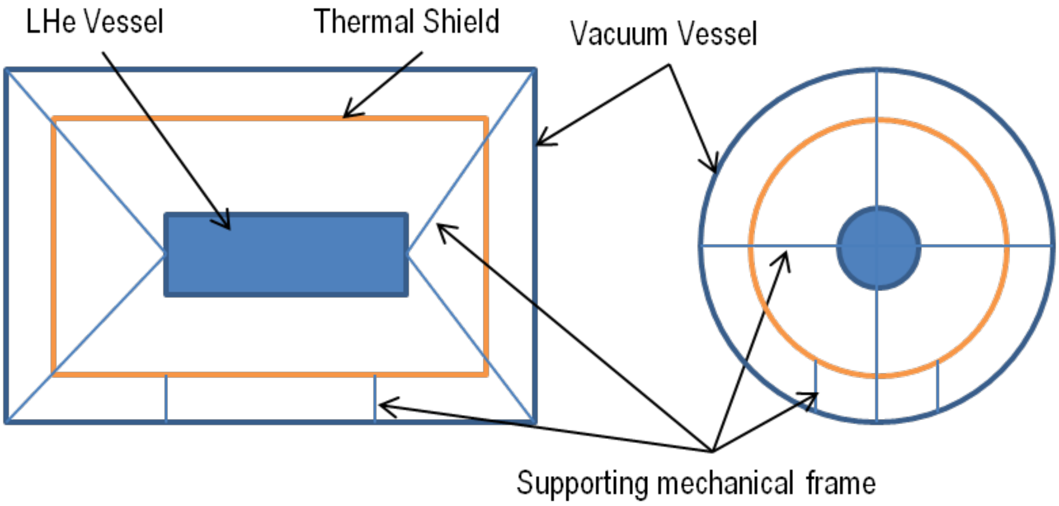


Figure 6: Typical cryostat layout

The vacuum vessel, compatible with High Vacuum, operates at a pressure below 10^{-6} mbar. It is first evacuated at around 10^{-4} mbar using a mechanical pumping group, typically a turbo-molecular pump associated with a primary pump. When the inner parts of the cryostat (first the thermal shield then the helium vessel) are cooled, cryopumping occurs and maintains the pressure below a typical value of 10^{-6} mbar.

The thermal shield surrounds, with optical tightness, the LHe vessel. It is cooled at an intermediate temperature between 300 K and 4/2 K and reduce efficiently (roughly, the radiative thermal loads goes with T^4 and the refrigeration efficiency goes with T) the thermal load going to the low temperature parts (LHe Vessel). Several Thermal shields may be used to optimize the electrical power associated to the required cryogenic power at 4/2 K.

A so called multilayer insulation (MLI) is used in addition with the thermal shield. The MLI is composed of several layers of reflecting foils that reduce the thermal radiative load to the shielded parts. MLI is placed on the intermediate parts (thermal shield) and on the cold part (LHe vessel).

The supporting Mechanical frame made from low thermal conduction material (Epoxy-glass, Stainless Steel, Titanium…) is optimized to have high thermal impedance (low section and great length) in order to minimize the solid thermal conduction flux going to the cold parts.

In most applications (Superconducting magnet, detectors, experimental apparatus…) the cryostat design constraint is mainly dominated by the minimization of the thermal loads.

In the peculiar case of the superconducting cavities, the cryostat design has to make a compromise between the reduction of the thermal losses and the cavity and its auxiliary systems (RF power coupler, cold tuning system) assembly inside the cryostat. The mechanical assembly is an issue for the high electrical field superconducting cavities (Electric field gradient superior to 6 MV/m) which must be prepared inside a very high quality class clean room (class ISO 4). This clean room requirement, mandatory for the cavities operation, adds complexity to the cryostat mechanical design.

Consequently we may have great differences in term of thermal loads between SC cavities cryostat and other applications. For instance the cryostat for the LHC SC magnet has static thermal losses (losses mainly due to the thermal exchange with the 300K environment) of the order of 1 W/m at 2K as for SC cavities the static losses are typically of the order of 3/4 W/m at 2K.

In the case of a test cryostat the thermal losses may also be greater due the mechanical design aspects which aim to improve the ease of assembly and the compliance. For a test cryostat of the Tiara Type, a heat load of around 10 W at 4/2 K is expected.

3.2. A Superconducting cavity horizontal test stand

Several tests stands for SC cavities fully equipped (Helium vessel, RF power coupler, cold tuning system…) operate or are in study in different laboratories. These test stands, currently in operation are dedicated only to elliptical cavities (CHECHIA, CryHolab, HobbyCat…). A new test bench, 'Freia', to be installed in the Uppsala University, developed in the framework of the ESS project, is under manufacturing and will be dedicated for the test of the ESS Spoke cavities and elliptical cavities.

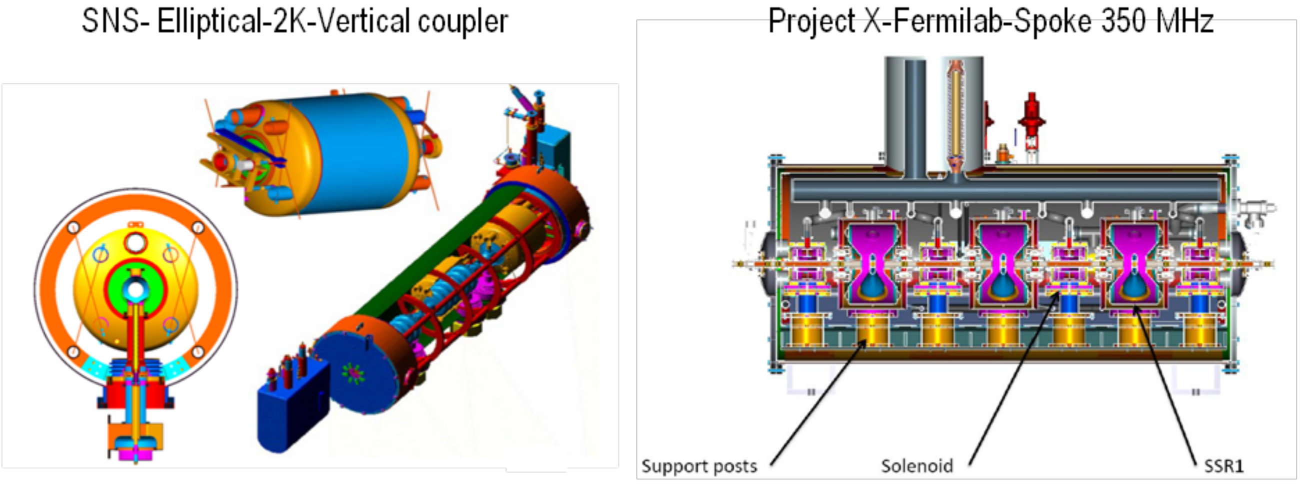
In all these cases the test cryostats have been designed for cylindrical cavities having a horizontal operating axis. All these cryostats are cylindrical with a horizontal axis.

The Tiara test stand has to be compatible with a large variety of low beta cavities which cover various cavity types such has Spoke, QWR, HWR… These cavities have a shape with either vertical or horizontal axis. The way to insert the cavity, from the side or from the top and the corresponding shape of the cryostat is therefore an issue for the conceptual design choice of the Tiara Test Cryostat.

3.3. Cryostating

The superconducting cavities cryostat has to insure, during assembly, the cleanliness of the RF surfaces. The volume constituted by the cavity and its power coupler have to be prepared in dust free conditions inside an Iso4 clean room. Once assembled inside the clean room, the cavity/coupler volume, up to the coupler’s window, is evacuated to a secondary vacuum level and insulated with a stop valve, typically full metallic UHV valve, able to be cooled down at cryogenic temperature. The cavity and its couplers are then inserted, insulated from the ambient air, inside the cryostat, outside the clean room. This peculiar requirement on assembly and the use of a protection stop valve has a major impact on the overall cryostat design which has to take into account these different assembly stages.

Two main concepts to insert the accelerating cavities inside the Cryostat (so called cryostating operation), are used for various superconducting cavities accelerator modules projects worldwide (See Figures 7&8).


