**ISTITUTO NAZIONALE DI FISICA NUCLEARE**

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# NOTE ON TYPE 3 TTF CRYOMODULE

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## Abstract

This document describes the design and production of a type 3 TTF cryomodule designed by INFN in the framework of the TESLA1-2) Collaboration. The aim of this report is to document the design and the cryomodule production, starting from the material choices up to the production tests. As reference for the cryomodule production and test have been considered the two cryomodule type 3+ fabricated at "E. Zanon" company during 2007.

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## INTRODUCTION

This document describes the design and production of a type 3 TTF cryomodule. It is a superconductive RF cryomodule designed by INFN in the framework of the TESLA1-2) Collaboration as a base component of the superconductive Linear Collider; the modules have been produced and successfully tested at the TESLA Test Facility (TTF), the facility realized at Desy (Hamburg) for the characterization of the modules.

The cryomodule design has reached its third generation introducing improvements to solve aspects and problems pointed out by the assembling of first cryomodule (type 1) and the fabrication of second and third (type 2). Guidelines and solutions have been changed through each step till coming to the actual design, tested at Desy TTF (now FLASH), and adopted as the reference design for both the international projects: ILC (the International Linear Collider) and XFEL (the European X-Ray Laser Project).

The aim of this report is to document the design (including physical or technical reasons of some critical aspects) and the cryomodule production, starting from the material choices up to the production tests. As reference for the cryomodule production and test have been considered the two cryomodules type 3+ fabricated at "E. Zanon" company during 2007. The main differences between type 3 and type 3+ are resumed in the final part of this report.

The layout of the document is the following:

Part 1 describes the general layout of the module followed by a list of the components and a detailed list of the geometrical parameters of the individual components. The properties of the parts are described and justified according to the physical or economical request.

Part 2 includes a description of the principal characteristics of all the materials used in the cryomodule and a "part – material" list; the aim of this part is to explain the choices of the materials related to the structural and physical properties of the different parts.

Part 3 resumes the required verifications, either ASME or PED code, for the parts under internal or external pressure.

Part 4 contains the operation list for the production of the cryomodule from the steel plates to the finished module and all the particular procedures needed to obtain the desiderated design within the specified tolerances and alignment needs.

Part 5 describes the quality control plans carried out on the single parts or on the whole assembly to verify the component production (e.g. vacuum seal of the welds, the presence of cracks ...).

Part 6 resumes the main differences between cryomodules type 3 and type 3+.

# 1 CRYOMODULE GEOMETRY

## 1.1 The cryomodule general layout

The cryomodule contains eight superconducting RF cavities and a superconducting quadrupole package. Cavity support, alignment, cooling and thermal insulation are all provided by the cryomodule. In addition, the cryomodule must provide the feedthroughs for the RF power and instrumentation, as well as the connection to adjacent cryomodules.

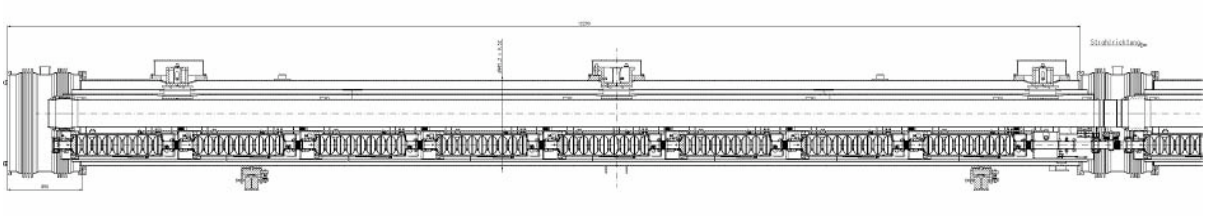

**Figure 1: longitudinal section**

Figure 1 shows a longitudinal view of a cryomodule. The 300 mm diameter helium gas return pipe (HeGRP) is the main support structure for the string of cavities and magnets. The HeGRP is supported from above by three composite material posts which provide the necessary thermal insulation from the environment. The posts are connected to large flanges on the upper part of the vacuum vessel by adjustable suspension brackets, allowing the axis of the cavities and quadrupoles to be correctly aligned, independent of the relative flange position[8)] [10-13)].

The support system is designed to allow the HeGRP (carrying the low pressure 2 K vapor from the cavity string) to contract/expand longitudinally with respect to the room temperature vacuum vessel during thermal cycling. The centre post is fixed to the vacuum vessel, while the two end brackets can slide in the axial (z) direction to accommodate differential shrinkage. A post consists of a fiberglass pipe terminated by two shrink-fit stainless steel flanges. Two additional shrink-fit aluminum flanges are provided to allow intermediate heat flow intercept connections to the 5 K[1] and 70 K[1] thermal shields; the exact location of these flanges has been optimized to minimize the heat load.

Each of the 8 cavities is encased in a titanium helium vessel, attached to the HeGRP by means of stainless steel shapes connected to four titanium pads on the vessel itself; each shape is equipped with a longitudinal sliding mechanism, adjusting screws and pushers for alignment. A mechanical and a piezo-electric tuner are mounted to the vessel. The length at warm condition of a cavity included the interconnection space (distance measured from coupler input to coupler input) is typically 1380 mm (1377.7 mm at cold); with a standard TTF cavity length 1036.2 mm results an inter-cavity spacing (defined as the end dish iris-to-iris distance between adjacent cavities) around 344 mm.

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[1] This is a nominal value: due to the length of the cryogenic string (hundreds of meters) there is a temperature gradient along the shields: 5-8 K and 40-70 K.

Manually operated valves required by the clean-room assembly terminate the beam pipe at both module ends. The valves are fitted with standard RF shields.

During cool down the two ends of the 12 m long gas return pipe move by up to 18 mm toward the centre of the module. To keep the cold input coupler head of each cavity fixed longitudinally within an accuracy of 1 mm, each cavity is anchored to one of the two invar rods attached to the suspension shape nearest to the centre of the gas return pipe, by a clamp at the coupler end of the cavity. The sliding rollers on the suspension shapes decouple the longitudinal cavity position from the huge HeGRP shrinkage.

The interconnection bellow between the cryomodules incorporates a Higher Order Mode (HOM) absorber, bellows, and a vacuum pumping port.

The cryostat includes two aluminum radiation shields operating in at the nominal temperature of 5 K and 70 K respectively. Each shield is constructed from a stiff upper part (conceptually divided into two structural halves), and 8 lower sections (according to the number of cavities). The upper parts are supported by the intermediate flanges on the fiberglass posts; they are screwed to the centre post but can axially slide on the other two posts, to which they are thermally connected with proper copper braids. The "finger welding" technique[7)] is used both to connect each thermal shield to its properly shaped aluminum cooling pipe, and the lower shield parts to the upper ones.

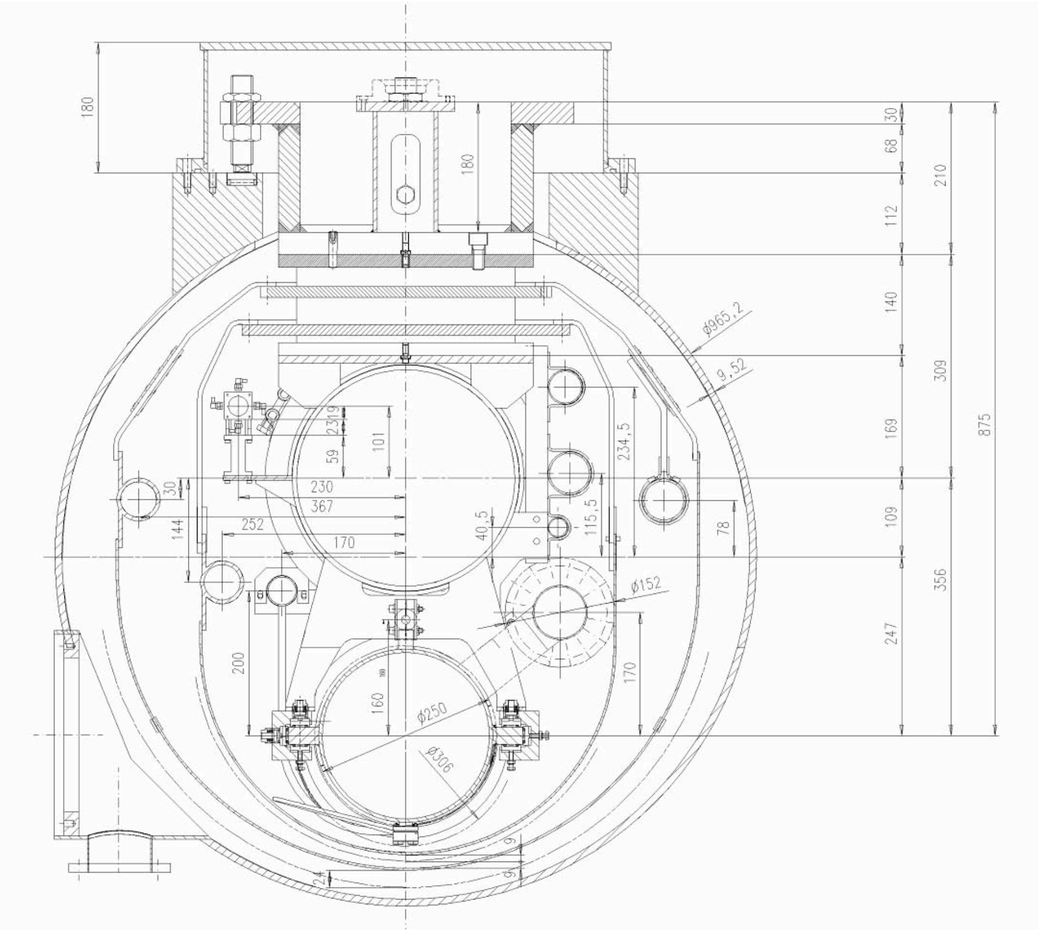

**Figure 2: transverse section**

Blankets of multi-layer insulation (MLI) are placed on the outside of the 5 K and the 70 K shields. The 5 K shield blanket is made of 10 layers while the 70 K blanket contains 30 layers. In addition the cavity and quadrupole helium vessels, gas return pipe and 5 K pipes are wrapped with 5 layers of MLI to reduce heat transfer in the event of a vacuum failure.

Figure 2 shows a cross section of the cryomodule. The cryostat outer vacuum vessel is made of carbon steel and has a standard diameter of 38” and thickness of 3/8”. Adjacent vacuum vessels are connected to each other by means of a cylindrical sleeve with bellows, which is preassembled at one side. Radiation shield bridges between adjacent modules are also provided. In the event of accidental spills of liquid helium from the cavity vessels, a relief valve on the sleeve prevents excessive pressure build-up in the vacuum vessel. Wires and cables of each module are extracted from the module using flanges with vacuum tight connectors.

The following helium lines (see Figure 2) are integrated into the cryomodules:

A: the 2 K forward line transfers pressurized single phase helium through the cryomodule to the end of the cryogenic unit.

B: the 2 K two phase supply line (made of titanium) is connected to the cavity helium vessels. It supplies the cavities with liquid helium and returns cold gas to the 300 mm HeGRP at each module interconnection.

C: the 2 K HeGRP returns the cold gas pumped off the saturated helium II baths to the refrigeration plant. It is also the key structural backbone for the cryomodule active components.

D/E: the 5 K forward and return lines. The 5 K forward line is used to transfer the helium gas downstream to the end of the cryogenic unit while cooling the quadrupole packages. The 5 K return line directly cools the 5 K radiation shield and, through the shield, provides the heat flow intercept for the main coupler and diagnostic cables, and the higher-order mode (HOM) absorber located in the module interconnection region.

F/G: the 70 K forward and return lines. The 70 K forward line is used to transfer helium gas to the cryogenic unit end and can eventually cool the high temperature superconductor (HTS) current leads for the quadrupole and correction magnets. The 70 K return line directly cools the 70 K radiation shield and the HOM absorber and, through the shield, provides an additional heat flow intercept for the main coupler and diagnostic cables.

The warm-up/cool-down line connects to the bottom of each cavity and magnet helium vessel. It is used during the cool down and warm up of the cryostat.

## 1.2 Parts List

### Vacuum Vessel (VV)

The vacuum vessel is the big pipe that surrounds the cold mass and performs the first level of thermal insulation from room temperature. It has also a crucial structural role: it supports through three support posts the entire cold mass weight.

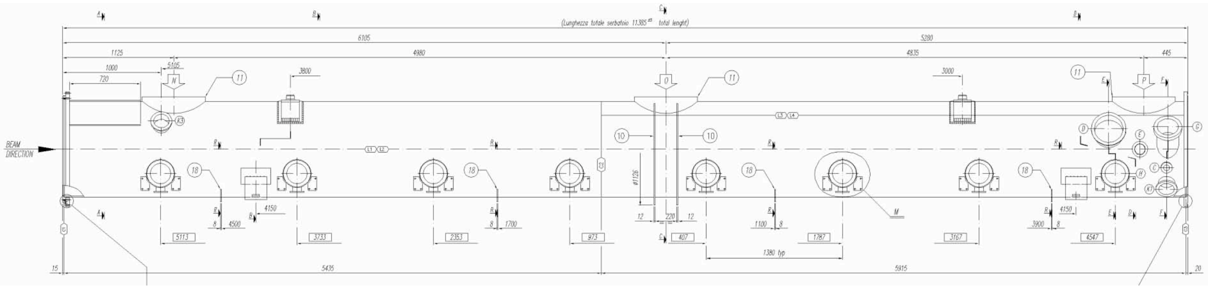

**Figure 3: vacuum vessel**

The vessel is a longitudinal welded pipe 11385 mm long, calendered from sheets. It has a standard outer diameter of 965.2 mm (38”), thickness of 9.52 mm (3/8”) and is made of carbon steel DIN 17155 H II (equivalent to ASTM A516/60). The main properties of this material are described in part 2 of this document. The vessel provides the insulating vacuum, to perform a first level of thermal insulation, avoiding gas convection between its room temperature inner surface and the 70 K thermal shield. The layout of the insulating vacuum system is strongly influenced by superconducting HERA magnets experiences.

The openings along the vessel provide the feedthroughs for the RF power couplers, the magnet current leads and instrumentation. The following paragraphs describe the main characteristics of these openings.

Both the internal and external surfaces of the vessel are painted: the internal wall has a first layer of primer paint and a second of epoxy paint; the external wall has a first layer of primer paint and a second of yellow paint (RAL 1003).

*Openings and nozzles*

The openings on the vessel surface are divided in three main groups: the coupler openings, the posts openings and the others openings for magnet and sensors. All the end flanges of the feedthroughs are made of stainless steel, the feedthroughs (in the following named nozzles, as used in ASME code) themselves are made either of carbon or of stainless steel, the choice is mainly due to production cost reduction.

The following drawing summarizes the openings positions:

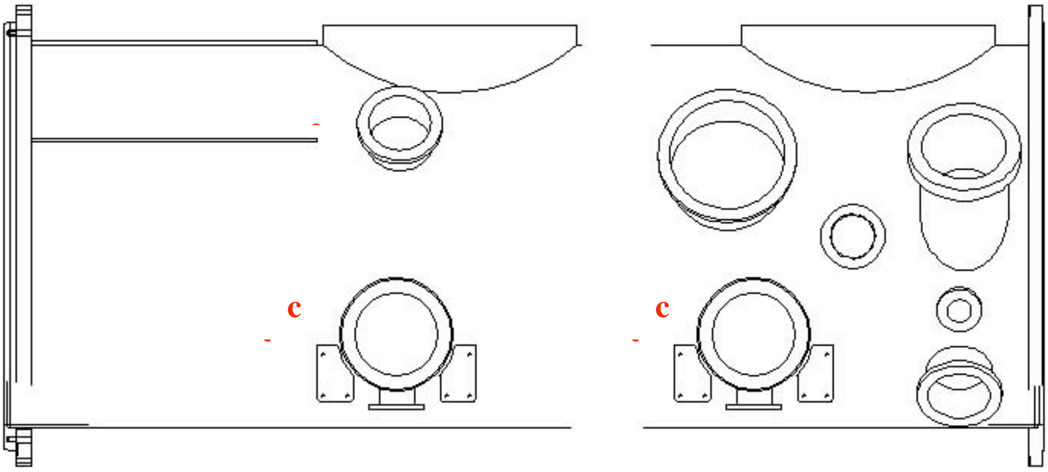

**Figure 4: nozzles**

*Coupler openings*

The 8 coupler openings are situated in the lower part of the vessel and separated by 1380 mm. These openings connect the cold position (position after the shrinkage due to cool down of the entire system) of the fundamental power coupler port on the cavity to the warm position of the external part of the coupler, facing the RF distribution waveguides. The surfaces of the eight coupler flanges are machined after welding, to obtain a planar vertical surface: the planarity and alignment of these surfaces is critical for the connection of the cold and warm part of the RF input system. The table resumes the characteristics of a coupler opening, nozzle and flange.

| | |
|---|---|
| Nozzle internal diameter (mm) | 278 |
| Opening maximum aperture (mm) | 329 |
| Nozzle maximum length* (mm) | 203 |
| Nozzle thickness (mm) | 5 |
| Distance of the nozzle axis to the horizontal axis of the vessel (mm) | 246 |
| Nozzle material (mm) | AISI 304L |

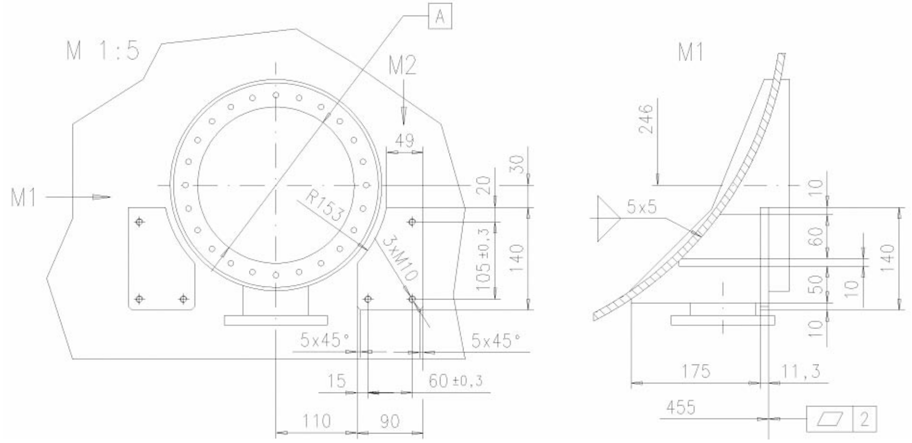

**Figure 5: coupler nozzles**

*Posts openings*

The posts are supported to large flanges on the upper part of the vacuum vessel by adjustable suspension brackets. The brackets are fastened to a support fixed on the vessel. The forged part supports the cold mass weight. The upper plane of the support is machined to obtain a planar surface, used as a reference for the alignment of the module (it is necessary to report the cold mass alignment to the outside surface of the vessel).

| | |
|---|---|
| Opening diameter (mm) | 394 |
| Nozzle maximum length* (mm) | 183 |
| Nozzle thickness (mm) | 123 |
| Nozzle Material (mm) | AISI 304L |

---

[*] from the inner surface of the vessel to the outer surface of the nozzle (nozzle flange if there is any)

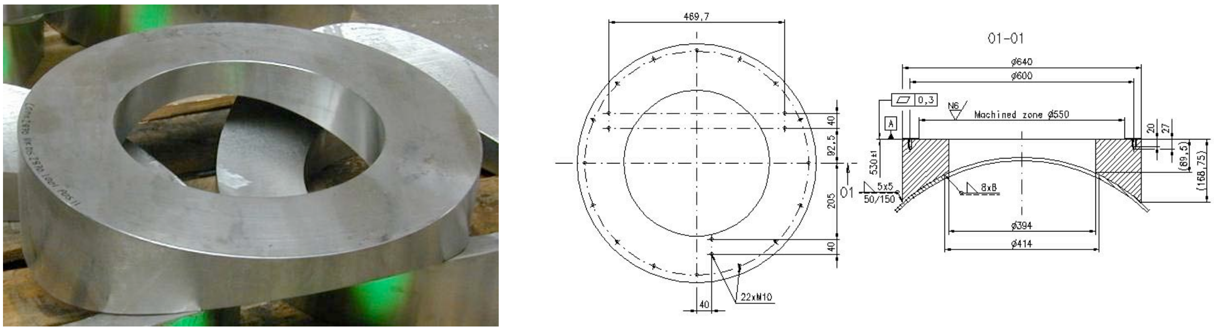

**Figure 6: post opening and nozzle**

*Other openings*

The other openings on the vessel are for instrumentations, sensors and feedthroughs for cables. In different cryomodule versions they have been changed, moved and removed. The following paragraph resumes the openings in the type 3 cyomodule.

**Nozzle C**

Nozzle C is dedicated to the magnet. It is a radial nozzle, tilted of 110°. The flange is a standard CF63 flange.

| | |
|---|---|
| Opening diameter (mm) | 64 |
| Nozzle length* (mm) | 75 |
| Nozzle thickness (mm) | 3 |
| Nozzle material | AISI 304L |

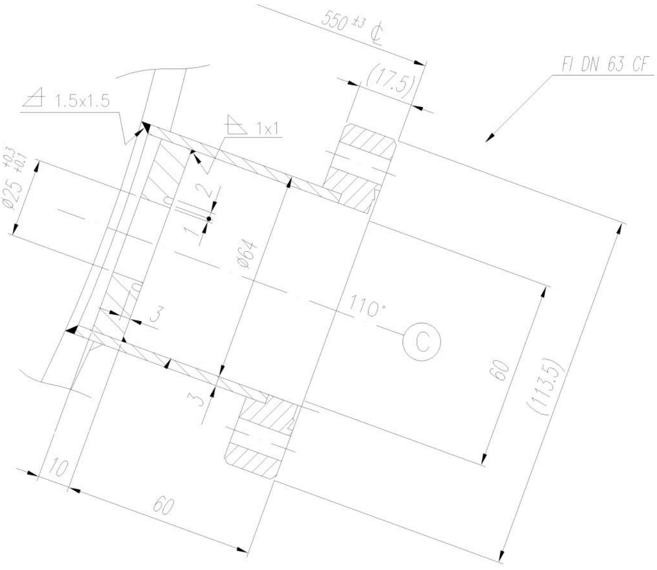

**Figure 7: Nozzle C**

**Nozzle D**

Nozzles D is brings the thermal sensors for the shields. It's a radial nozzle, tilted of 70°. Here are the main parameters:

| | |
|---|---|
| Opening diameter (mm) | 290 |
| Nozzle length* (mm) | 151.3 |

| | |
|---|---|
| Nozzle thickness (mm) | 5 |
| Nozzle material | AISI 304L |

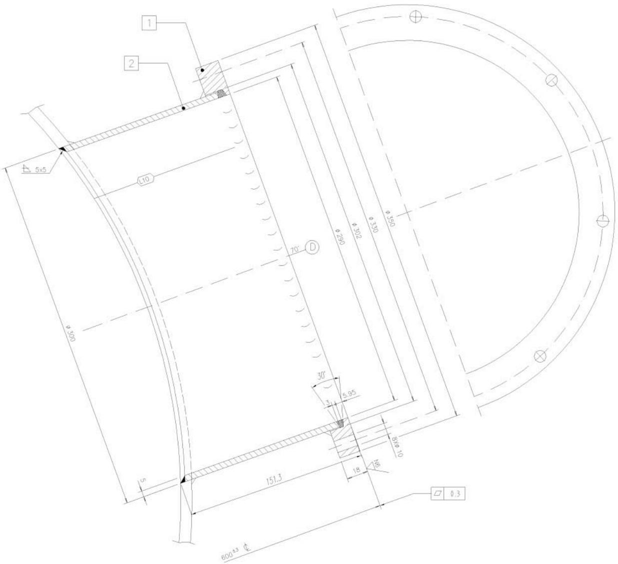

Figure 8: Nozzle D

## Nozzle E

Nozzle E is spare, it’s a horizontal radial nozzle. Here are the main parameters:

| | |
|---|---|
| Opening diameter (mm) | 108.2 |
| Nozzle length* (mm) | 70.4 |
| Nozzle thickness (mm) | 3.05 |
| Nozzle material | AISI 304L |

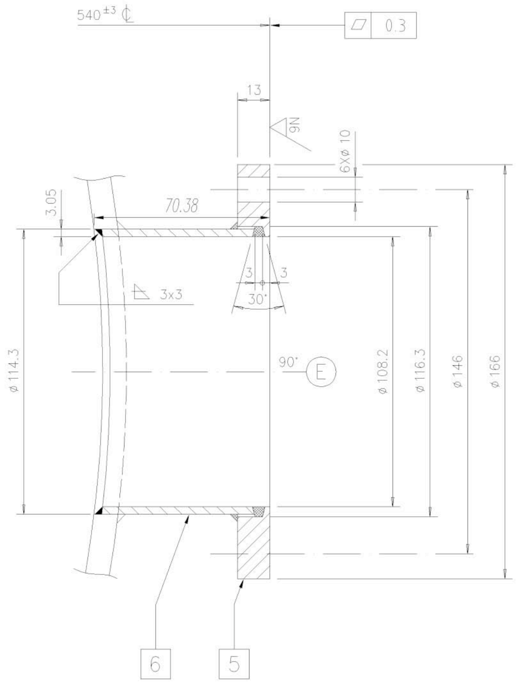

Figure 9: Nozzle E

### Nozzle G

Nozzle G is for the magnet current leads. It's a radial nozzle, tilted of 30° respect to the horizontal axis.

| | |
|---|---|
| Nozzle internal diameter (mm) | 213 |
| Opening maximum aperture (mm) | 259 |
| Nozzle maximum length* (mm) | 368.5 |
| Nozzle thickness (mm) | 5 |
| Vertical distance of the nozzle axis to the horizontal axis of the vessel (mm) | 340 |
| Angle of the nozzle axis respect to the vertical axis | 50° |
| Nozzle material (mm) | AISI 304L |

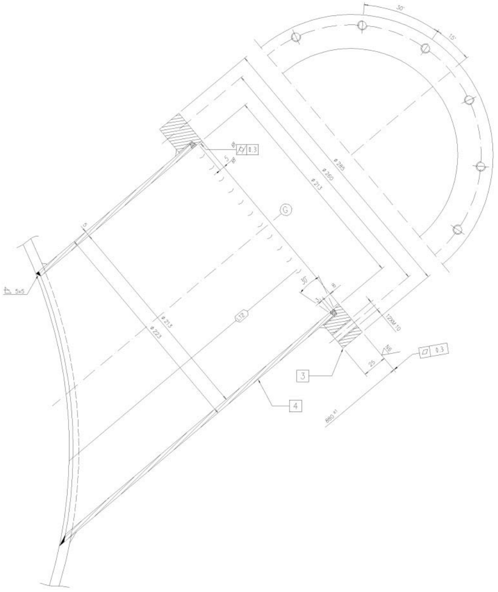

**Figure 10: Nozzle G**

### Nozzles K3 – K1

Nozzle K3 is positioned over the first coupler opening and is the opening dedicated to temperature sensors of the cooling pipes. Nozzle K1 has the same configuration as nozzle K3, but it's positioned at the other end of the vessel and is spare. Both the nozzles are axial nozzles, tilted of 60° (K3) and 135° (K1).

| | |
|---|---|
| Opening diameter (mm) | 158.3 |
| Nozzle length* (mm) | 104 |
| Nozzle thickness (mm) | 5 |
| Nozzle material (mm) | AISI 304L |

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[*] from the inner surface of the vessel to the outer surface of the nozzle (nozzle flange if there is any)

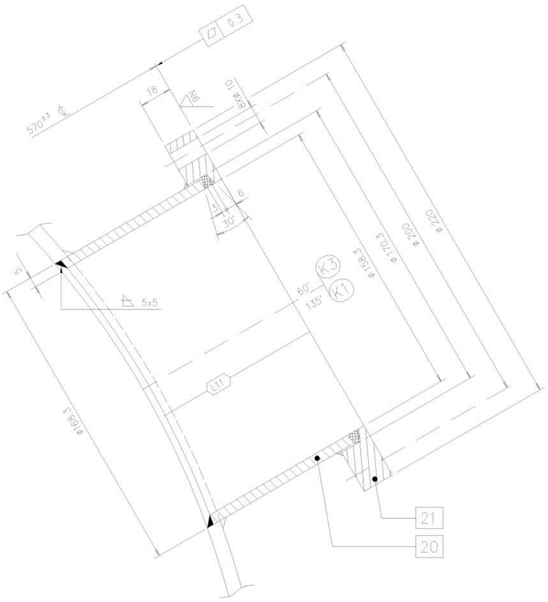

**Figure 11: nozzles K1 - K3**

*Reinforcing*

To ensure the structural stability of the shell under external pressure, the vacuum vessel has two stiffening rings; they are two rings of carbon steel positioned at the middle of the vessel, near the central post.

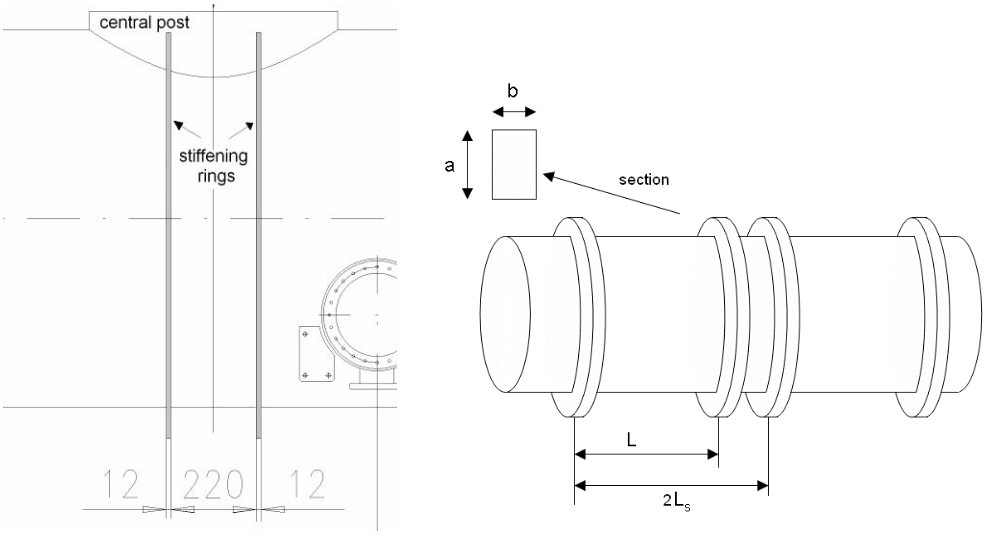

**Figure 12: stiffening rings**

Figure 12 shows the design of the rings. In the following table are listed the main parameters of the stiffeners.

| | |
|---|---|
| a – Height (mm) | 80.5 |
| b – Base (mm) | 12 |
| Ls – mean distance between consecutive rings (mm) | 3107.5 |

The design of the rings satisfies the requirements of the “ASME (American Society of Mechanical Engineers) Boiler and Pressure Vessels Code” (see part 3).