SNS- Elliptical-2K-Vertical coupler

Project X-Fermilab-Spoke 350 MHz

Figure 7: Horizontal cryostating examples (accelerator cryomodules)

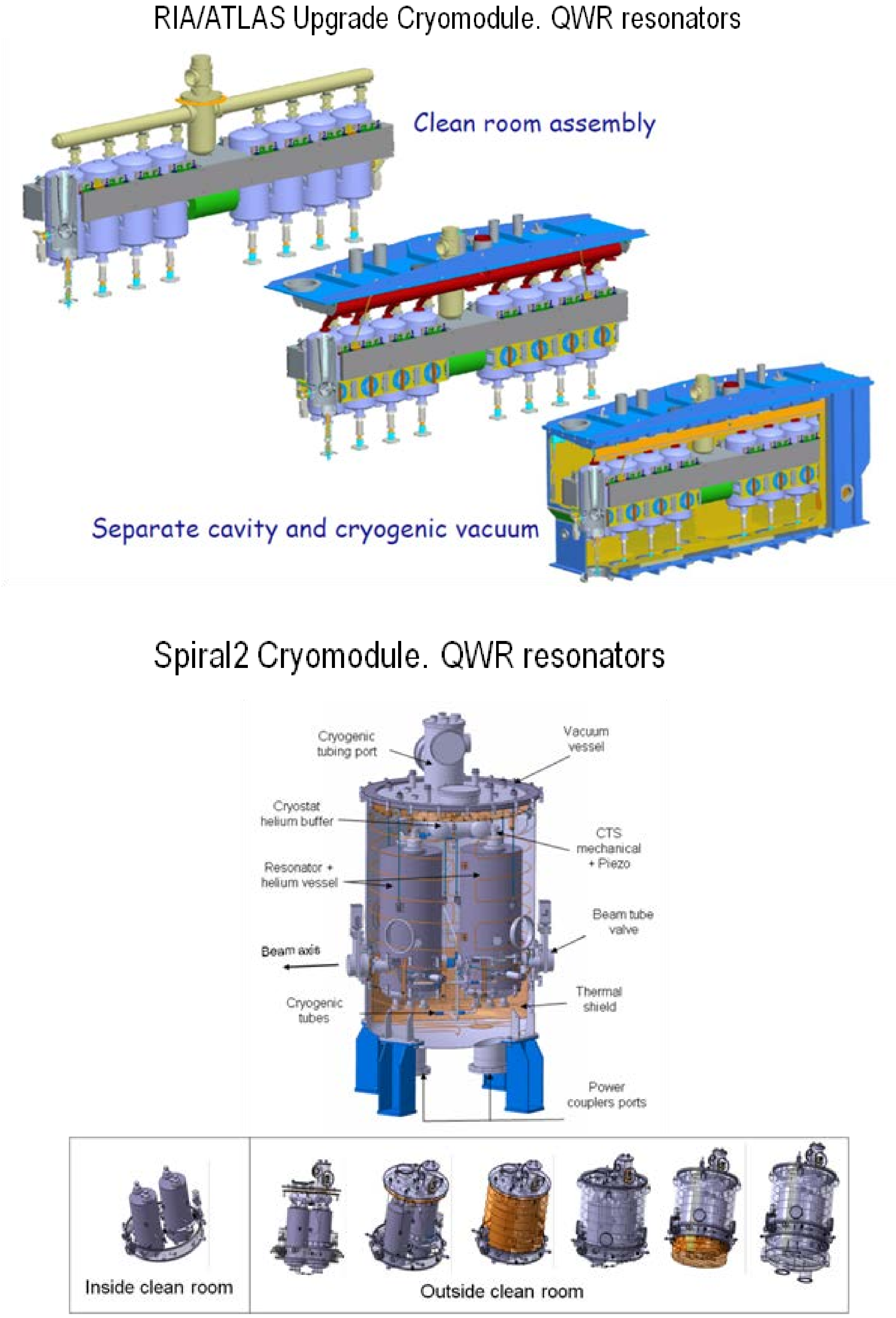


Figure 8: Vertical cryostating examples (accelerator cryomodules)

These two concepts can be schematically summarized on figure 9. The case one corresponds to an insertion of the cavity from the cryostat sides (Horizontal cryostating) and case 2 to an insertion from the cryostat top or the bottom (Vertical cryostating).

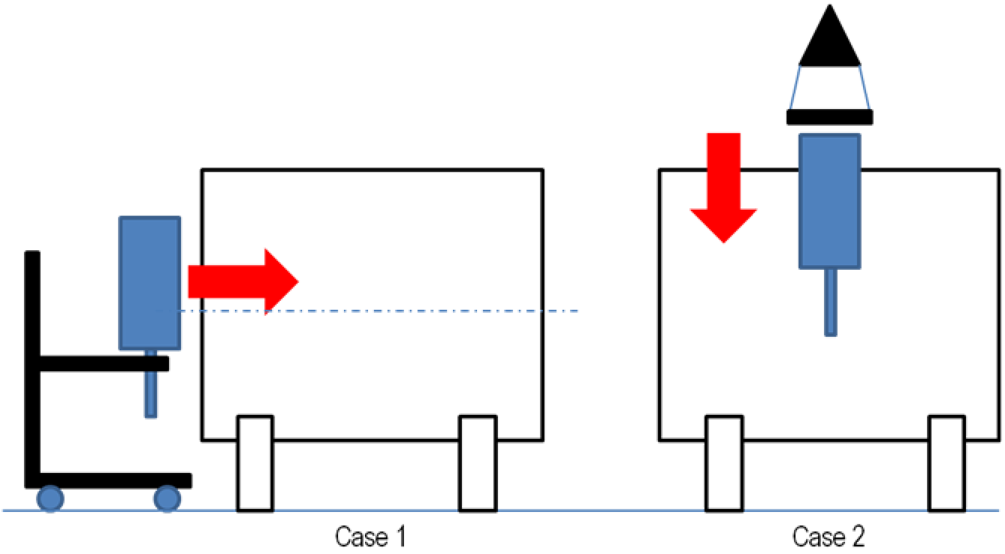


Figure 9: Case 1: Horizontal cryostating -Case 2: Vertical cryostating

Case 1 – Horizontal Cryostating.

This concept is the most common as it is well suited to elliptical cavities, having a horizontal axis symmetrical shape. Elliptical cavities being the most used cavities for superconducting accelerators there is a favorable feedback for the design and the manufacturing of such cryostat.

The cryostat cost, mainly dominated by the cost of the vacuum vessel and the thermal shield is also reduced as the cylindrical shapes are easy to manufacture. Concerning the vacuum vessel the cylindrical shape is well suited to withstand mechanical pressure loads involved by vacuum. The mechanical design and consequently the manufacturing are then easier and cheaper as it doesn't require additional stiffening elements or material. It is generally chosen for long accelerators project mainly to reduce the manufacturing cost of the cryostat vacuum vessel.

In the framework of a versatile test stand for low beta cavities, this solution exhibits several important drawbacks.

A special frame is required to insert the cavity and its coupler as well as the magnet inside the cryostat. This frame is expensive which may be relevant for a single cryostat unit as for a test stand.

The second drawback is related to the overall dimensions of the set composed by the cavity and its power coupler. The commonly designed power couplers have, for cost and reliability reasons, only one warm window at 300K. This window for thermal optimizations has to be far from the cold cavity part, at least 300/400 mm. This increase the overall length of the cavity/coupler set. In any case the cryostat must have, inside the thermal shield space, an available section sufficient for the overall length of the cavity/coupler assembly. The figure 10 of the section of the Freya test cryostat dedicated for ESS spoke and elliptical cavities shows this assembly aspect of horizontal cryostating.

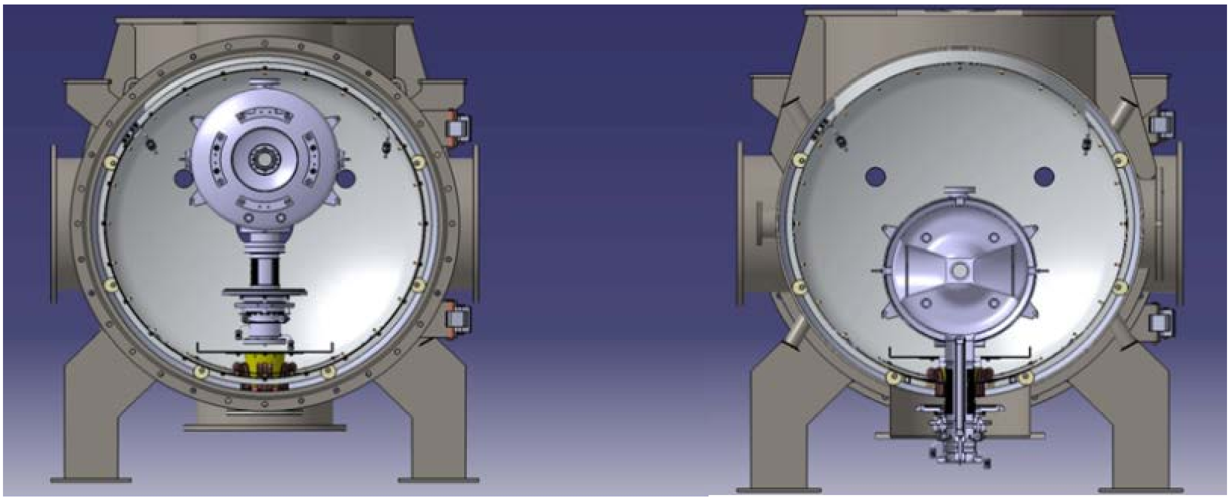


Figure 10: Freia – Assembly of ESS Spoke Cavity

The cavity/coupler set is inserted off-axis and then moved to the bottom or the side of the cryostat to allow the warm part of the coupler to be connected out of the cryostat vacuum vessel. It leads that the minimal diameter (nearly the vacuum vessel diameter) of the thermal shield section is at least the cavity/ coupler set overall length.