*Supports*

The vessel supports are three: their longitudinal position has been optimized with vibrational computations.

| Length (mm) | 840 |
|---|---|
| Dept (mm) | 200 |
| Height (mm) | 216.5 |

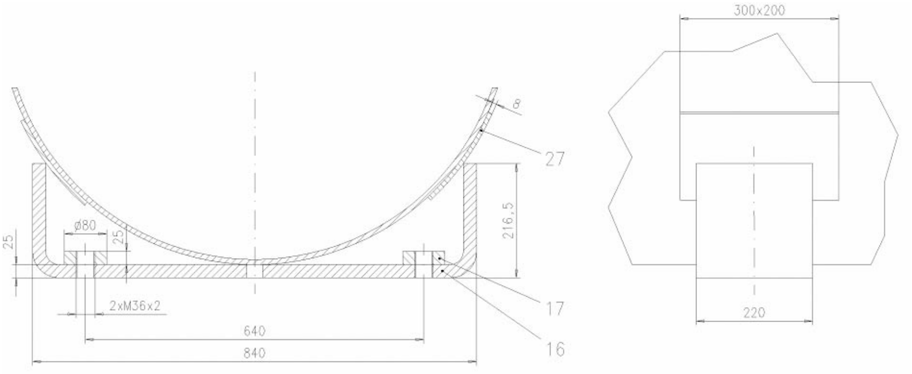

**Figure 13: supports**

*End Bellow*

This bellow performs the connection between two adjacent cryomodules. The design data and specifications have been fixed by Zanon, the bellow is produced by an external company. For the first cryomodules (bigger diameter) it was a custom single bellow; now it is a standard bellow, divided in two pieces and adapted via adaptive rings to the vessel diameter. Between the two bellows there is a flange for spare service: it has never been used, just covered with an ISO flange closure[2].

Design data [2]

| Internal diameter (mm) | 1084 |
|---|---|
| Length (mm) | 850 |
| Joint efficiency3 | 0.85 |
| Axial movement (mm) | ±10 |
| Lateral movement (mm) | ±10 |
| Cross area (cm2) | 10982 |
| Material | ASTM A240 TP 304L |

| | Design condition | Operating condition | Test |
|---|---|---|---|
| Temperature (K) | 300 | 300 | 300 |
| Internal pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

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[2] TTF drawing 09_010300REV01.DWG

[3] Coefficient relative to weld quality, influenced by kind of weld and weld verifications

| | | | |
|---|---|---|---|
| External pressure (bar) | 1 | 1 | 1 |
| Axial spring rate (N/mm) | 700 | | |
| Lateral spring rate (N/mm) | 2982 | | |

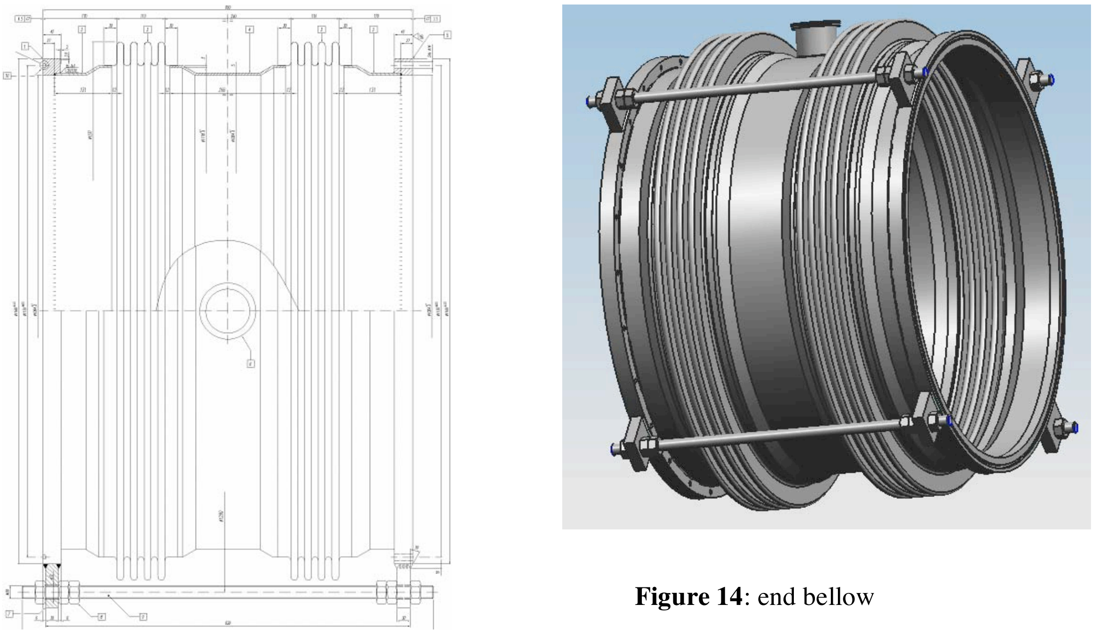
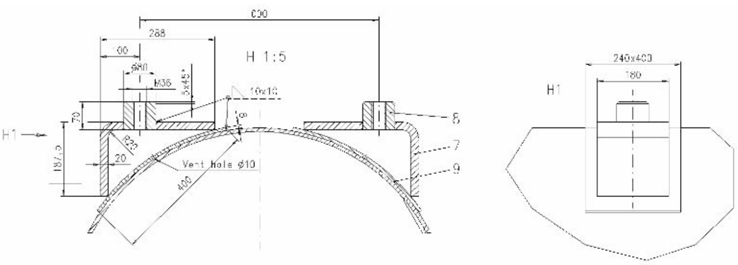


**Figure 14**: end bellow

*Lifting brackets*

To move the vessel (before and after the cold mass assembly) the vessel has two lugs in the upper part; they’re made of carbon steel with the following design:



*Taylor Hobson sphere supports*

**Figure 15: Taylor-Hobson sphere supports**

To ensure the alignment of the cold mass (cavities and magnet) the cryomodule is equipped with three Taylor-Hobson spheres that reproduce the alignment of the helium gas return pipe at the vacuum vessel surface. These sphere stays on three supports positioned next to the post opening (see Figure 15). The supports are made of carbon steel ASTM A516/60.

### Shields

Between the room temperature vacuum vessel and the cold mass there are 3 levels of shields to thermally and magnetically isolate the cold mass at the temperature of 2 K from the external environment.

Two layers of thermal insulation are provided by two aluminum surfaces cooled respectively at a nominal temperature of 70 K and 5 K. A magnetic shield built with cryoperm sheets around the helium tank surface screens the superconducting cavities from the earth magnetic field, in order to preserve their potential performances.

*The thermal shields*

The shields7) are made from Al foils (AA 1050A), cut with water jet and bent. All the holes in Al foils are water-jet cut and than bent. Their cross-section is divided in two parts, a lower one, thinner (3 mm) with holes at the coupler input positions, and the upper one, thicker (6 mm), that supports the weight of the whole shield. The parts are cut in many panels, one for each cavity, to have better handling. Holes in the top shield parts, pipes and bottom shields allow provisional mounting of the components prior to the welding of the fingers (see Figure 19).

The refrigerating system consist of a forward tube bringing helium at 70 K or 5 K to the end of the cryogenic unit and a return pipe, directly welded to the shields, that cools the shield and maintains it at the required temperature.

The shields are connected to the return pipe through a finger welding system, which allows good thermal conduction and reduces stresses during cool-down of the shields.

The cool down process of the shields have been simulated with a finite elements model. The results show, for both the shields, that the maximum gradient in the temperature distribution never exceeds 30 K; that gradient produces deformations which are compatible with the geometry of the cryostat and with the tensile characteristic of the aluminum used to build the shields[3)].

*The magnetic shield*

To avoid magnetic flux trapping in the niobium superconducting cavities the cryostat needs a magnetic shield to reduce the magnetic field inside the cavities to a residual field of ~10 mgauss. To obtain such a residual field, the helium tank is covered with a layer of a material with high magnetic permeability, which concentrates the field lines in their volume, thus attenuating the field in the vicinity of the cavity. Typical materials are cryoperm, mumetal and Conetis. The choice of cryoperm is strictly connected to the magnetic behavior of this material at cryogenic temperature which is better than for mumetal and other materials.

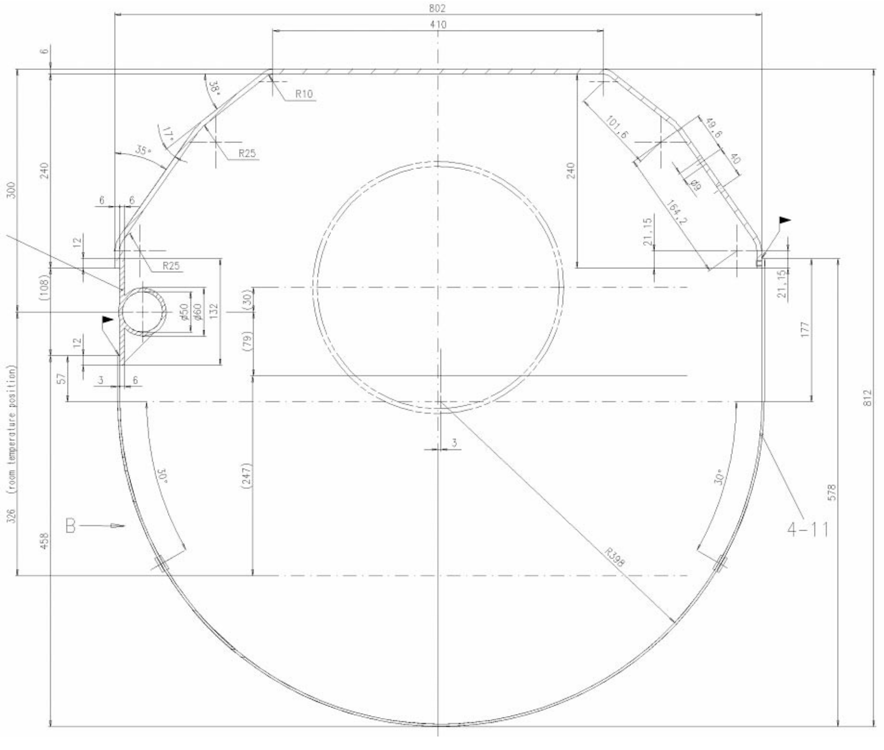


**Figure 16: thermal shields general layout (70 K shield)**

Figure 17: shields upper part

Figure 18: shields lower part

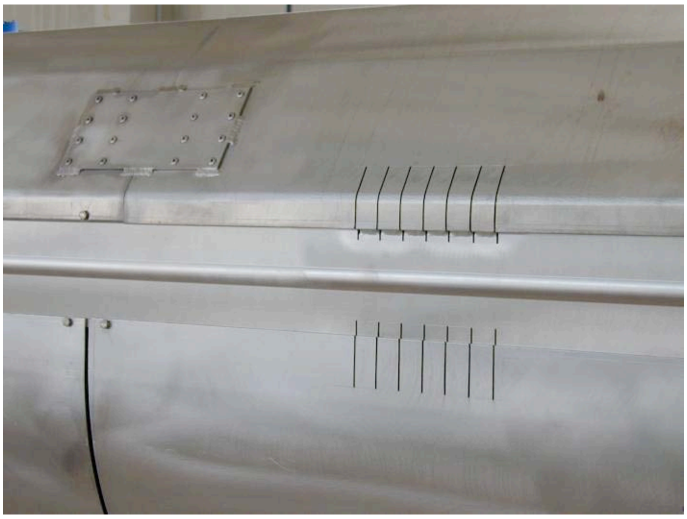


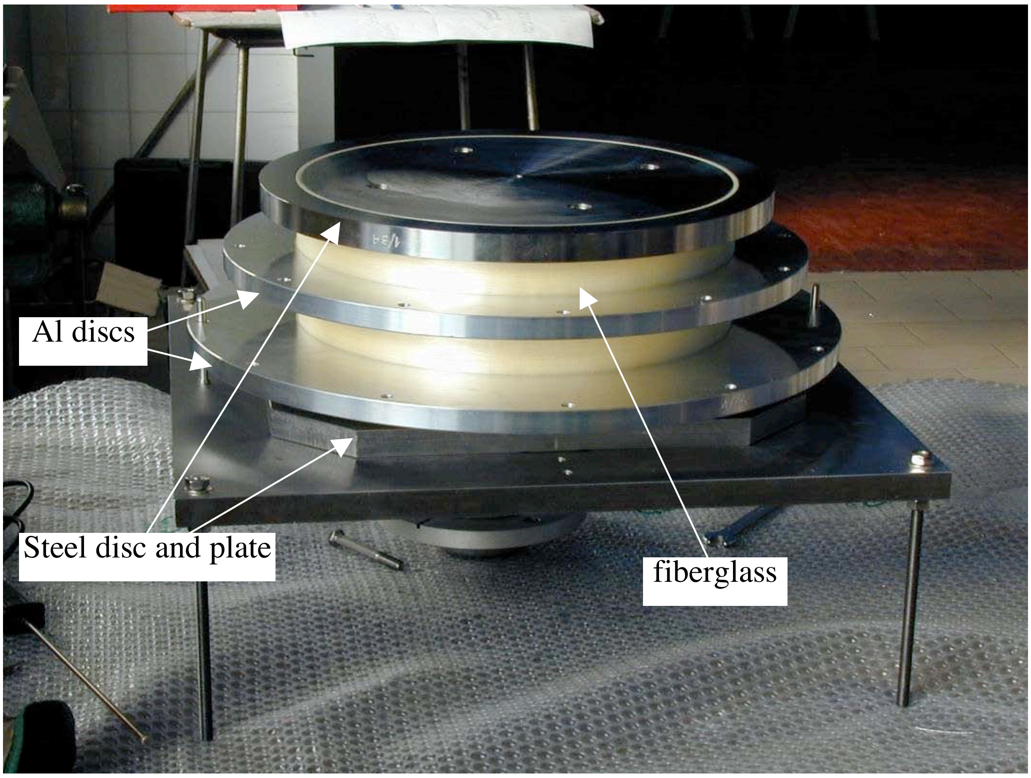
Figure 19: finger welding

### Superinsulation

In order to reduce radiative effects from the hot surfaces, blankets of multi-layer insulation (MLI) are placed on the outside of the 5 K and 70 K shields, on the HeGRP, helium tank and helium 2 phase pipe. A layer of vitrulan is inserted between two layers of mylar to keep them separated. On the 5 K shields are positioned 10 layers of mylar, alternated with 10 layers of vitrulan, on the 70 K shields, 30 layers of mylar and 30 layers of vitrulan. The HeGRP has 5 layers of mylar and 5 layers of vitrulan. The 2-phase tube has 3 layers of two-component sheets.

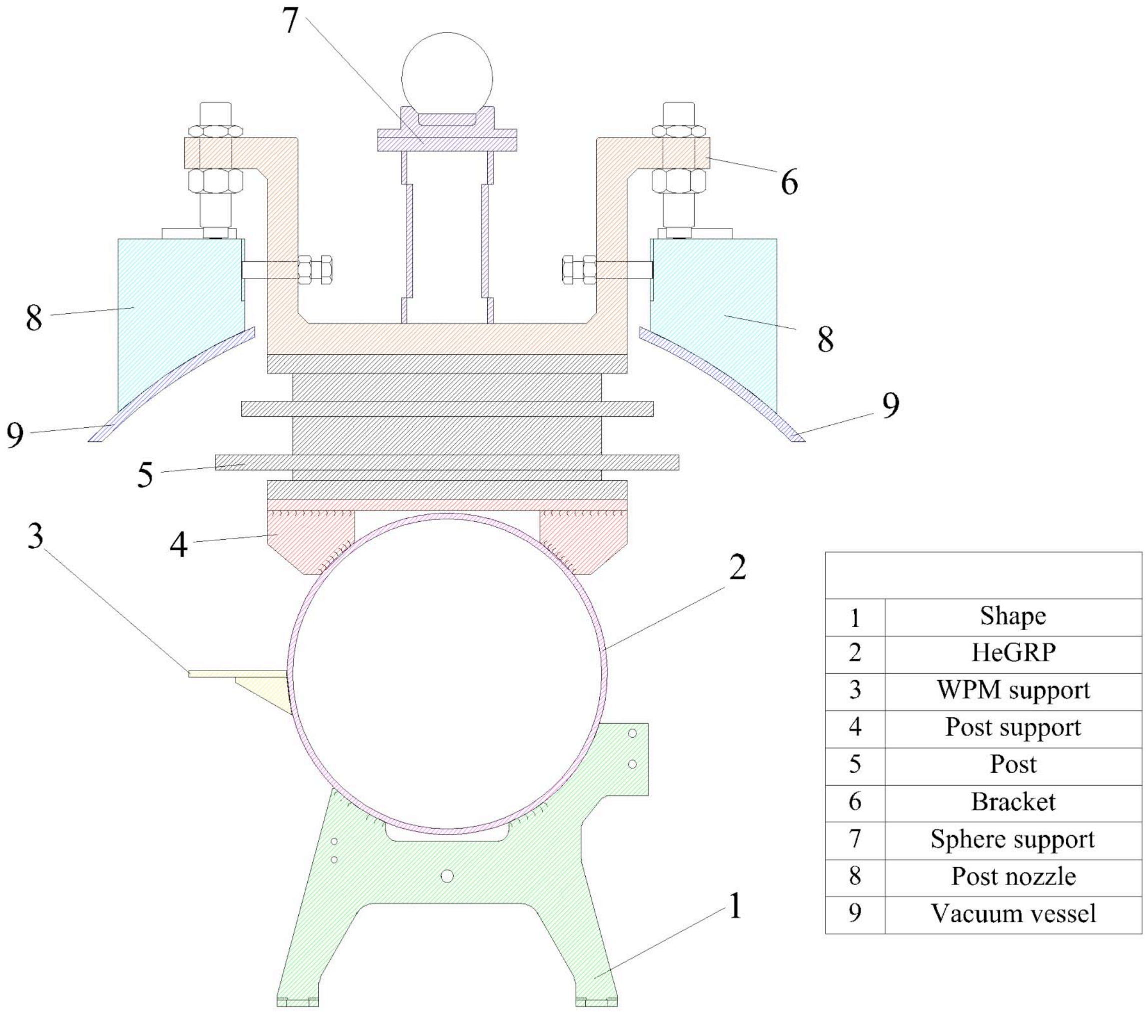
### Posts

The support posts are the low thermal conduction mechanical-cryogenic connections of the HeGRP to the vacuum vessel. There are three support posts, one at centre of the module, the others at the beginning and at the end. The lateral posts are positioned ad far as possible from the centre one, in order to improve the stability with respect to external unknown and asymmetric forces acting on the HeGRP and on the vacuum vessel during cool-down and under vacuum. Moreover the post on the beam-out side is positioned over the quadrupole, to avoid movement of the quadrupole itself: the magnet has stricter alignment tolerances than the cavities[9)].



A post is an assembly of a low thermal conduction composite material pipe (fiberglass pipe) and some shrink-fit aluminum and steel discs and rings. Stainless steel and aluminum flanges are shrink-fit for mechanical connection: the strict tolerances in pipe, discs and rings dimensions assure a mechanical interference in the range of a few percent of the pipe thickness that supports more than one third of the entire cold-mass weight. Each support post has been tested by tension cycles to verify the strength of the interference junction. A break test showed that the post break force is about 100 kN.

The following drawing illustrates the entire connection between vacuum vessel and HeGRP:



| | |
|---|---|
| 1 | Shape |
| 2 | HeGRP |
| 3 | WPM support |
| 4 | Post support |
| 5 | Post |
| 6 | Bracket |
| 7 | Sphere support |
| 8 | Post nozzle |
| 9 | Vacuum vessel |

**Figure 20: post system**

## Helium Gas Return Pipe (HeGRP)

The HeGRP returns the low pressure cold gas evaporated from the He II two phases pipe to the refrigeration plant. It is also a key structural component of the cryomodule: through the shapes it supports the niobium cavities, including the helium tank, the tuner, the quadrupoles, etc... The design of the cryomodule, including fabrication procedures and tolerances, is the key factor to obtaining the required alignment precision for cavities and magnets, while at the same time limiting the costs. The final alignment of the individual active components is performed once the string of cavities is out of the clean room and anchored to the supporting GRP. The alignment of the GRP, via three Taylor-Hobson spheres, is used to reference the axis of the active components. Assembly and cool down do not affect this external reference, except for a predictable and reproducible parallel vertical motion. In particular, the GRP is now fabricated according to the standard tolerances for a high quality welded pipe, including straightness.

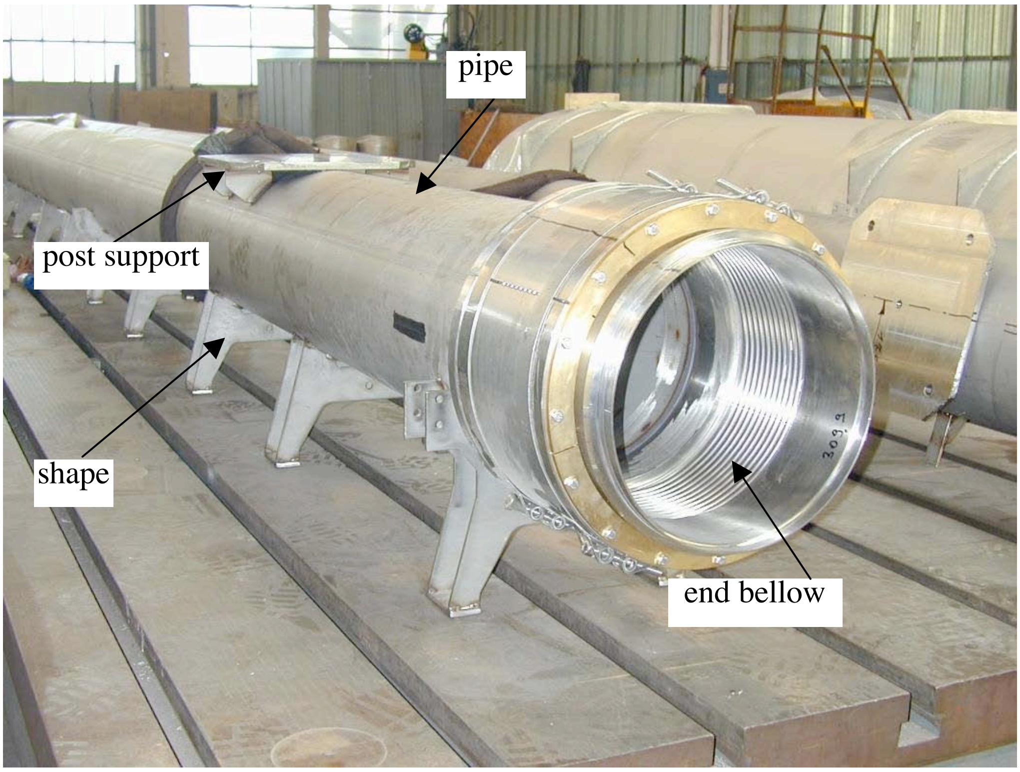


**Figure 21: helium gas return pipe**

*The pipe*

The pipe is a custom made fabrication, calendered from sheets and longitudinally welded. The pipe is made of stainless steel ASTM A240 316L (AISI 316L); the required magnetic permeability is $\mu<1.05$. The end bellow, 346 mm long press-formed, and the end rings, 75 mm was supplied by Desy.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 312 |
| Internal diameter (mm) | 300 |
| Length (mm) | 11555 |
| Longitudinal tolerance (mm/m) | value around 1 |
| Welding joint efficiency[4] | 1 |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 1.8 | 1.8 | 300 |
| Internal pressure (bar) | 4 | 0.031 | 5.2 |
| External pressure (bar) | $<10^{-9}$ (insulating vacuum) | $<10^{-9}$ (insulating vacuum) | 1 |

---

[4] Coefficient used in stresses evaluations, influenced by kind of weld and weld verifications

*The shapes*

The HeGRP has the important role to support the weight of the cavities, helium tanks and 2 K pipes; the connection between the HeGRP and helium tanks is performed with steel shapes welded on the pipe surface. They are made of stainless steel ASTM A240 Type 316L. At the end of the shapes there is a sliding fixture that allows the helium tank to slide in the longitudinal direction, avoiding stresses due to different thermal expansion coefficient in steel (shapes and HeGRP) and titanium (helium tank). This mechanism is named “C-support”, due to his design similar to the letter “C”. The longitudinal position of the cavity with respect to the central post position, needed for the coupler alignment, is ensured by an invar rod (material with very low thermal expansion coefficient) clamped to the HeGRP surface near the centre post, and to the cavities through the shape nearest to the RF input. The pads on the helium tank have been positioned near the end sides of the tank, to increase the movement of the cavity due to the movement of the pads with respect to the C-supports$^{4)}$.

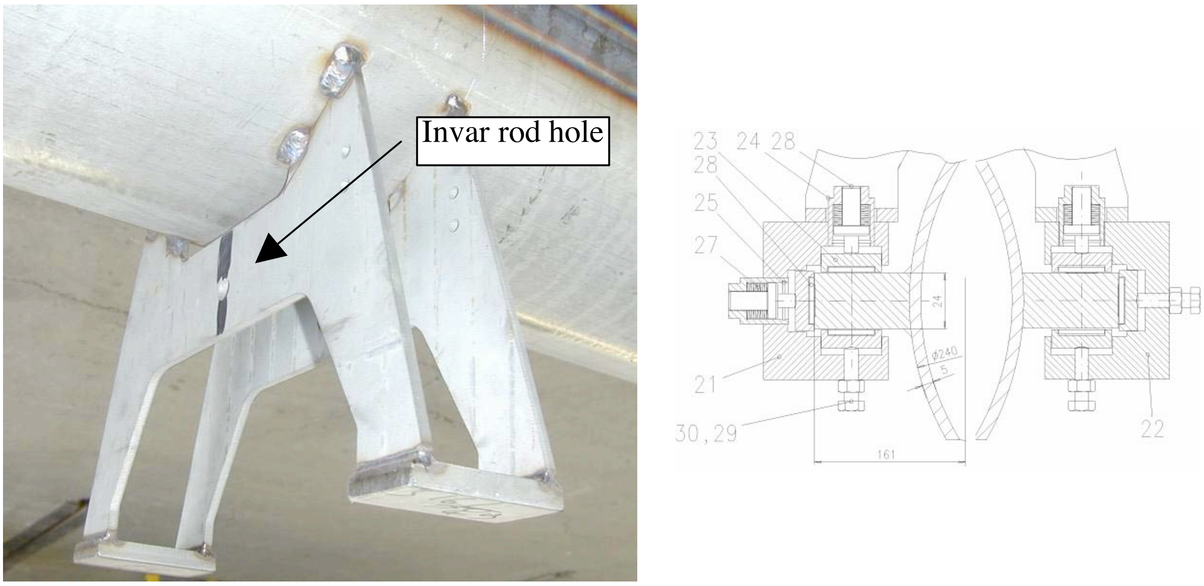


**Figure 22: shape and C-support**

*The invar rod*

The invar rod has been added to the 3rd iteration of the cryomodule design, to ease and simplify the coupler port positioning tolerances. Invar is a material with very low thermal expansion coefficient: the integral Δl/l between 300 and 2 K is 0.4 mm/m.

The invar rod is divided in two rods (each shorter than standard invar rods length) both fixed at the shape nearest to the centre post: each cavity is than fixed to the invar itself. This solution allows an easier positioning and alignment of the cold part of the coupler port.

| | |
|---|---|
| Diameter (mm) | 12 |
| Length (mm) | 11500 |
| Thermal expansion coefficient from 300 to 2 K (mm/m) | 0.4 |

*The posts supports*

The whole helium gas return pipe hang on the vacuum vessel via the posts: they are the low thermal conduction mechanical connection between HeGRP and vacuum vessel and they are described in the following paragraph. The posts are connected to the HeGRP via a support plate welded to the return pipe. The most important parameter of the support plates is the relative flatness of the three horizontal faces and the relative parallelism with the cavity supports. The distance between these two planes (the post supports and the cavity supports) is fundamental for the alignment of the cavities after cool-down.

**Figure** 23**: posts supports**

*Cold mass alignment thanks to HeGRP*

The HeGRP has a crucial role in the cold mass alignment. The HeGRP longitudinal axis is the reference axis for the cavity alignment: once the shapes are welded to the tube and the tube is straightened the axis is referenced to the end bellow (compressed and fixed at a position where no lateral forces result) rings and used to straighten the shapes planes and the post supports plates. In this way, being the posts and brackets thickness precise, the alignment of the cold mass coming out of the clean room is referenced at the Taylor-Hobson spheres and from this to the vessel surface.

### Piping

The following section resumes all the pipes present in the cryomodule (except HeGRP) and their main characteristics and specifications.