For the Tiara cryostat, first studies on the various cavities foreseen to be tested, show that a height (Half waves and Quarter Waves cavities have a vertical Axis) of around 2 m is required for the cavity/coupler plus an additional space for the cryogenic components (Cryogenic tubes, Helium vessel buffer…). It would lead to an around 2,5 m diameter cylinder vacuum vessel, which would occupy an important surface on the test stand site. It will also because of the great diameter of the vacuum vessel with respect to the cavity size make difficult the accessibility to the center of the cryostat. This is not compatible with a test cryostat which must enable a good accessibility around the cavity for test preparation purposes (sensor positioning and wiring, components assembly and disassembly as the cold tuning system…).

Case 2 – Vertical Cryostating

In this case the price of the Cryostat vacuum vessel is more expensive but the insertion can be performed using a typical crane instead of a special cryostating frame.

The surface occupied by the cryostat on the hall ground is also reduced, around 2,7 m long for 1,5 m large, saving space on the test site. It gives more compliance and makes easier the assembly of the cavity in the cryostat. For a large accelerator project (many units) this design would be merely adopted, because of the cost. But for a test cryostat for which many mounting and dismounting are required the easiness of assembly is a major issue.

A major drawback is related to the building where the test stand will be installed, as, to perform the insertion from the top a minimal height of about 2,5 m, in first approximation, is required from the top of the cryostat vacuum vessel. It leads to have the cryostat assembly inside a hall equipped with a handling crane having a hook height of at least 6 m.

The main advantages and drawbacks of the two options are summarized in Table 1 below.

Cryostat type	Pros	Cons
Option 1 (horizontal)	Vacuum vessel low cost	require a special frame for cavity string insertion (different for each cavity type) large diameter (large test stand footprint)
Option 2 (vertical)	more versatile reduced dimensions	cost

Table 1: advantages and drawbacks of the two different cryostat configurations

The design solution based on a vertical cryostating is the one adopted, mainly based on the versatility criteria. It leads, in order to be convenient with the gain of place that vertical cryostating offers, to chose a parallelepipedic cryostat shape design.

4. TIARA Test Cryostat Design

4.1. Cryostat layout

The layout of the cryostat and its conceptual cryogenic flow scheme is shown in figure 11.

The thermal shield of the cryostat will be cooled using LN2 (77 K at 1 atm.) which easily available for a test stand. Two separate cool down loop, one for the SC Magnet and the other one for the SC cavity, enter from the bottom of each helium vessel components in order to have an efficient cooling. The cold vapors having a greater surface exchange (better use of the gas enthalpy) with the material to cool, before exhausting.

The LHe Buffer is maintained at a constant level by mean of a regulation cryogenic valve, situated inside the cold valves box. It fills the cavity and the SC magnet helium vessels as well as an auxiliary loop that can be used to perform various thermal interceptions (power coupler outer conductor for instance) if required.

The SC magnet power supply wires are cooled with the cold sc magnet helium vessel returning vapors. For this stage of the study, the filling of the sc magnet and its power supply wires cooling is performed in parallel with the sc cavity cooling. Great flow difference (to be studied) resulting in the difference of the cryogenic power required for the cavity and the sc magnet may occur. It would then be necessary to separate these two loops from the LHe cryostat buffer. The filling of the SC cavity and the Sc magnet would then be in parallel from the filling cold valves box LHe buffer.

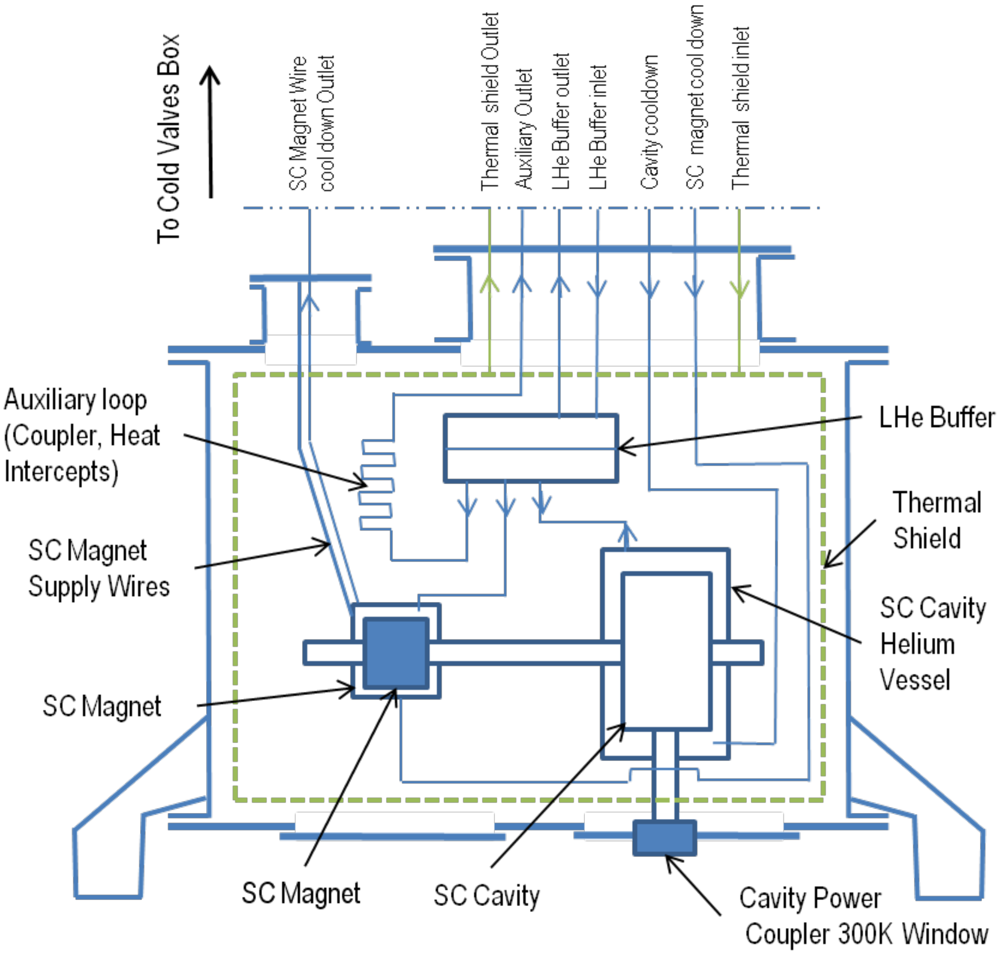


Figure 11: Tiara Cryostat flow scheme overview

4.2. Main components

The different components and features of the cryostat are described on figure 12.

The vacuum vessel features large top and bottom flanges. The top flange will sustain the LHe volume buffer and the cryogenic tubes, the cavity and the SC magnet supporting frame and the thermal shield, the cryogenic feeding line connection, the generic instrumentations feed through.

The bottom flange will have 2 large DN 500 flanges to allow the positioning of the power coupler warm windows. The position of this window will be different from one cavity type to another. It will then be required to machine a new flange for each cavity type to be tested. The vacuum vessel sides are design with large rectangular flanges, to allow good accessibility inside the cryostat toward the cavity, and eventually to add horizontal feed through when required by the cavity type to be tested (Horizontal power coupler for instance).

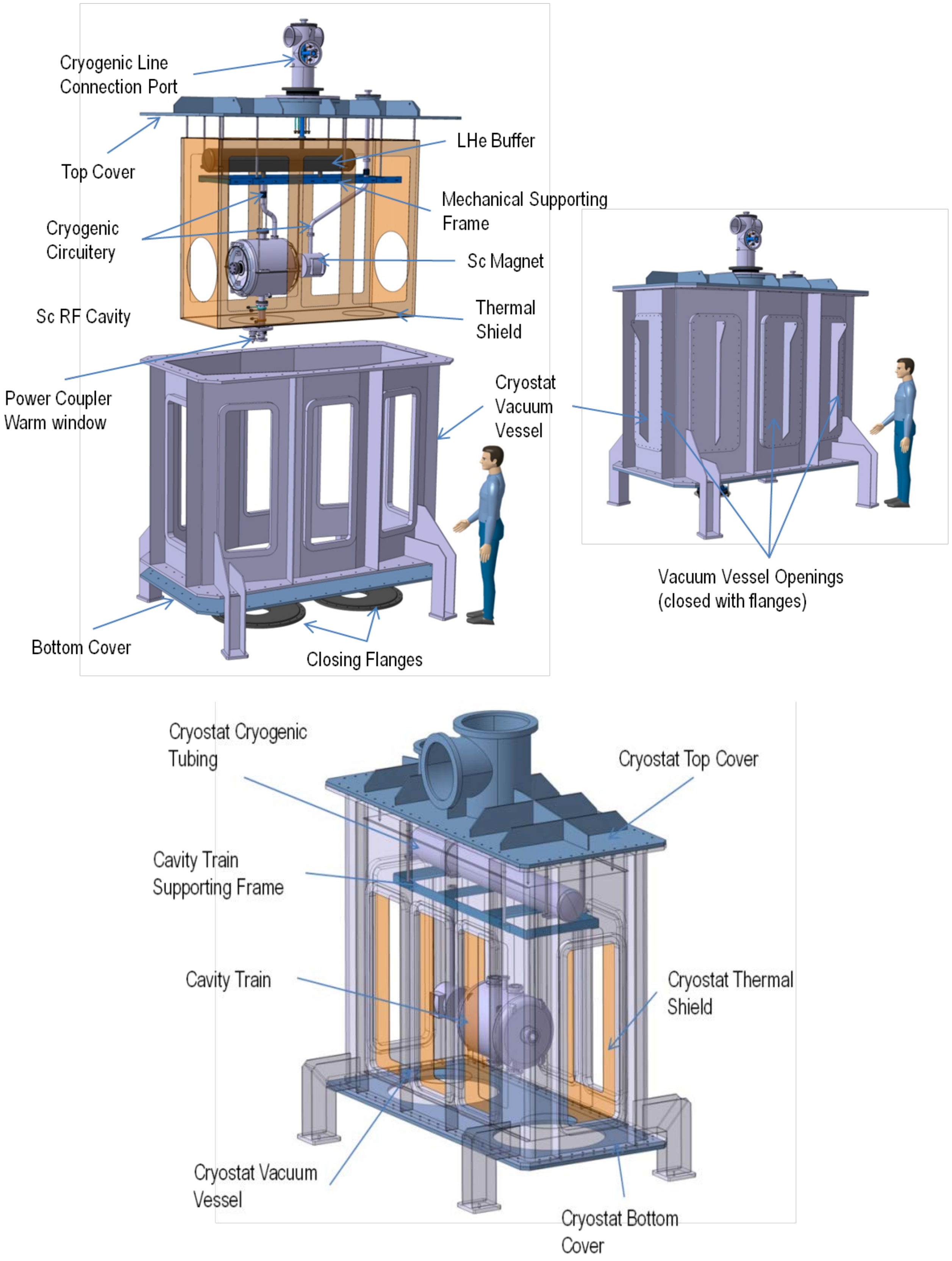


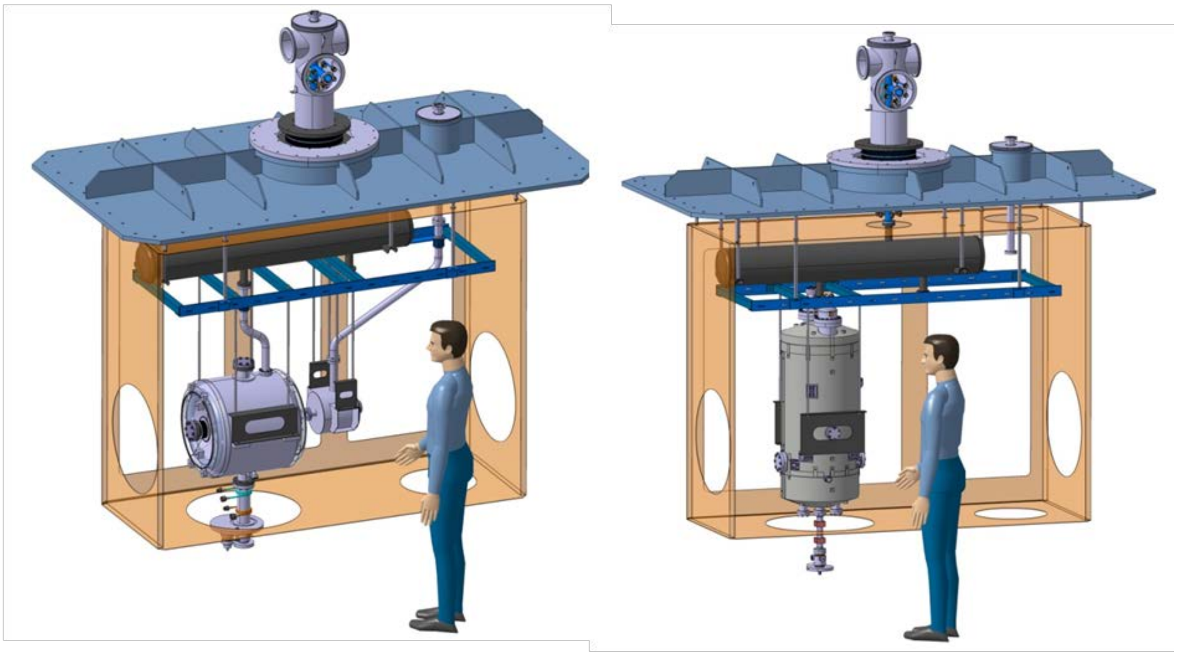
Figure 12: Different views of the cryostat main components

The thermal shield made from Copper is sustained by the Top cryostat flange. It is cooled with LN2 circulating inside a DN 10 tube, brazed on the shied. The shield features large dismountable parts that will have to be machined for each cavity/coupler set type in order to allow the coupler warm block window to be connected to the vacuum vessel.

The cryogenic circuitry and the LHe buffer, having a large capacity, are supported by the top cover. The helium buffer capacity currently designed is around 20 liters, but may be increased to around 50 liters. The evaporation of LHe at 4K is corresponding to a loss of liquid of around 1,4 liters per hour. With an estimated 10 W static dissipation at 4 K, a LHe buffer of around 50 liters gives an autonomy (keeping the cold mass at 4K, and with no additional liquid filling in the cryostat) of around 3.5 hours, which is convenient for cryogenic tests operations. This cryostat autonomy is compatible with the two LHe supply possible configurations: from large dewars (typically 400 to 500 liters) or from an helium liquefier (providing that an intermediate connection box is interfacing the cryostat valve box with the liquefier cryogenic supply lines).

4.3. Cryostat overall dimensions

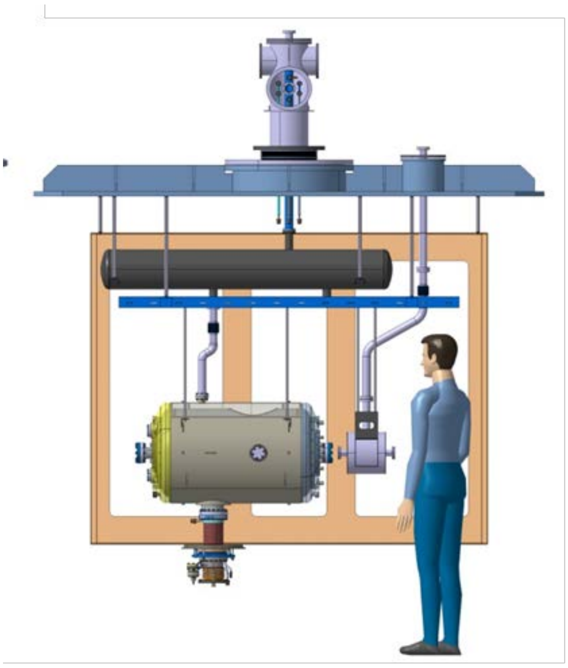
The cryostat overall dimensions are determined from the dimensions of several existing low beta cavities (see figure 13 & 14) taking into account their operating position and the length (and assembly) of the associated power coupler.



350 MHz One bar Spoke Cavity (MYRRHA)+ Sc Magnet

88 MHz QWR (Spiral2)+ Sc Magnet

Figure 13: Various cases of low beta cavity integration inside the cryostat (with a single spoke cavity on left hand side, and with a quarter wave resonator on the right)



350MHz Two bar Spoke Cavity (Ess) +
Sc Magnet

Figure 14: Case of low beta cavity integration inside the cryostat with a double spoke cavity

A special case was studied for the IFMIF 175 MHz half wave resonator cavity for which the cavity axis is horizontal in its accelerator configuration (see Figure 15 & 16).