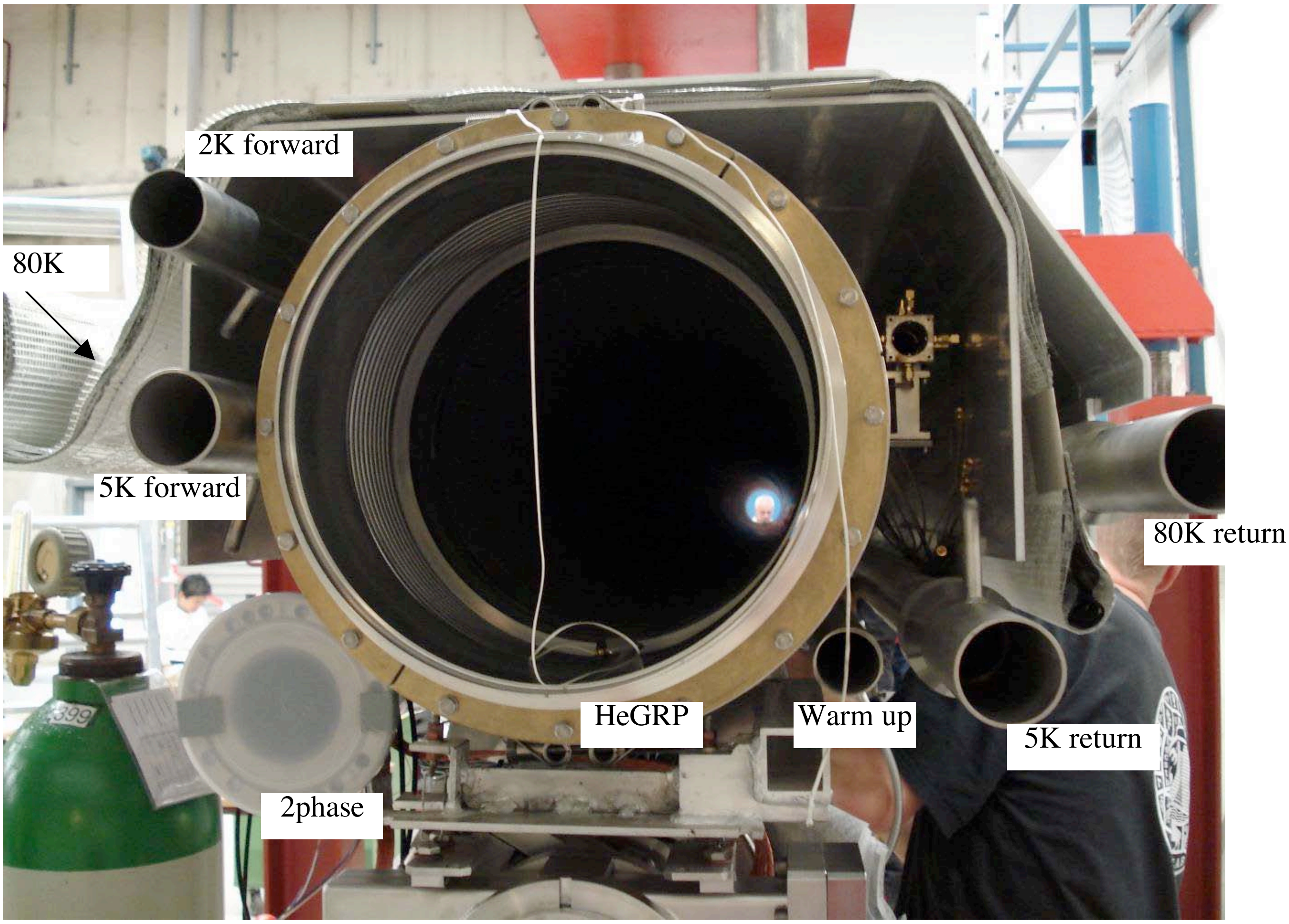


Figure 24: pipes

*2 K forward line*

This pipe transfers pressurized liquid helium through the cryomodule to the end of the cryogenic unit. It is a standard pipe.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 48.3 (1.9”) |
| Thickness (mm) | 1.65 (0.065”) |
| Length (mm) | 11900 + over-length for test and fitting |
| Material | ASTM A312 TP 316L |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 1.8 | 1.8 | 300 |
| Internal Pressure (bar) | 20 | 1.2 | 20 +30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

*2 K two phase line*

It supplies the cavities with liquid helium and returns cold gas to the HeGRP at each module interconnection. It is not a unique tube, but each helium tank is built with a piece of two phase pipe already welded. Once the cavities are aligned the pieces of tubes are welded together.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 76.1 |
| Thickness (mm) | 2 |
| Material | Titanium |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 1.8 | 1.8 | 300 |
| Internal Pressure (bar) | 4 | 0.016 | 20 + 30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

*5 K forward line*

The 5 K forward line transfer helium gas to the magnet package and to end of the cryogenic unit. It is a standard pipe.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 60.3 (2”3/8) |
| Thickness (mm) | 2.77 (0.109”) |
| Length (mm) | 11900 + over-length for test and fitting |
| Material | ASTM A312 TP 316L |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 5 | 5 | 300 |
| Internal Pressure (bar) | 20 | 5.5 | 20 + 30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

*5 K return line*

The 5 K return line directly cools the 5 K radiation shield and, through the shield, provides the heat flow intercept for the main coupler and diagnostic cables, and the higher-order mode (HOM) absorber located in the module interconnection region. It is an extruded pipe, with fins for the connection to the shields. The connection between two consecutives pipes (at the interconnection region between consecutive cryomodules) is performed via two bimetallic aluminum – stainless steel transition junctions supplied by Thevenet + Clerjouine and a stainless steel bellow.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 60 |
| Thickness (mm) | 5 |
| Length (mm) | 11234 + over-length for test and fitting |
| Material | Aluminum AA 6060 T5 |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 5 | 5 | 300 |
| Internal Pressure (bar) | 20 | 8 | 20 + 30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

*70 K forward line*

The 70 K forward line is used to transfer Helium gas to the cryogenic unit end and cools the high temperature superconductor (HTS) current leads for the quadrupole and correction magnets. It is a standard pipe.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 60.3 (2”3/8) |
| Thickness (mm) | 2.77 (0.109”) |
| Length (mm) | 11900 + over-length for test and fitting |
| Material | ASTM A312 TP 316L |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 70 | 70 | 300 |
| Internal Pressure (bar) | 20 | 20 | 20 + 30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

*70 K return line*

The 70 K return line directly cools the 70 K radiation shield and the HOM absorber and, through the shield, provides an additional heat flow intercept for the main coupler and diagnostic cables. It is an extruded pipe, with fins for the connection to the shields. As for the 5 K aluminum return line the connection between two pipes is performed via two bimetallic aluminum – stainless steel transition junction supplied by Thevenet + Clerjouine and a stainless steel bellow.

Geometrical properties

| | |
|---|---|
| External diameter (mm) | 60 |
| Thickness (mm) | 5 |
| Length (mm) | 11234 + over-length for test and fitting |
| Material | Aluminum AA 6060 T5 |

Physical properties

| | Design | Operating conditions | Test |
|---|---|---|---|
| Temperature (K) | 70 | 70 | 300 |
| Internal Pressure (bar) | 20 | 18 | 20 + 30% |
| External pressure (bar) | <10-9 (insulating vacuum) | <10-9 (insulating vacuum) | 1 |

**Figure 25: Al 5 K and 70 K return pipes**

*Warm-up/cool-down line*

It is a line entirely dedicated to the cool down and warm up of the cryostat. It is composed by a 2 K gas forward line connected to each helium tank via a capillary with an end flange directly fixed on the tank surface.

The 2 K line is fixed to the shapes. To avoid stresses due to different thermal expansion of the HeGRP and the assembly, the capillary is longer than required and makes a turn of 360°.

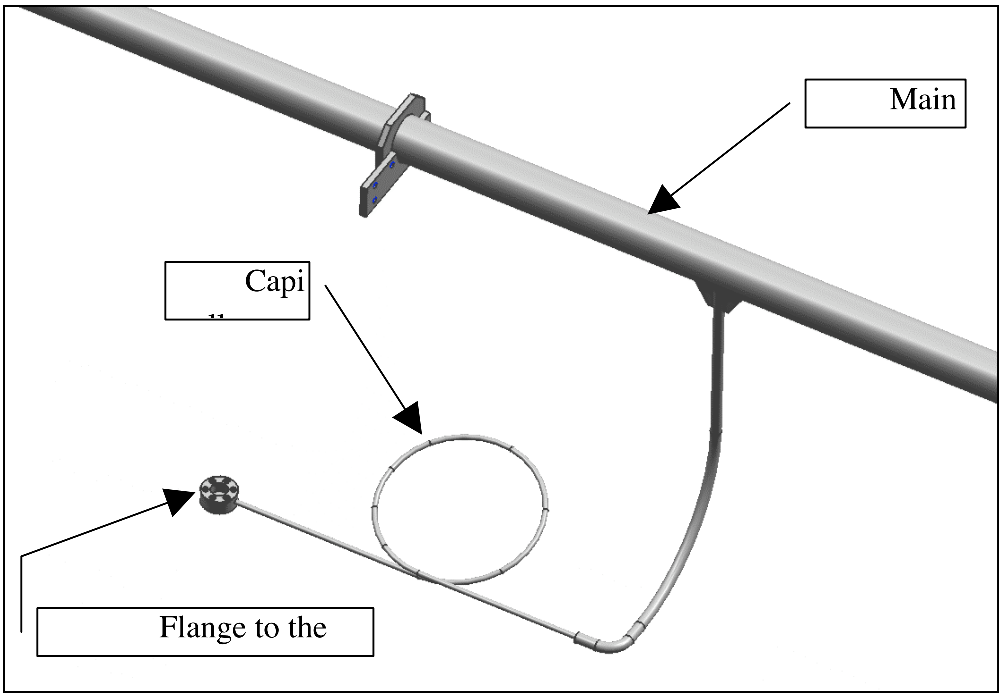


**Figure 26**: warm up / cool down pipe

## Wire Position Monitor system

**Figure 27:** WPM parts

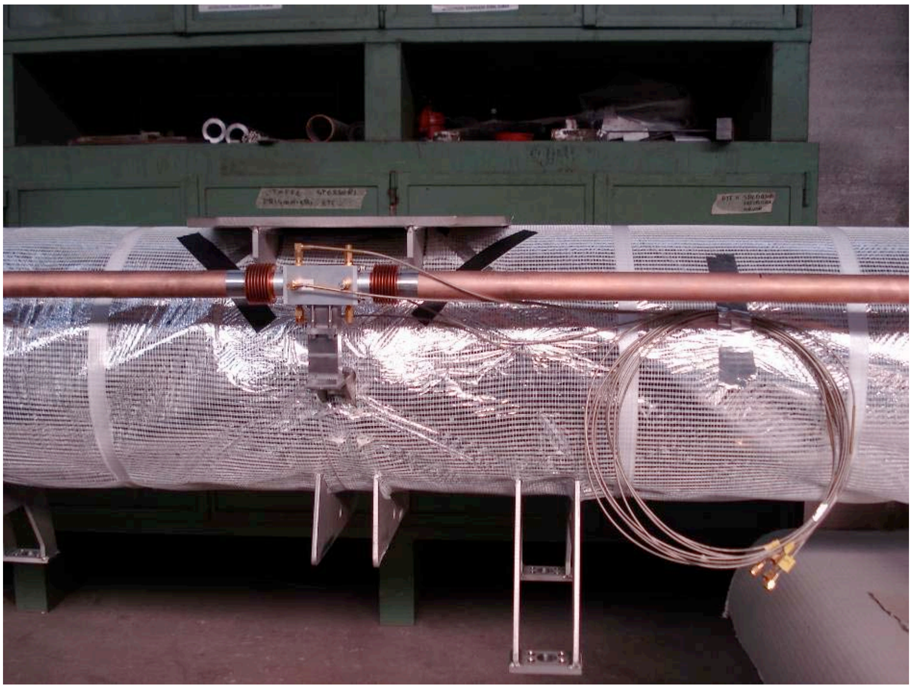


**Figure 28:** WPM system assembled

A Wire Position Monitor (WPM) system has been developed for on-line monitoring of the cold mass movements during cool-down and operation$^{6)}$.

The analysis of the WPM measurements allows checking the alignment reproducibility between successive cool-down cycles. Each WPM has 4 microstrip-based directional couplers, that capacitively read the displacements of the CuBe wire stretched in the sensor (nominal) center and fed by a 140MHz RF signal.

Some WPMs, equipped with fast readout electronics, have been used as vibration detectors. The low frequency vibrations of the cold mass amplitude modulate the RF signals picked up by the microstrips. The microphonics (and the sub-microphonics) can be recovered de-modulating the microstrip RF signal. Only transverse vibration in the horizontal and vertical planes can be detected$^{5)}$.

The WPM system is supplied by INFN Milano, and assembled after the preassembly of the HeGRP. Each WPM is directly bolted to its supporting brackets (welded to the HeGRP) with moveable positioning bolts. The WPM clearance is of circular shape, with a diameter of 28 mm. The monitor is composed of one aluminum block; the pipe surrounding the wire is made of copper-beryllium, a material with good thermal and electrical conductivity, completely a-magnetic, suited for low temperature operation.

# 2 MATERIALS

The material selection of every cryomodule part has been determined on the basis of its main function, choosing like mechanical properties, thermal contraction at low temperature, thermal conduction characteristics accordingly. Another important factor in the selection of a material has been the economic impact, thinking on the big series production (hundred of modules for the XFEL or thousand for ILC).

In the following section there is a list of the material used in the cryomodule production together with the most relevant physical and structural characteristics. All the information, except otherwise specified, are from the following books:

- "Casti Metals Black Book, North American Ferrous Data", 5th edition, CASTI Publishing Inc., Canada;
- "Casti Metals Red Book, Nonferrous Metals", 4th edition, CASTI Publishing Inc., Canada.

## 2.1 Materials properties

*Nomenclature*

| | |
|---|---|
| Ts | Tensile Strength |
| Ys | Yield strength |
| S | Maximum allowable stress value up to 310 K |
| E | Modulus of elasticity at 295 K |
| $\alpha$ | Thermal expansion coefficient |

## 2.2 Steel ASTM A516 grade 60 (H II DIN 17155)

Used for Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service

*Part list*

- Vacuum vessel tube
- Vacuum vessel stiffening rings, supports, lifting brackets
- Taylor-Hobson sphere supports

*Composition % (thickness <= 12.5 mm)*

| | |
|---|---|
| Carbon | 0.21 |
| Manganese | 0.55 – 0.98 |
| Phosphorus | 0.035 |
| Sulfur | 0.035 |
| Silicon | 0.13 – 0.45 |

*Mechanical and physical properties*

| | |
|---|---|
| Ts (MPa) | 415 |
| Ys (MPa) | 220 |

| | | |
|---|---|---|
| S (MPa) | 118 | ASME 2001 - sect. II, part D, subpart 1, table 1A |
| E (GPa) | 203.4 | ASME 2001 - sect. II, part D, subpart 2, table TM-1, Carbon steel with C<=0.30% |
| α | - | |

## 2.3 Steel ASTM A312 Type 316L

Used for Seamless and Welded Austenitic Stainless Steel Pipes

*Part list*

- 2 K forward pipe
- 5 K forward pipe
- 70 K forward pipe
- Warm-up cold-down pipe

*Composition*[5] *%*

| | |
|---|---|
| Carbon | 0.030 |
| Manganese | 2.00 |
| Phosphorus | 0.045 |
| Sulfur | 0.030 |
| Silicon | 0.75 |
| Nickel | 10.0-14.0 |
| Chromium | 16.0-18.0 |
| Molybdenum | 2.00-3.00 |

*Mechanical and physical properties*

| | | |
|---|---|---|
| Ts (MPa) | 485 | |
| Ys (MPa) | 170 | |
| S (MPa) | 115 | ASME 2001 - sect. II, part D, subpart 1, table 1A seamless & welded pipe |
| E (GPa) | 195.1 | ASME 2001 - sect. II, part D, subpart 2, table TM-1, group G |
| α 300 K□2 K (mm/m) | 3.1 | |

## 2.4 Steel ASTM A 240 Type 304L and Type 316L

Heat-Resisting Chromium and Chromium Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessel

*Part list*

- Vacuum vessel end bellow (304L)
- Vacuum vessel nozzles (304L)
- Helium Gas Return Pipe (316L)
- Shapes (316L)

---

[5] Chemical composition of Steel UNS S31603 - type 316L

- Post support plates (316L)

*Composition %*

| Element | 304L | 316L |
|---|---|---|
| Carbon | 0.030 | |
| Manganese | 2.00 | |
| Phosphorus | 0.045 | |
| Sulfur | 0.030 | |
| Silicon | 0.75 | |
| Nickel | 8.0-12.0 | 10.0-14.0 |
| Chromium | 18.0-20.0 | 16.0-18.0 |