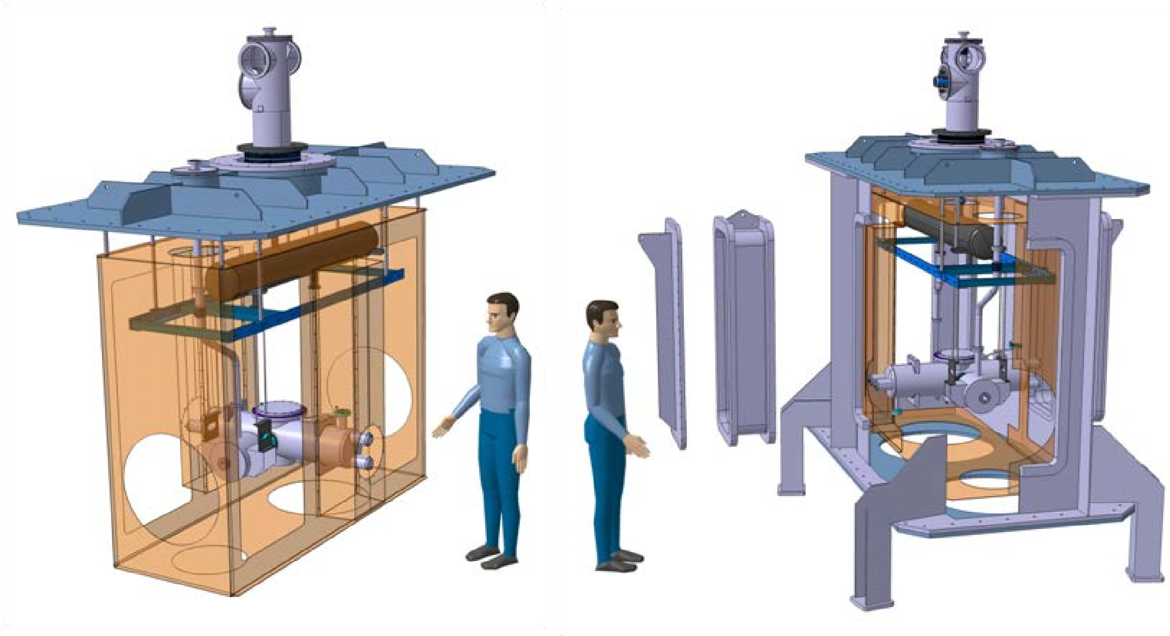


Fig 15: Integration of the IFMIF 175 MHz HWR in the horizontal position

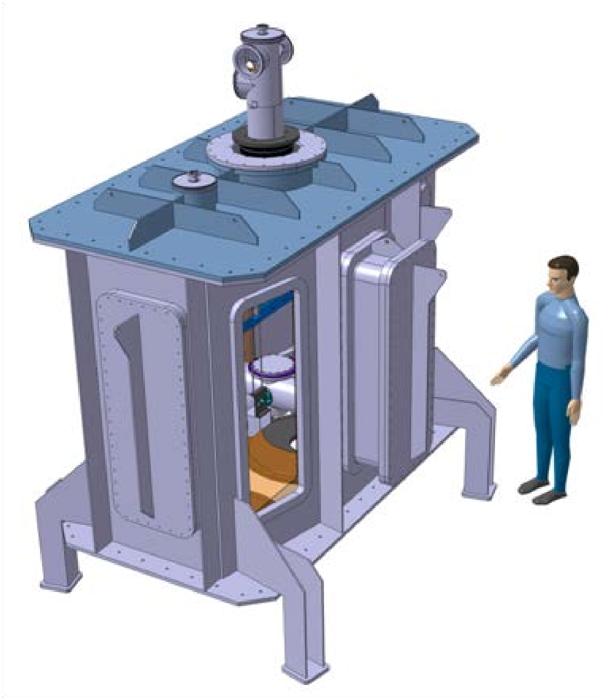


Fig 16: Integration of the IFMIF 175 MHz HWR in the horizontal position

In the case of IFMIF the lateral overall length imposed by the cavity position will be managed by adding length on the cryostat side flanges.

A large LHe vessel situated inside the cryostat has been chosen to allow an important buffer volume, convenient for the cryogenic tests operations as it provides more autonomy in case the LHe feeding dewar is empty. A cryostat filling valve box, composed of buffer volumes, heat exchanger, cryogenic valves, gas heater…, required for the cryogenic fluid supply and the overall cryogenic operation of the cryostat is not part of the study. This valves box, will be apart from the cryostat, located to its side, and will be connected to the cryostat top cover by mean of a cryogenic line. This line insures the thermal insulation for the different, inlet and outlet liquid and cold gas circuits required for the cryogenic process. The connecting flange of this line is placed on the Cryostat top cover.

The overall dimensions of the cryostat are given in figure 17.

The cryostat height itself is 2000 mm. The bottom flange is situated at around 500 mm from the ground in order to leave space for the assembly of the coupler power supply transition for either coaxial line or wave guides. At this stage of the study the top cover and the connection to the cold valves box is 900 mm. This important height could to be reduced and constitute a design optimization for a further design stage. The top and bottom flanges are 2700 mm long and 1500 mm large and the rectangular flanges on the 4 sides of the cryostat are identical and are 1400 mm height and 500 mm large.

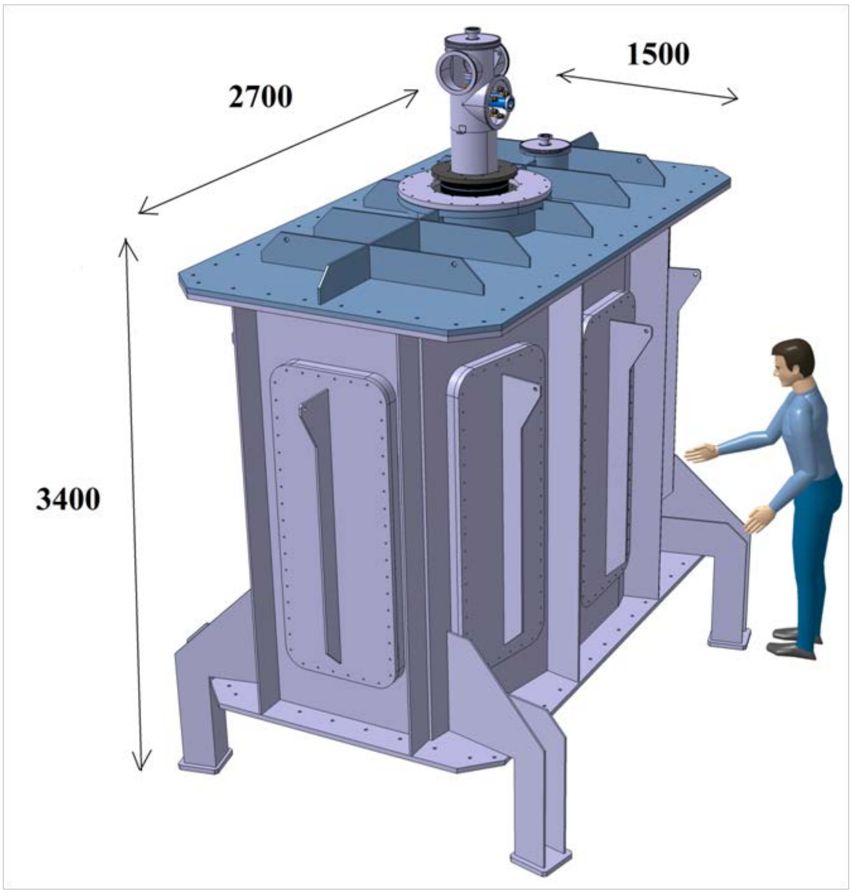


Figure 17: Test cryostat overall dimensions

4.4. Versatility / compliance

The main constrain on the versatility of this type of test cryostat comes from the parts having a rigid connection between 4 /2 K to 300 K (mainly the RF coupler for SC cavities applications). As the cavity may have different dimensions for a same type, may be of different types and may have different RF coupler dimensions and types, it is impossible to reach a universal cryostat shape. The solution is to design the cryostat with as much modularity possible with the lowest manufacturing cost. It is the reason why the cryostat will have a large number of flanges and openings, giving a large amount of possible positions for the cold/warm rigid connections. Thus the cavity/coupler set and the SC magnet could be positioned inside the cryostat taking into account their relative position to the available openings. The closing vacuum vessel flanges would then be machined to allow the mechanical interface with the power coupler warm window connecting part.

4.5. Cryostat assembly

As already mentioned the cavity/coupler set has to be assembled inside iso4 clean room to minimize dust pollution and prevent the electric field emission during operation with RF power. Working inside clean room requires important rules to insure a dust free assembly. Introducing inside the clean some materials as MLI for instance has to be avoided. A rule of thumb is to have as less material and mechanical parts close to the parts that have to be assembled inside the clean room, mainly, in our case, the cavity and coupler connection. It is the reason why the general design goal of a SC cavity cryostat aims to have, for the clean room assembly stage, only the minimal parts (the cavity, the RF coupler and a light supporting frame) inserted inside clean room. The remaining parts of the cryostat have then to be assembled, around the cavity/coupler set, outside the clean room. Once assembled inside the clean room the RF volume defined by the cavity inner volume and the coupler inner volume up to the warm window must be protected from any air contamination. A stop valve (all metallic UHV valve), assembled inside the clean room is dedicated to isolate the RF volume from the clean room stage, up to the final installation stage for tests at 4/2K.

Once prepared inside clean room the cavity/coupler set, supported on a simple table-like frame, is released outside the clean room and hanged to the mechanical support frame of the cryostat top cover, itself hanged to the assembly hall handling crane. All the mechanical and instrumentation operations, on the inner part of the cryostat, called ‘cold mass’, (SC magnet assembly, sensors, cryogenic pipes assembly, MLI assembly, thermal shield assembly, cold tuner assembly…) can then be performed with a good accessibility.

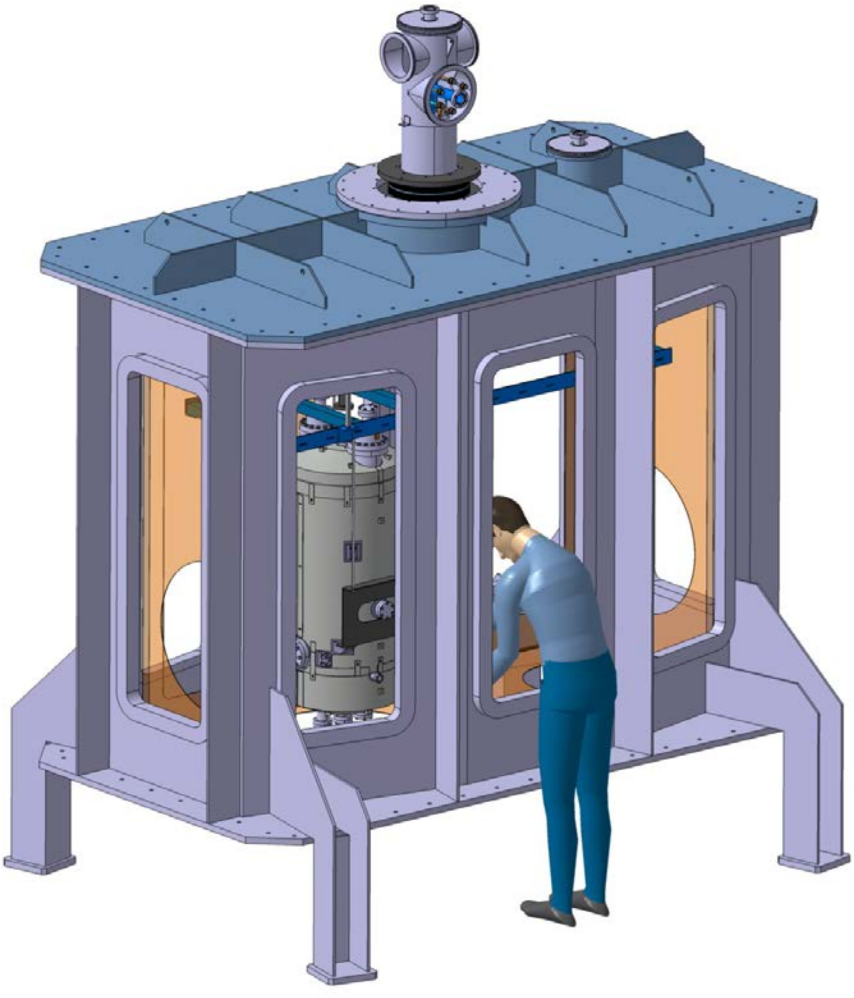


Figure 18: Large openings all around the cryostat for cold mass accessibility and assembly or connection of instrumentation.

When these assembly operations are achieved, the so-called 'insert', composed by the top cover and the cold mass is assembled within the cryostat vacuum vessel. Once the insert is inside the cryostat it is still possible, with a good accessibility provided by the large openings on the sides of the cryostat vacuum vessel (see Figure 18), to work on the cold mass, close to the cavity, to mount or connect the remaining specific instrumentation…

At least, the thermal shield and the vacuum vessel openings are closed with cups and flanges. The power coupler interface flange is finally connected to the coupler warm window mechanical interface, which might be specific for the different cavity/power coupler cases.

This assembly sequence is summarized in figure 19.

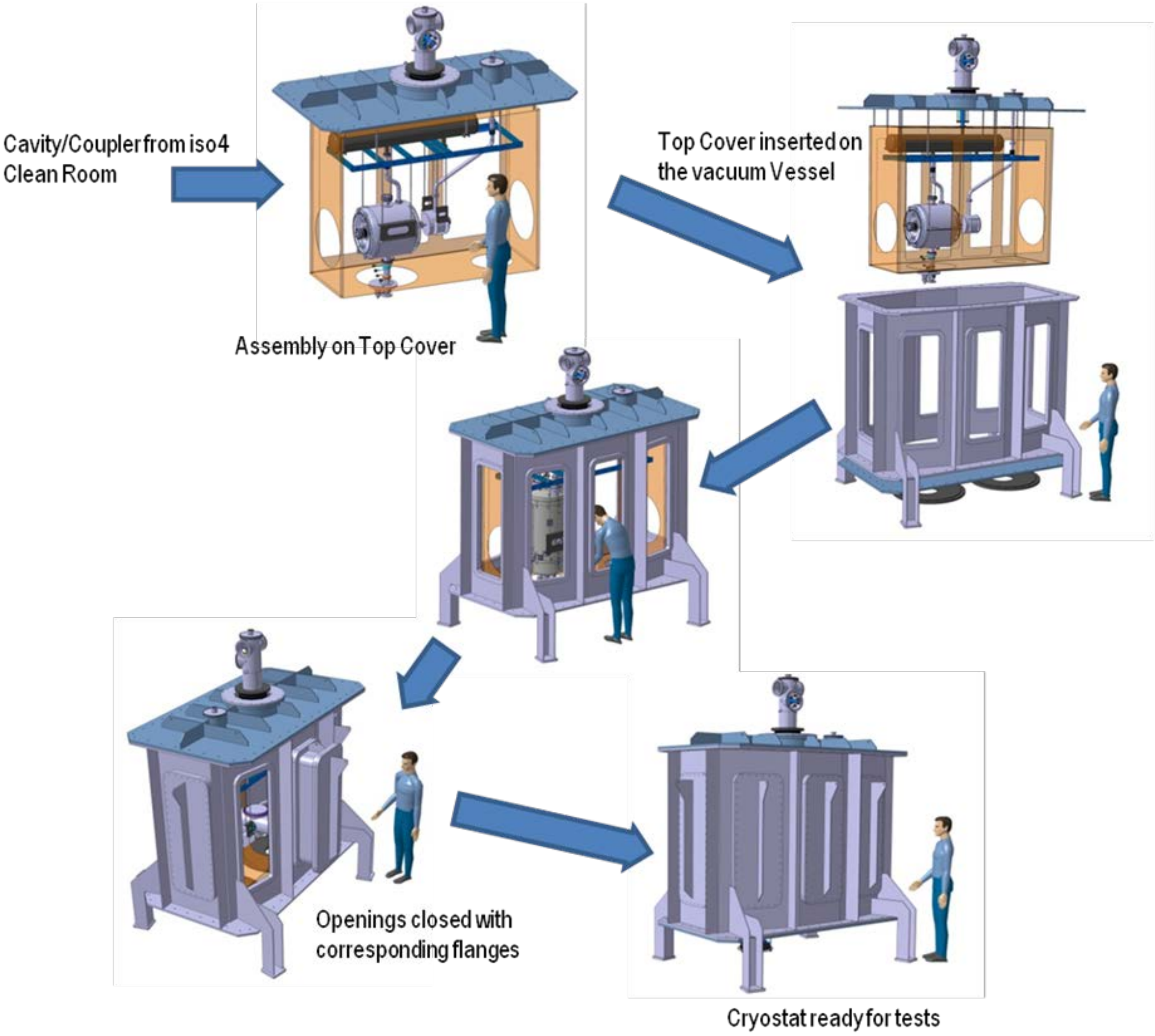


Figure 19: Cryostat assembly sequences

4.6. Vacuum vessel detailed design and mechanical analysis

The main issue for this type of cryostat is concerning the vacuum vessel mechanical design. Because of its flat sides, the vessel is subjected to high deformation and stress while under vacuum. To achieve resistance to the required 1 bar external pressure, a specific design has to be done with the goal to optimize the thickness of the vessel and the number of stiffening parts, in order to reduce the weight and the manufacturing cost.

A detailed study using Finite Element Method (FEM) mechanical simulations for static and buckling load cases have been performed to determine the best suited vessel shape, vessel parts thicknesses and required stiffeners.

A first simulation was performed on a simple parallelepipedic vacuum vessel, with smaller dimensions than the final dimensions cryostat, loaded by 1 bar external pressure (see Figure 20). It shows high deformations (15 mm maximum on the vessel sides) and maximal Von Mises stress (430 MPa maximum). These values are above the typical yield stress for stainless steel, of around 185 MPa, meaning that this cryostat could not sustained the pressure load.