*Mechanical and physical properties*

| | | |
|---|---|---|
| Ts (MPa) | 485 | |
| Ys (MPa) | 170 | |
| S (MPa) | 115 | ASME 2001 - sect. II, part D, subpart 1, table 1A seamless & welded pipe |
| E (GPa) | 195.1 | ASME 2001 - sect. II, part D, subpart 2, table TM-1, group G |

### 2.5 Aluminum AA 6061 T6

*Part list*

- post plates

*Composition %*

| | |
|---|---|
| Aluminum | remainder |
| Chromium | 0.4-0.35 |
| Copper | 0.15-0.40 |
| Iron, max | 0.7 |
| Manganese, max | 0.15 |
| Silicon | 0.40-0.8 |
| Titanium, max | 0.15 |
| Zinc, max | 0.25 |
| Magnesium | 0.8-1.2 |
| Others, max | each 0.05<br>total 0.15 |

*Mechanical and physical properties*

| | | |
|---|---|---|
| Ts (MPa) | 310 | |
| Ys (MPa) | 275 | |
| S (MPa) | 75.1 | ASME 2001 - sect. II, part D, subpart 1, table 1B A96061 T6 |

| | | |
|---|---|---|
| E (GPa) | 68.9 | ASME 2001 - sect. II, part D, subpart 2, table TM-2, A96061 |
| α 300 K□70 K (mm/m)[6] | 4.172 | |
| α 300 K□4 K (mm/m)[6] | 4.348 | |

## 2.6 Aluminum AA 1050A (EN-AW-1050A, Al 99.5)

*Part list*

- 5 K shield parts
- 70 K shield parts

*Composition %, max*

| | |
|---|---|
| Aluminum, min | 99.5 |
| Copper | 0.05 |
| Iron | 0.40 |
| Manganese | 0.05 |
| Silicon | 0.25 |
| Titanium | 0.05 |
| Zinc | 0.07 |
| Magnesium | 0.05 |

*Mechanical and physical properties (temper O/H111)*

| | | |
|---|---|---|
| Ts (MPa) | 65-95 | |
| Ys (MPa) | 20 | |
| S (MPa) | 11.7 | ASME 2001 - sect. II, part D, subpart 1, table 1B A91060 |
| E (GPa) | 68.9 | ASME 2001 - sect. II, part D, subpart 2, table TM-2, A91060 |
| α 300 K□70 K (mm/m)[7] | 4 | |
| α 300 K□4 K (mm/m) [7] | 4.2 | |

## 2.7 Aluminum AA 6060 T5

*Part list*

- 5 K return pipe
- 70 K return pipe

*Composition %, max*

| | |
|---|---|
| Aluminum | remainder |
| Copper | 0.10 |
| Iron | 0.10-0.30 |
| Manganese | 0.10 |

---

[6] Cryocomp data

[7] Source: cry3+ drawings

| | |
|---|---|
| Silicon | 0.30-0.6 |
| Titanium | 0.10 |
| Zinc | 0.15 |
| Magnesium | 0.35-0.6 |
| Chromium | 0.05 |

*Mechanical and physical properties*

| | | |
|---|---|---|
| Ts (MPa) | 160 | |
| Ys (MPa) | 120 | |
| S (MPa) | 75.1 | ASME 2001 - sect. II, part D, subpart 1, table 1B A96061 T6 |
| E (GPa) | 68.9 | ASME 2001 - sect. II, part D, subpart 2, table TM-2, A96061 |
| α 300 K□70 K (mm/m)[7] | 4 | |
| α 300 K□4 K (mm/m) [7] | 4.2 | |

# 3 COMPUTATIONS: ASME CODE VERIFICATION OF VESSEL

This part summarizes the ASME verifications regarding:

- pressure and thickness requirements for vacuum vessel main body (cylindrical shell) and openings;
- reinforcements for openings;
- momentum of inertia for stiffening rings.

The final part resumes the calculations of stresses in the vessel body due to dead loads.

## 3.1 Codes, specification and reference documents

The following codes, standards and documents have been adopted:

| | |
|---|---|
| Reference Drawings | dwg n. TTF-CRY3-01.01.00 rev. 1 (main body and stiffeners)<br>dwg n. TTF-CRY3-01.01.02 rev. 2 (nozzles) |
| ASME 2001, sect. VIII, div. 1 | Rules for construction of pressure vessels |
| ASME 2001, sect. II | Materials |

## 3.2 Materials

The following materials are selected for structural design:

- For vacuum vessel main body and stiffening rings: ASTM A 516 Grade 60
- For vacuum vessel nozzles: AISI 304 L (equivalent to ASTM A 240 Type 304L)

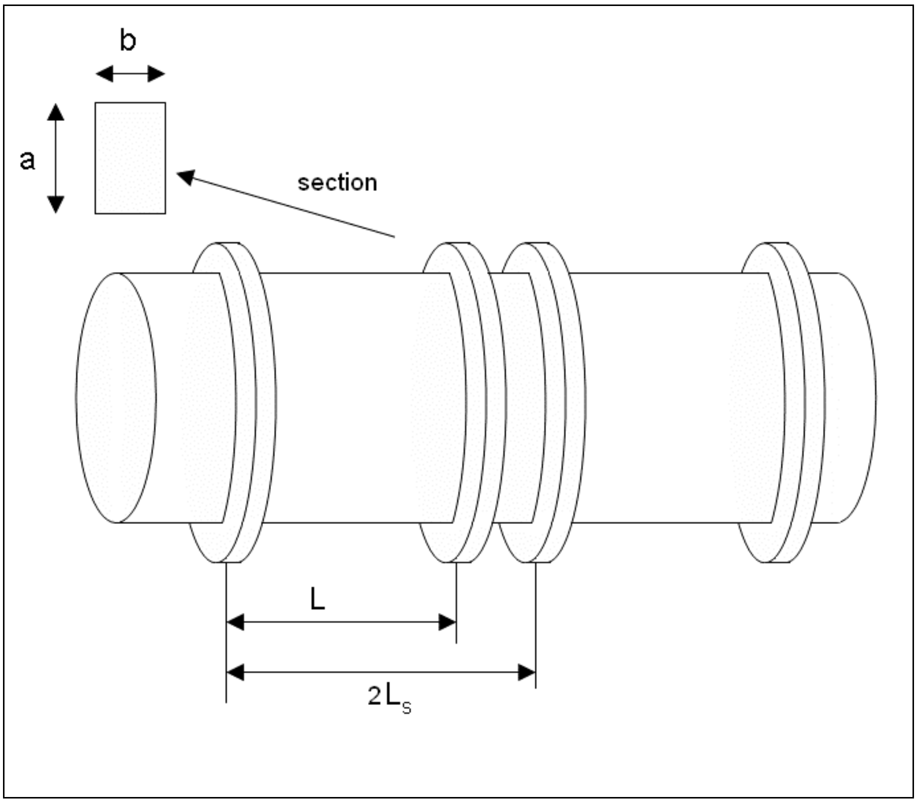
## 3.3 Site conditions

According to the design of the cryomodule the following conditions have been considered:

| Condition | Design | Operating | Test |
|---|---|---|---|
| Internal Pressure (bar) | $<10^{-9}$ | $<10^{-9}$ | 1 |
| External Pressure (bar) | 1 | 1 | 1 |
| Temperature (°C) | 25 | 25 | 25 |

## 3.4 Geometry

*Summary of most important parameters*



Main body

| | |
|---|---|
| $D_o$ – external diameter (mm) | 965.2 |
| $t_s$ – nominal thickness (mm) | 9.52 |
| $P_d$ – external design pressure (bar) | 1 |
| L – distance between stiffening rings (mm) | 6105 |
| $L_{tot}$ – total length of the vessel (mm) | 11385 |
| Cylindrical shell with longitudinal joints<br>Uncorroded geometrical characteristics | |

Stiffening rings

| | |
|---|---|
| a – height (mm) | 80.5 |
| b – base (mm) | 12 |
| $L_s$ – distance between stiffening rings (mm) | 3107.5 |

Nozzles

| Parameters | Nozzles K1 – K3 | Nozzle C | Nozzle D | Nozzle E | Nozzle G | Coupler nozzle | Post opening |
|---|---|---|---|---|---|---|---|
| $D_i$ - internal diameter (mm) | 158.3 | 64 | 290 | 108.2 | 213 | 278 | 394 |
| d – max opening dimension[*] (mm) | 158.3 | 64 | 290 | 108.2 | 259 | 329 | 394 |
| $t_s$ (mm) | 5 | 3 | 5 | 3.05 | 5 | 5 | 123 |
| $P_d$ (bar) | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $L_n$ – length (mm) | 104 | 75 | 151.3 | 70.4 | 368.5 | 203 | 183 |
| Cylindrical tube with longitudinal joints – Uncorroded geometrical characteristics | | | | | | | |

## 3.5 Verification of pressure and thickness requirements for main body and nozzles

The vessel is checked according to the ASME 2001, sect. VIII, div. 1, part UG-28 code.

*Main body*

| Parameters | Values |
|---|---|
| A[8] | 1.84e-4 |
| B[9] (kPa) | 18.24e3 |
| P – Max allowable pressure[10] (bar)<br>$P=4*B/(3*D_o/t_s)$ | 2.40 |
| T – min required thickness[11] (mm) | 6.70 |

*Nozzles*

| Parameters | nozzles K1-K3 | nozzle C | nozzle D | nozzle E | nozzle G | coupler nozzle | post opening |
|---|---|---|---|---|---|---|---|
| A [8] | 1.27e-2 | 1.18e-2 | 6.54e-3 | 1.07e-2 | 2.96e-3 | 4.71e-3 | n.a. |
| B [9] (kPa) | 89.01e3 | 88.52e3 | 85.77e3 | 87.97e3 | 73.44e3 | 80.38e3 | n.a. |
| P [10] (bar) | 35.26 | 50.58 | 19.06 | 31.30 | 21.96 | 18.61 | 344.57 |
| T [11] (mm) | 0.45 | 0.25 | 0.75 | 0.30 | 0.85 | 0.80 | <10 |

*Results*

As in ASME 2001 sect. VIII div. 1 part UG-28 (c) (1) step 8, being for main body and nozzles $P_d < P$ AND $t < t_s$, the thickness and operating pressure of the vacuum vessel are satisfactory.

---

[*] $d = D_i$ for radial openings

[8] ASME 2001, sect. II, part D, subpart 3, table G

[9] ASME 2001, sect. II, part D, subpart 3, table HA-3

[10] ASME 2001, sect. VIII, div. 1, part UG-28 (c) (1)

[11] ASME 2001, sect. VIII, div. 1, part UG-28 (c) (1), repeat the calculation of P changing $t_s$ until $P \approx P_d \Rightarrow t = t_s$

### 3.6 Verification of opening reinforcements

The openings reinforcing areas are checked according to the ASME 2001, sect. VIII, div. 1, part UG-37 code.

*Summary of most important parameters*[12]

$F = 1$ for external pressure design

$f_{r1} = 1$ for nozzle wall abutting the vessel wall

$f_{r2} = 0.98$

$E_1 = 1$ for openings in solid plate or category B butt joint

$h = 0$ distance nozzle projects beyond the inner surface of the vessel wall

$t_i = 0$ nominal thickness of internal projection of nozzle wall

$S$ [13]$= 115$ MPa

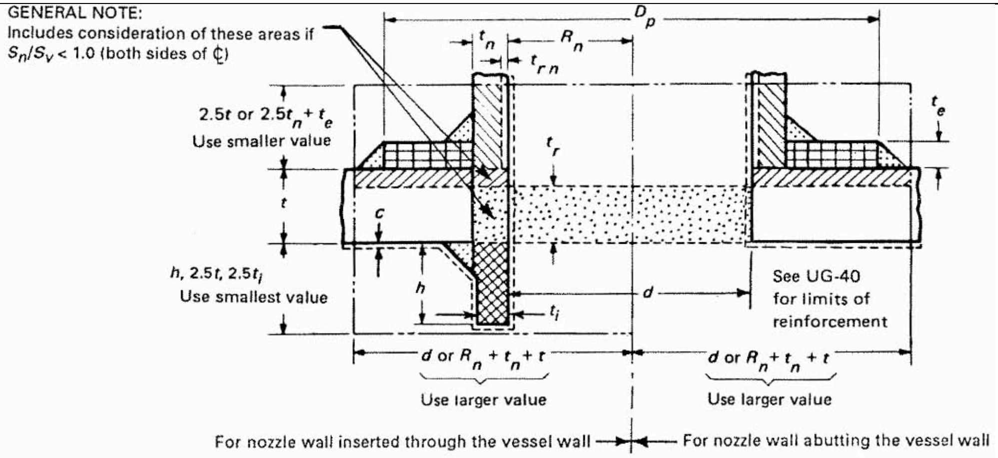
| Parameters[14] | nozzles K1-K3 | nozzle C | nozzle D | nozzle E | nozzle G | coupler nozzle | post opening |
|---|---|---|---|---|---|---|---|
| $A_1$ ($mm^2$) | 446.41 | 180.48 | 817.80 | 305.12 | 600.66 | 783.96 | 1111.08 |
| $A_2$ ($mm^2$) | 111.09 | 40.29 | 103.76 | 40.96 | 101.32 | 102.54 | 5252.98 |
| $A_3$ ($mm^2$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_{41}$, $A_{42}$, $A_{43}$ ($mm^2$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_1+A_2+A_3+A_{41}+A_{42}+A_{43}$ available reinforcing area | 557.50 | 220.77 | 921.56 | 346.08 | 701.98 | 886.50 | 6364.06 |
| A/2 ($mm^2$) – required reinforcing area, external P | 530.31 | 214.40 | 971.50 | 362.47 | 713.55 | 931.30 | 1319.90 |

---

[12] ASME 2001, sect. VIII, div. 1, part UG-37 (a)

[13] ASME 2001 - sect. II, part D, subpart 1, table 1A

[14] ASME 2001, sect. VIII, div. 1, part UG-37 (d) (1)



**Without Reinforcing Element**

| | |
|---|---|
| ▒ = $A = d\,t_r\,F + 2t_n\,t_r\,F(1 - f_{r1})$ | Area required |
| ▨ = $A_1 \begin{cases} = d(E_1\,t - Ft_r) - 2t_n\,(E_1 t - Ft_r)\,(1 - f_{r1}) \\ = 2(t + t_n)(E_1 t - Ft_r) - 2t_n(E_1 t - Ft_r)(1 - f_{r1}) \end{cases}$ | Area available in shell; use larger value |
| ▧ = $A_2 \begin{cases} = 5(t_n - t_{rn})\;f_{r2}t \\ = 5(t_n - t_{rn})f_{r2}t_n \end{cases}$ | Area available in nozzle projecting outward; use smaller value |
| ▩ = $A_3 = 5t\,t_i\,f_{r2}$<br>$= 5t_i\,t_i\,f_{r2}$<br>$= 2h\,t_i\,f_{r2}$ | Area available in inward nozzle; use smallest value |
| ◺ ◺ = $A_{41}$ = outward nozzle weld = $(\text{leg})^2 f_{r2}$ | Area available in outward weld |
| ◸ ◸ = $A_{43}$ = inward nozzle weld = $(\text{leg})^2 f_{r2}$ | Area available in inward weld |
| If $A_1 + A_2 + A_3 + A_{41} + A_{43} \geq A$ | Opening is adequately reinforced |
| If $A_1 + A_2 + A_3 + A_{41} + A_{43} < A$ | Opening is not adequately reinforced so reinforcing elements must be added and/or thicknesses must be increased |

**With Reinforcing Element Added**

| | |
|---|---|
| $A$ = same as $A$, above | Area required |
| $A_1$ = same as $A_1$, above | Area available |
| $A_2 \begin{cases} = 5(t_n - t_{rn})f_{r2}t \\ = 2(t_n - t_{rn})\,(2.5t_n + t_e)\,f_{r2} \end{cases}$ | Area available in nozzle projecting outward; use smaller area |
| $A_3$ = same as $A_3$, above | Area available in inward nozzle |
| ◺ ◺ = $A_{41}$ = outward nozzle weld = $(\text{leg})^2 f_{r3}$ | Area available in outward weld |
| ◺ ◺ = $A_{42}$ = outer element weld = $(\text{leg})^2 f_{r4}$ | Area available in outer weld |
| ◸ ◸ = $A_{43}$ = inward nozzle weld = $(\text{leg})^2 f_{r2}$ | Area available in inward weld |
| ▦ = $A_5 = (D_p - d - 2t_n)\,t_e\;f_{r4}$ [Note (1)] | Area available in element |
| If $A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43} + A_5 \geq A$ | Opening is adequately reinforced |

NOTE:
(1) This formula is applicable for a rectangular cross-sectional element that falls within the limits of reinforcement.