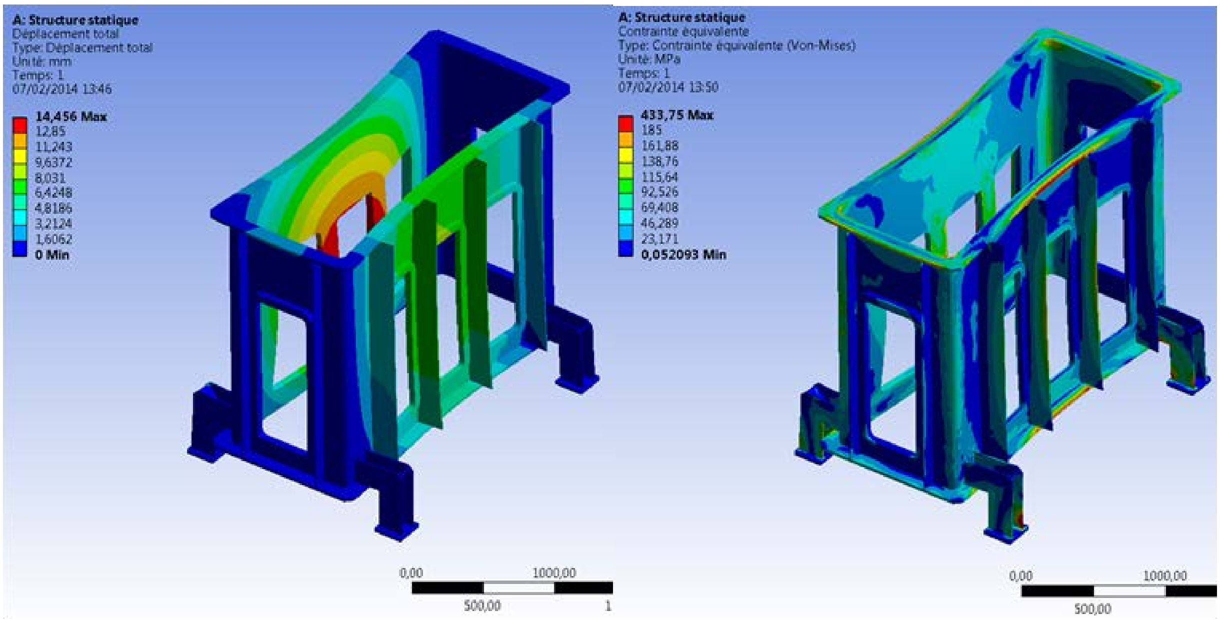
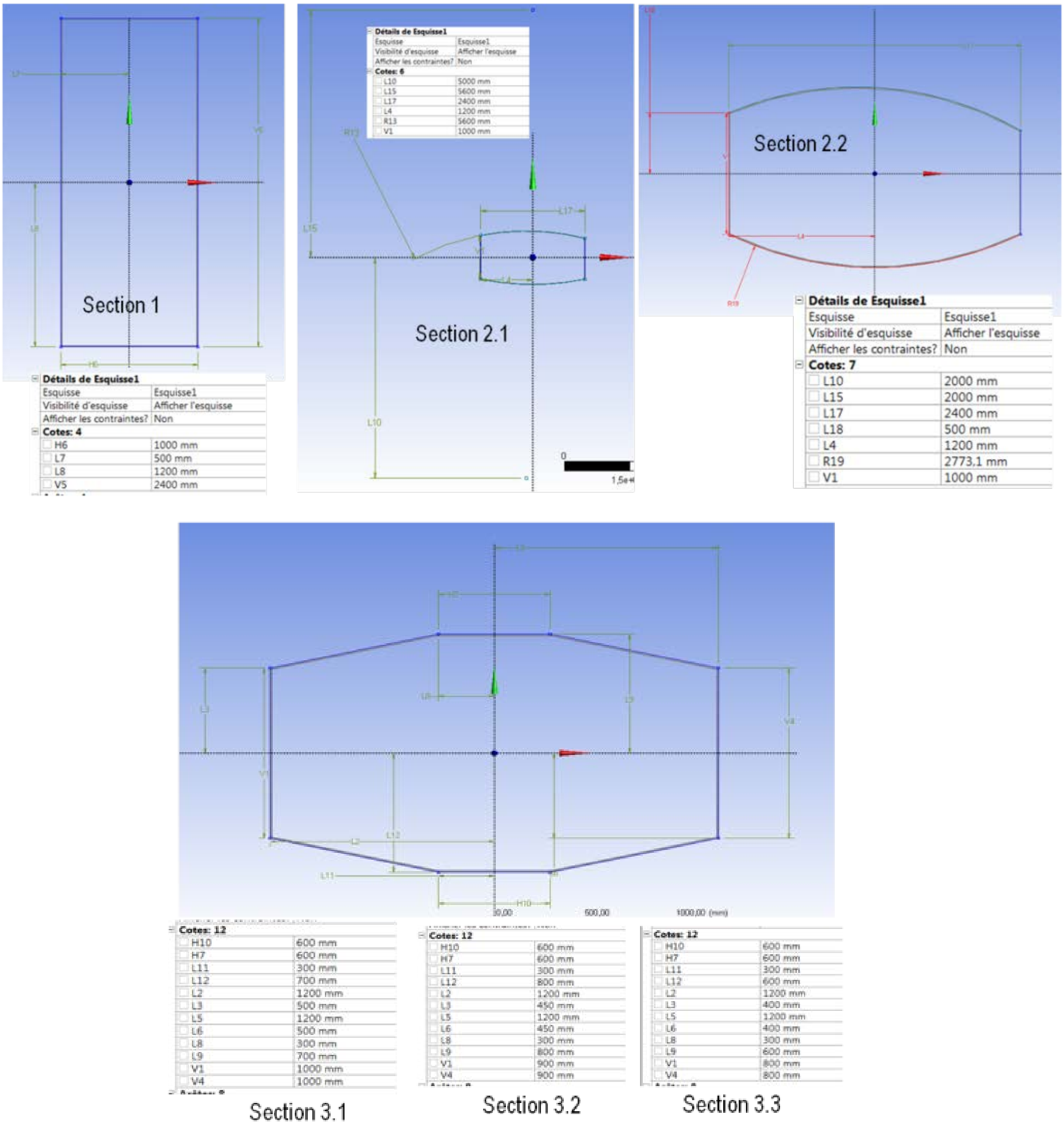


Figure 20: FEM simulation on a simple cryostat configuration (parralelepipedic vacuum vessel)

To increase the vacuum vessel resistance, without increasing its wall thickness and the number and the inertia of the stiffeners, a study on the vessel section was done. A simple rectangular section (section 1) was compared with hexagonal (section 3) and semi circular sections (curved on the large sides- section 2) shown on figure 21. The numerical calculations were done without taking into account the effects of stiffening parts, taking for all models a wall thickness of 10 mm with an applied load of 1 bar external pressure.



Section 1

Détails de Esquisse1	
Esquisse	Esquisse1
Visibilité d'esquisse	Afficher l'esquisse
Afficher les contraintes?	Non
Cotes: 4	
☐ H6	1000 mm
☐ L7	500 mm
☐ L8	1200 mm
☐ V5	2400 mm

Section 2.1

Détails de Esquisse1	
Esquisse	Esquisse1
Visibilité d'esquisse	Afficher l'esquisse
Afficher les contraintes?	Non
Cotes: 6	
☐ L10	5000 mm
☐ L15	5600 mm
☐ L17	2400 mm
☐ L4	1200 mm
☐ R13	5600 mm
☐ V1	1000 mm

Section 2.2

Détails de Esquisse1	
Esquisse	Esquisse1
Visibilité d'esquisse	Afficher l'esquisse
Afficher les contraintes?	Non
Cotes: 7	
☐ L10	2000 mm
☐ L15	2000 mm
☐ L17	2400 mm
☐ L18	500 mm
☐ L4	1200 mm
☐ R19	2773,1 mm
☐ V1	1000 mm

Section 3.1

Cotes: 12	
☐ H10	600 mm
☐ H7	600 mm
☐ L11	300 mm
☐ L12	700 mm
☐ L2	1200 mm
☐ L3	500 mm
☐ L5	1200 mm
☐ L6	500 mm
☐ L8	300 mm
☐ L9	700 mm
☐ V1	1000 mm
☐ V4	1000 mm

Section 3.2

Cotes: 12	
☐ H10	600 mm
☐ H7	600 mm
☐ L11	300 mm
☐ L12	800 mm
☐ L2	1200 mm
☐ L3	450 mm
☐ L5	1200 mm
☐ L6	450 mm
☐ L8	300 mm
☐ L9	800 mm
☐ V1	900 mm
☐ V4	900 mm

Section 3.3

Cotes: 12	
☐ H10	600 mm
☐ H7	600 mm
☐ L11	300 mm
☐ L12	600 mm
☐ L2	1200 mm
☐ L3	400 mm
☐ L5	1200 mm
☐ L6	400 mm
☐ L8	300 mm
☐ L9	600 mm
☐ V1	800 mm
☐ V4	800 mm

Figure 21: Vacuum vessel section optimization.

The section 3.3 was chosen as it gives a rather good resistance without stiffening parts, far more than the simple rectangular shape (deformation reduced by a factor around 10), and a sufficient space to work around the cavity, once the cold mass is inside the cryostat. The section 2 also offers a good resistance to external pressure, but it is supposed, in a first approximation, more difficult to manufacture. The definitive choice, between section 2 and section 3 will be done after further discussions with vacuum vessel manufacturers, on the manufacturing risks and costs.

We give below the numerical results for section 3.3 without stiffening parts (see Figure 22).

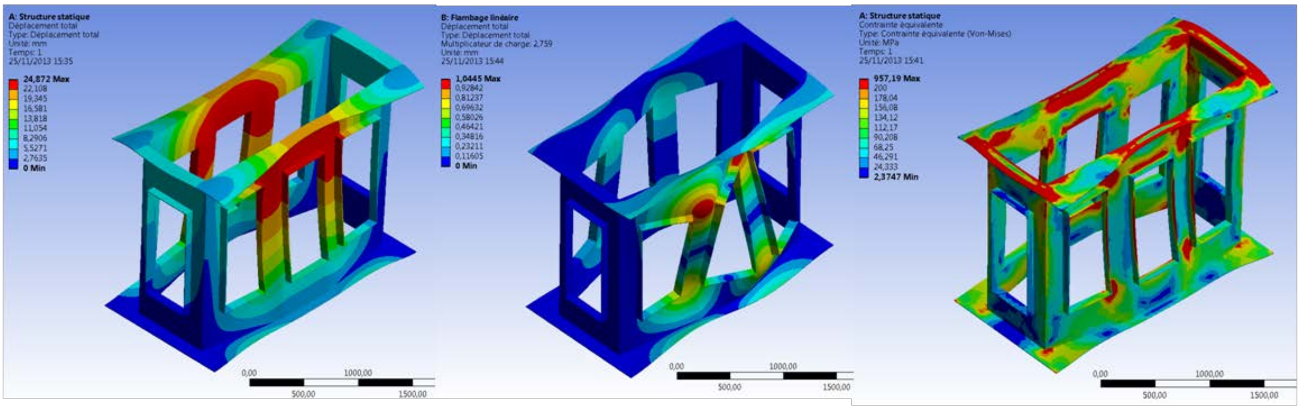


Figure 22: FEM simulation. Model section 3.3 without stiffeners

A design with simple stiffening elements has been done for a vacuum vessel having a 10 mm walls thickness (See figure 23). It gives good results but there is probably still some room for a further optimization. It appears that the weak parts are on the top and bottom flanges which then must be stiffened in the transversal direction. Further study may lead to increase the thickness of these flanges and add stiffening elements. Modification of the flange shape in order to increase its transversal inertia may also be investigated.

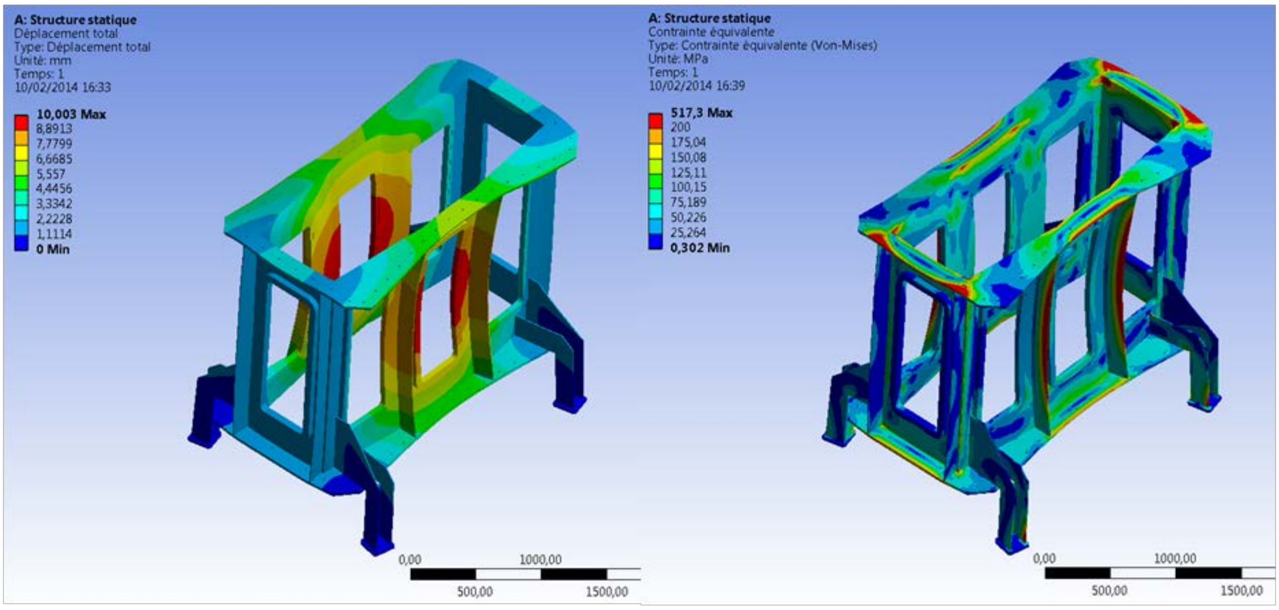
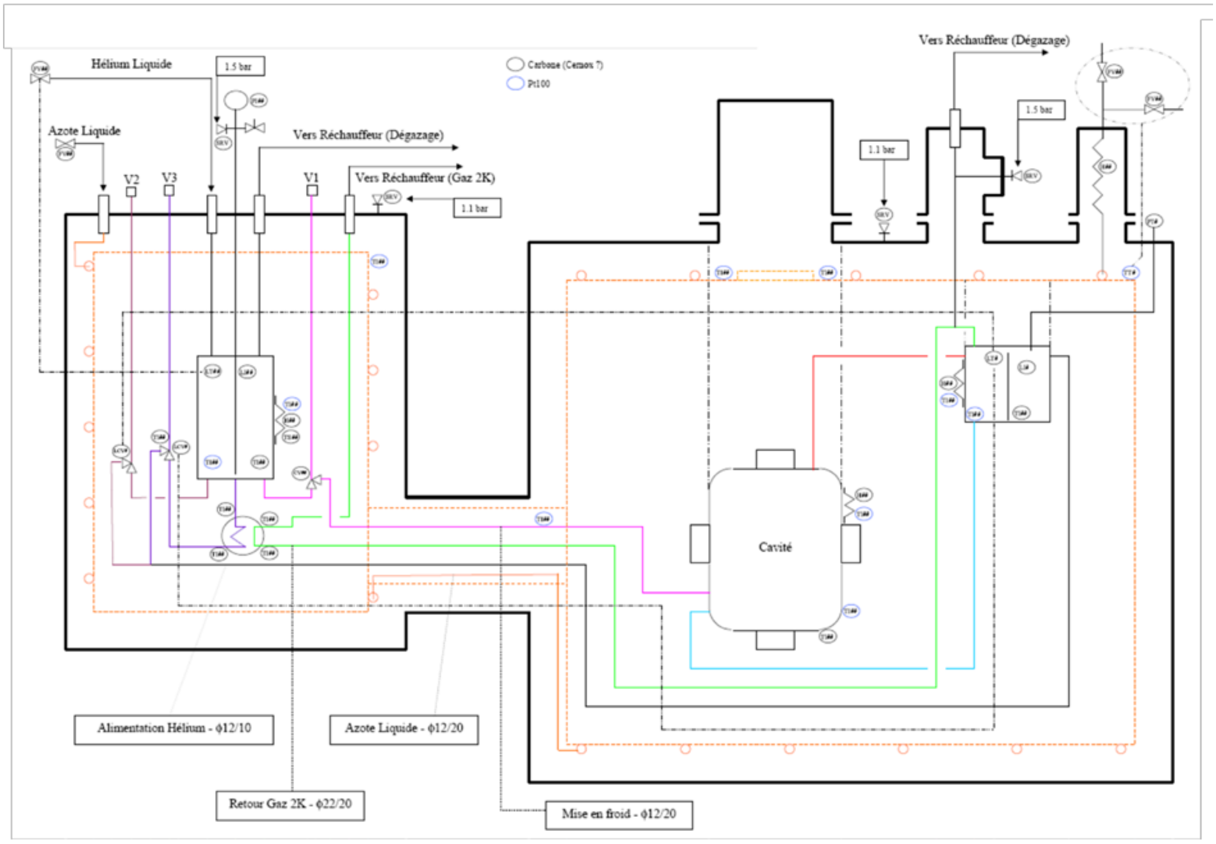


Figure 23: FEM simulations Model section 3.3 with simple stiffeners.

4.7. Associated valve box

The cold valves box, required for the cryofluids filling, has also been studied in the scope of Tiara, but at a conceptual level only, as defined in the work plan.

Its main purpose is to feed and evacuate the cryostat with the different cryogenic fluids, under different temperature and state (helium and nitrogen, under liquid or gaseous state). The principle of the valve box is given in figure 24, together with the required instrumentation (temperature sensors) and actuators (feed and relief valves). Such a cold valves box, delivering around 80 W @2K, enough to operate RF cavities cryogenic tests, is quite typical and its design is mainly orientated on the mechanical interface concerning the way it is installed inside the test hall and its connection, trough a cryogenic line to the cryostat. Its design does not present any major issues in term of complexity or required cryogenic power level.



Conceptual scheme of the cryogenic valve box and associated instrumentation for supplying the cryostat with the required cryogenic fluids.

5. CONCLUSION

Within TIARA-PP, we have performed an engineering detailed study of a versatile test cryostat for RF testing at cryogenic temperature low beta superconducting cavities equipped with their ancillaries systems such as the cold tuners and the power couplers. We have taken into account the user requirements for many projects (either in an R&D phase or a close to fabrication phase) and even imagine potential future needs of the accelerator community for testing this type of accelerator components.

A solution was found for the cryostat layout, which is compatible to almost all the user requirements. The overall dimensions of the space required to test a large amount of low beta cavity types was studied and led to define the final cryostat dimensions. The choice of a vertical cryostating and the use of the top cover, as a typical vertical cryostat insert, in order to hang the cavity/coupler set and the SC magnet, reveal to be best suited for such a versatile test cryostat. The assembly and insertion of the different cavity types has been study to check the effective versatility of the cryostat. The design of the thermal shield, the cryogenic tubing, the LHe buffer and the supporting frame are typical for this kind of cryostat and these components have been defined at a conceptual level as these parts does not bring any specific complexity.

The main mechanical design issue was the vacuum vessel, as it integrates many large openings, the only possible technical answers to reach a high degree of versatility. Numerical simulations were performed on several vacuum vessel shapes and allowed to achieve the optimization of the vessel in term of mechanical resistance to external pressure load. Some specific optimization points may still be studied further on, such as the overall height of the cryostat, currently dominated by the height of the cryogenic line connection port: there is a potential of optimization here, and it could be minimized to reduce the required height of the cryostat assembling hall.

Such a cryostat would be a key R&D infrastructures for accelerators in order to give the possibility to test fully equipped low beta cavities in an accelerator-like configuration, and then to definitively validate and assess their performances for beam acceleration.

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