FIG. UG-37.1 NOMENCLATURE AND FORMULAS FOR REINFORCED OPENINGS
(This Figure Illustrates a Common Nozzle Configuration and Is Not Intended to Prohibit Other Configurations Permitted by the Code.)

**Figure 29: nomenclature and formulas for reinforced openings**

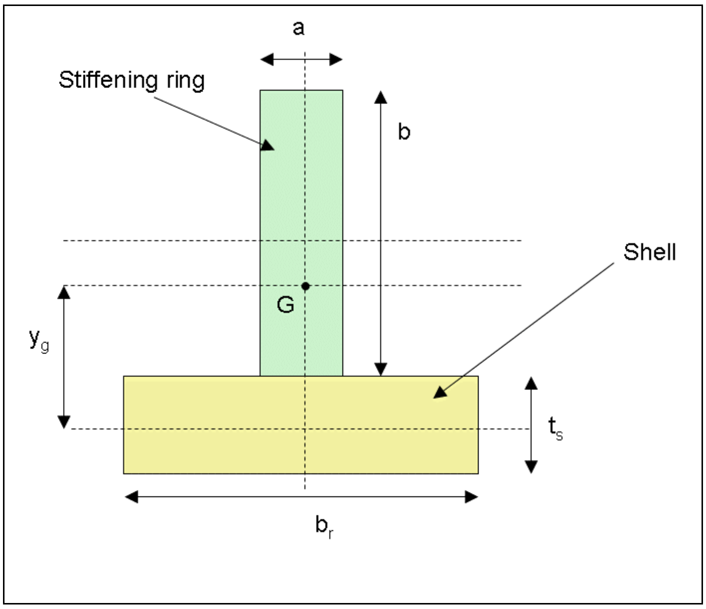
*Results*

As in ASME 2001, sect. VIII, div. 1, part UG-37 (d) (1):

- being for nozzles C, K1, K3 and post opening $A/2 <= A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43}$ these openings are adequately reinforced;
- being for coupler openings and nozzles D, E, G $A/2 > A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43}$ these openings aren't adequately reinforced and need stiffeners or increased thickness.

## 3.7 Verification of the required momentum of inertia for the stiffening rings

The stiffening rings are checked according to the ASME 2001, sect. VIII, div. 1, part UG-29 code. We considered the stiffening ring and the shell.



*Formulas*

$B_r$ [15] $= 2*1.1*(D_o*t_s)^{0.5}$

$y_g$ [16] $= (a*b*(b+t_s)/2)/(a*b+t_s*b_r)$

$A_s'$ [17] $= a*b + t_s*b_r$

$B'$ [18] $= 3/4(P*D_o/(t+A_s'/L_s))$

$I_s'$ [19] – Required momentum of inertia (mm$^4$) $= (D_o^2*L_s*(t_s+A_s'/L_s)*A')/10.9$

I' – Available momentum of inertia (mm$^4$)$=a*b^3/12+b_r*t_s^3/12+a*b*(b/2+t_s/2-y_g)^2+t_s*b_r*y_g^2$

---

[15] ASME 2001, sect. VIII, div. 1, part UG-29 (a), definition of I'

[16] distance between the barycentre of the "T" and the axis of the shell section (yellow rectangle)

[17] stiffening ring and shell cross section

[18] ASME 2001, sect. VIII, div. 1, part UG-29 (a)

[19] ASME 2001, sect. VIII, div. 1, part UG-29 (a)

*Values*

$B_r$ = 211 mm
$y_g$ = 29.2 mm
$A_s$’ = 2974 mm$^2$
B’ = 1002 psi
A’ [20] = 6.97e-5
$I_s$’ = 194e3 mm$^4$
I’ = 2494e3 mm$^4$

*Results*

As in ASME 2001, sect. VIII, div. 1, part UG-29 (a), step 8, being I’ > $I_s$’ the ring section is satisfactory.

### 3.8 Stresses evaluation

*Loadings*

According to the ASME 2001, sect. VIII, div. 1, part UG-22 code in our design the loadings to be considered are:

- external design pressure;
- weight of the vessel and normal contents under operating condition.

This are the weights considered:

| | |
|---|---|
| Vessel (kg) | 3225 |
| HeGRP + shapes + 3shape supports (kg) | 640 |
| Cavities (kg) | 480 |
| Fixed post (kg) | 125 |
| Sliding posts (kg) | 220 |
| 5 K shield (kg) | 365 |
| 70 K shield (kg) | 380 |
| Quadruple (kg) | 120 |
| **Total weight (kg)** | **5555** |

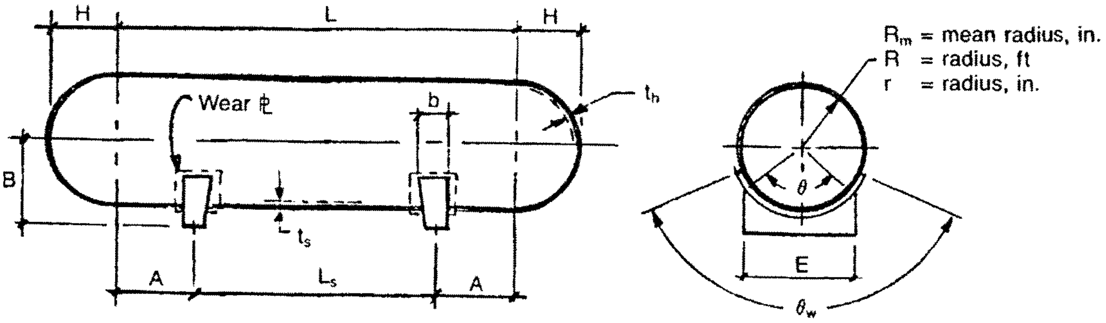
*Maximum allowable stress values*

S - Maximum Allowable Tensile Stress [21] = 118 MPa
$S_c$ - Maximum Allowable Longitudinal Compressive Stress [22] = 65 MPa

*Calculations*[23]

---

[20] ASME 2001, sect. II, part D, subpart 3, table CS-2
[21] ASME II, part D, subpart 1, table 1A
[22] ASME VIII, div.1, UG-23 (b)
[23] all the calculations have been made in inch, lbf and psi than converted to SI



| Q –load on one support (kg) | 5555 |
|---|---|
| A (mm) | 1955 |
| H (mm) | 0 |
| r - radius of shell (inch) | 19 |
| R - radius of shell (foot) | 1.58 |
| L (mm) | 11385 |
| θ- supports angle (deg) | 120 |
| $t_s$, $t_h$ - thicknesses of shell and head (mm) | 9.52 |
| b – support length (mm) | 220 |
| $P_e$ - external pressure (bar) | 1 |

| R/2 | 0.79 |
|---|---|
| A/R | 4.05 |
| R/t | 50.69 |

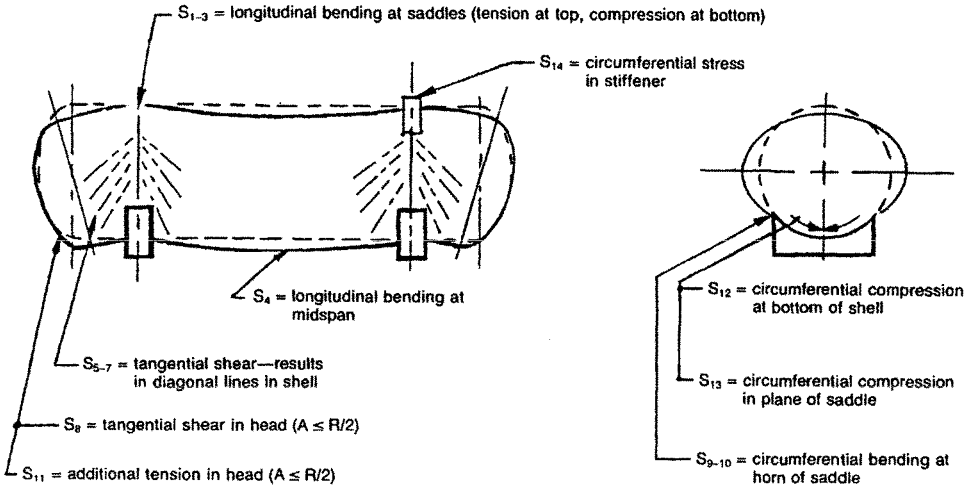


**Figure 30: stesses**

Longitudinal bending at saddles: tension

$$S_1 = +\frac{6Q\left(\frac{(8AH + 6A^2 - 3R^2 + 3H^2}{3L + 4H}\right)}{K_1 r^2 t_s}$$

$S_1 = +11.94MPa*$

Longitudinal bending at saddles: compression

$$S_2 = -\frac{6Q\left(\frac{(8AH + 6A^2 - 3R^2 + 3H^2}{3L + 4H}\right)}{K_2 r^2 t_s}$$

$S_2 = -6.63MPa*$

Longitudinal bending at midspan: tension and compression

$$S_4 = \pm\frac{3Q\left(\frac{3L^2 + 6R^2 - 6H^2 - 12AL - 16AH}{3L + 4H}\right)}{\pi r^2 t_s}$$

$S_4 = \pm 3.53MPa*$

* to calculate $S_1, S_2, S_4$ insert values of A, H, R, L in foot; r, ts in inch; Q in lbf and obtain psi

Tangential shear: shell not stiffened, $A > 0.5R$

$$S_6 = \frac{K_2 Q}{r t_s}\left[\frac{L - 2A}{L + \frac{4}{3}H}\right]$$

$S_6 = 4.56MPa$

Circumferential bending at horn of saddle, shell not stiffened, $L < 8R$

$$S_{10} = -\frac{Q}{4t_s\left(b + 1.56\sqrt{rt_s}\right)} - \frac{12K_6QR}{Lt_s^2}$$

$S_{10} = -10.30MPa$

Circumferential compression

$$S_{12} = -\frac{K_5 Q}{t_s\left(b + 1.56\sqrt{rt_s}\right)}$$

$S_{12} = -6.68MPa$

Pressure stress, external pressure

$$\sigma_e = \frac{P_e r}{2t_s}$$

$\sigma_e = +2.53MPa$

Values of constants

$K_1 = 0.335$
$K_2 = 1.171$
$K_3 = 0.880$
$K_4 = 0.401$
$K_5 = 0.760$
$K_6 = 0.053$

*Results*

| Existing stress | Stress value (MPa) | Limit stress | Limit value (MPa) |
|---|---|---|---|
| +S1 | 11.94 | <SE | 100.22 |
| $\lvert -S2-\sigma_e \rvert$ | $\lvert -6.63-2.53 \rvert = 9.16$ | $<S_c$ | 65.50 |
| +S4 | 3.53 | <SE | 100.22 |
| $\lvert -S4-\sigma_e \rvert$ | $\lvert -3.53-2.53 \rvert = 6.06$ | $<S_c$ | 65.50 |
| +S6 | 4.56 | <0.8S | 94.32 |
| $\lvert S10 \rvert$ | 10.30 | < min(1.5S , 0.9Fy) | 176.85 |
| $\lvert S12 \rvert$ | 6.68 | $<0.5F_y$ or <1.5S | 100.32 |

Being all the conditions fulfilled the design of the vessel is satisfactory.

# 4 CRYOMODULE FABRICATION

This part resumes the operations needed to produce an entire cold-mass for cryomodule type 3+, excluding the string (cavities, helium tanks, tuners preassembled in a clean room). This information have been collected in the period between July 2006 and January 2007, during the fabrication of two modules type 3+ at E. Zanon company.

## 4.1 Vacuum Vessel

*Forming and welding of the tube*

the tubes are calendered from steel sheets, approximately 6m long, and longitudinally welded;

the tubes extremities are beveled;

two 6m long tubes are circumferentially welded to obtain the vessel required length;

the reference axis (horizontal and vertical reference) are marked on the vessel external surface.

*Closure procedure of cryomodules*

between adjacent cryomodules there is a big bellow, bolted on the beam-out side to a fixed flange, on the beam-in side to a sliding one; the closure procedure is the following:

- the bellow is bolted to the beam-in sliding flange;
- all the connection are done (pipes, HeGRP, cables, ...);
- the sliding flange is bolted to a fixed flange already welded to the vessel beam-in side;
- the bellow is clamped to the beam-out fixed flange.

*Welding of the end flanges*

all the flanges (fixed and sliding beam-in and beam-out flanges) are pre-machined: holes are made only on the in-flange (flange welded to the tube on the beam input side);

the in-flange is welded to the tube;

n° 3 weld deposit are done on the tube at the beam input side to allow the flange for the interconnection bellow to slide on the vessel tube;

**Figure 31:** vacuum vessel in-flange

the sliding flange is pre-positioned on the tube, the position of the holes of the in-flange is marked, the flange is removed to make the holes;

the sliding flange is positioned on the tube;

the end-flange (flange welded to the tube on the beam output side) is fit up to the tube and welded.

*Opening and nozzles*

the opening for the nozzles and the post supports, except the 8 coupler nozzles, are machined and beveled;

the nozzles, except coupler nozzles, the post flanges (with over-material for port flattening and hole), the supports of the Taylor-Hobson spheres, the reinforcing rings and the external supports are pre-fabricated, fit up to the tube and welded;

**Figure 32:** nozzles

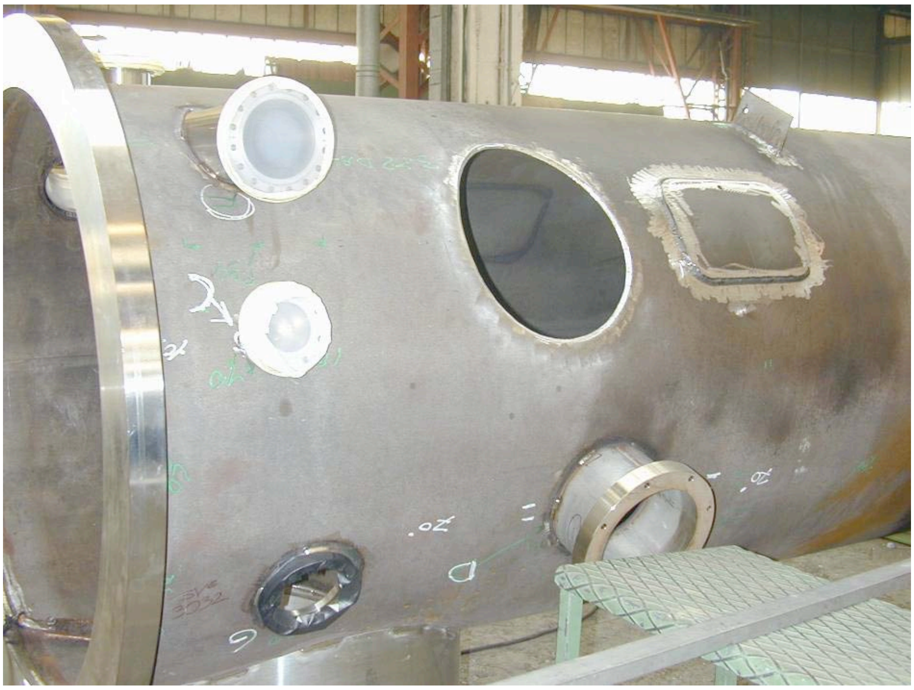


**Figure 33:** opening and nozzles

the coupler nozzles and all the part needed for the coupler connection (with over-material for port flattening and holes) are pre-fabricated;

the eight openings for the coupler nozzles are machined and beveled, paying attention to the alignment requirements;

the coupler nozzles are pre-assembled and tack-welded to the tube;

before weld the alignment of the coupler ports is verified;

the coupler nozzles are welded to the tube;

if needed, the tube is straightened.

*Final machining*

the final machining is done on a long milling machine, with a vertical and horizontal precision of 0.01 mm;

the vessel is positioned on the machine using its previously defined reference axis;

**Figure 34:** vacuum vessel positioning for final machining

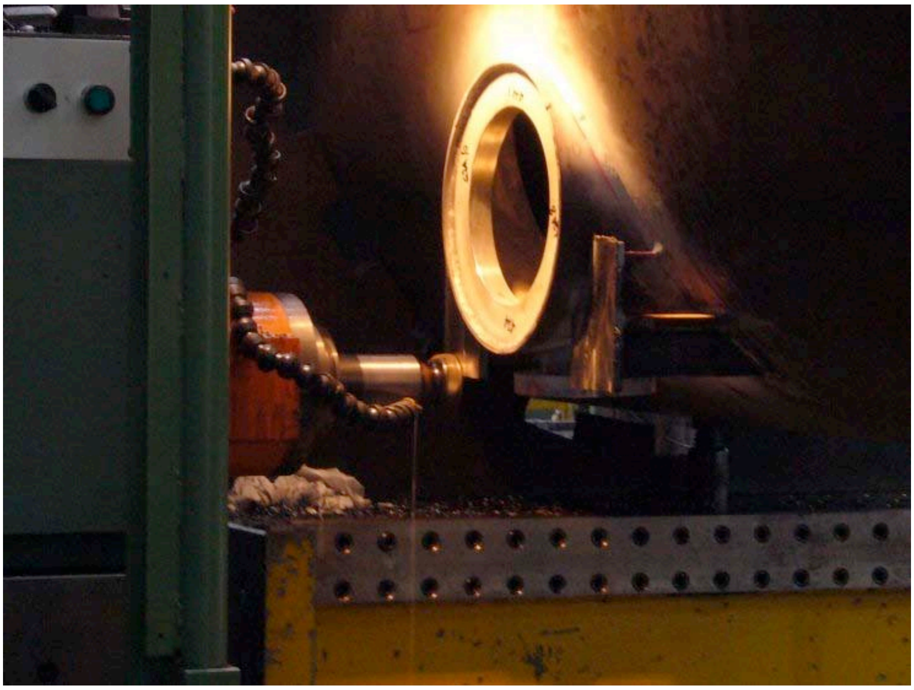


**Figure 35:** coupler flange machining

the coupler ports are flattened with reference to the vertical vessel plane;

the holes in the coupler front flange are done;

the post supports are flattened with reference to the horizontal vessel plane;

the holes in the post support flange are done.

*The vessel is painted*

internal painting: 1st layer: primer, 2nd layer: epoxy paint

external painting: 1st layer: primer, 2nd layer: yellow paint

## 4.2 Helium Gas Return Pipe

*Forming and welding of the tube*

The tubes are calendered from steel sheets and longitudinally welded

The tubes extremities are butted and beveled

Two tubes are circumferential welded to obtain the vessel required length

The reference axis (horizontal and vertical reference) are marked on the vessel external surface

*Welding of the in and out rings*

The ring for the tube beam output side is pre-fabricated.

The bellow for the beam input side is provided by Desy.

The bellow and the ring are fit up and welded to the tube.

*Other parts*

the 3 post supports are pre-fabricated (with over-material for the final machining) and welded to the tube;

the 20 shapes (4 different kinds: 2 supports for each cavities, the others for the quadrupole, the invar rod and the beamline valve) are pre-fabricated (with over-material for the final machining), fit up and welded to the tube;

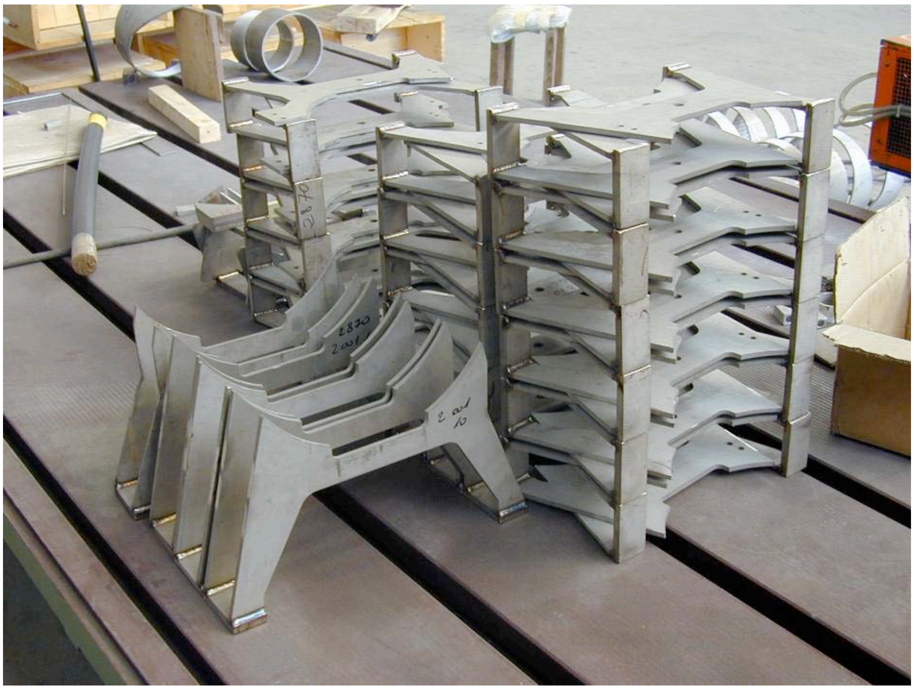


**Figure 36:** shapes pre-assembled

the 7 WPM supports are pre-fabricated (with over-material for the final machining) and welded to the tube;

the weld of the shapes is done by steps:

2 shapes are welded to the tube paying attention to preserve approximately the planarity of the cavity connection

the tube with the 2 welded shapes is translated and one of the shapes is chosen as the planarity reference

one more shape is welded to the tube and so on;

after the weld of the shapes the tube is straightened: heating the tube with welds on the opposite side respect to the shapes.

*Final machining:*

the final machining is done on a long milling machine, with a vertical and horizontal precision of 0.01 mm;

the vessel is positioned on the machine using the previously defined reference axis;

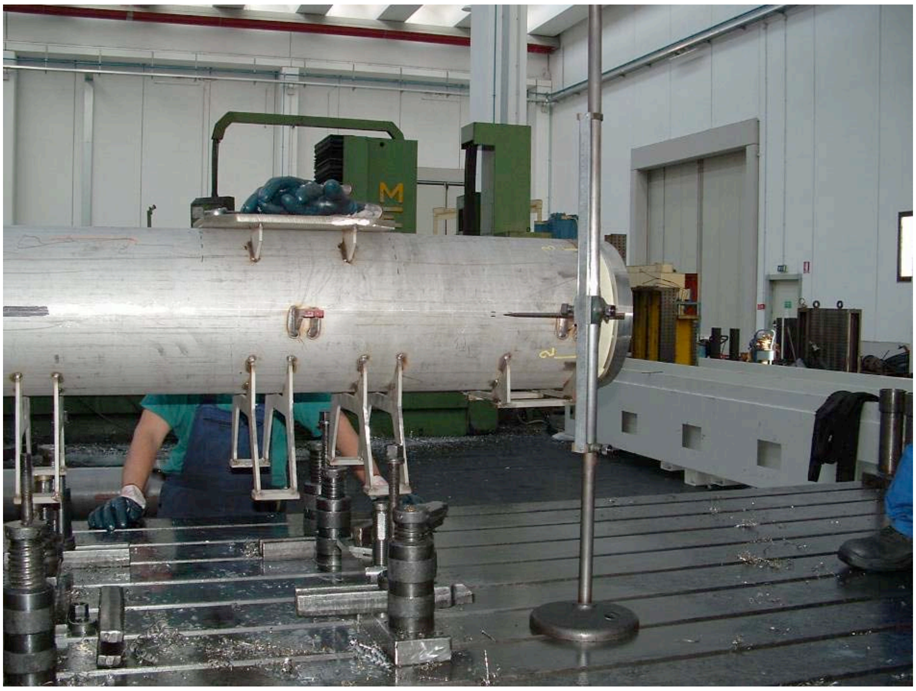


**Figure 37:** HeGRP positioning for the final machining

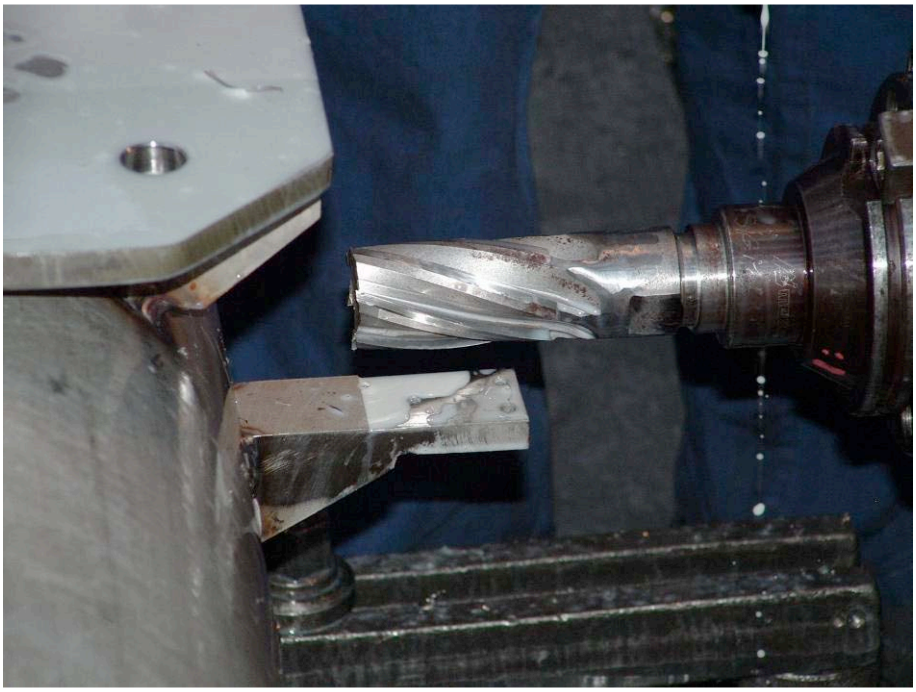


**Figure 38:** WPM supports flattening

the post supports are flattened with reference to the horizontal plane;

the holes in the post supports are done;

the shapes bases are flattened with reference to the horizontal plane;

the holes in shapes bases are done.

the WPM supports flattened with reference to the horizontal plane.

## 4.3 Thermal shields: 5 K and 70 K

the sheets are water jet cut, including the openings for the couplers and the finger welding cuts, with a tolerance of +/-2mm;

the upper and lower sectors are bent;

**Figure 39:** aluminum shields, lower parts

**Figure 40:** aluminum shields, upper part

4 upper parts are pre-assembled;
the finned 5 K tube is pre-assembled with the upper sectors;
the 8 lower sectors are pre-assembled to the upper sectors;
the upper and lower sectors are disassembled
the sectors are cleaned and pickled
the 4 upper sectors are assembled and riveted
the 5 K tube is assembled and welded to the upper sectors
the inter-connection sectors are pre-fabricated

## 4.4 Cryogenic tubes

*Warm-up tube*
the capillaries (connection to the helium vessel) are bent and welded
the tube is holed for the capillaries
the capillaries are welded to the main tube

*Aluminum tubes and bimetallic joints*
the finned tubes are butted
the bimetallic joints are welded to the tube, avoiding the heating of the joint

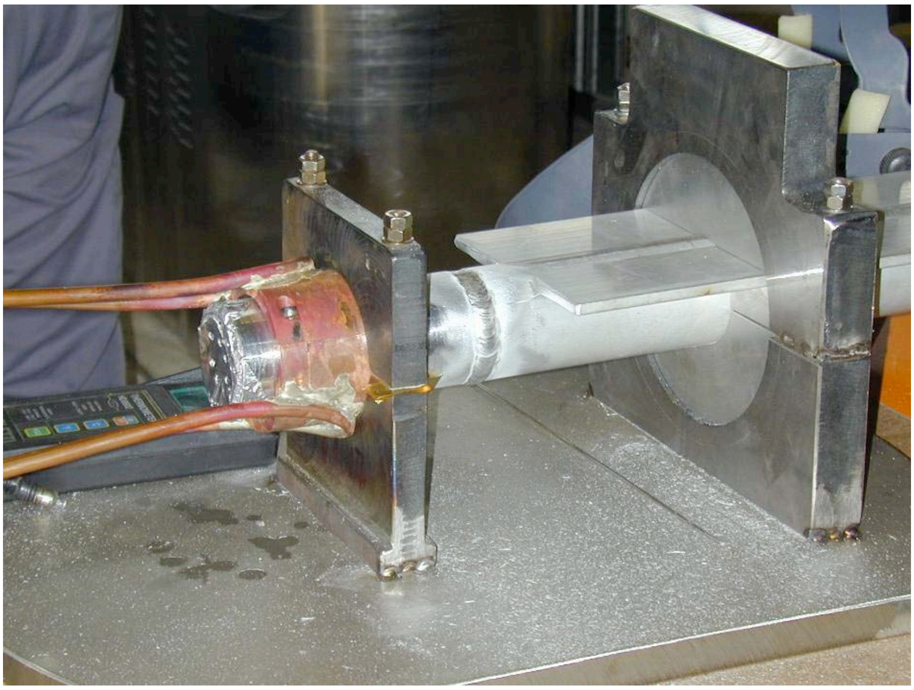


**Figure 41:** bimetallic joint weldment

*2 K, 5 K and 70 K Stainless steel tubes*
the fiberglass supports for the tube connection to the shapes are bolted

## 4.5 Cold-Mass preassembly

The fiberglass cryogenic supports (post) are fit up on the HeGRP
The upper and lower parts of the 5 K shield are assembled

The superinsulation blankets are assembled

The upper and lower parts of the 70 K shield are assembled

The bracket is placed on the warm post surface and referenced through its positioning pin

The bracket is positioned at the post center by means of the centering pin. 2 additional positioning pins are then inserted to fix the relative positions of the 2 objects and guarantee reproducibility between assembling and disassembling sequences

**Figure 42:** superinsulation

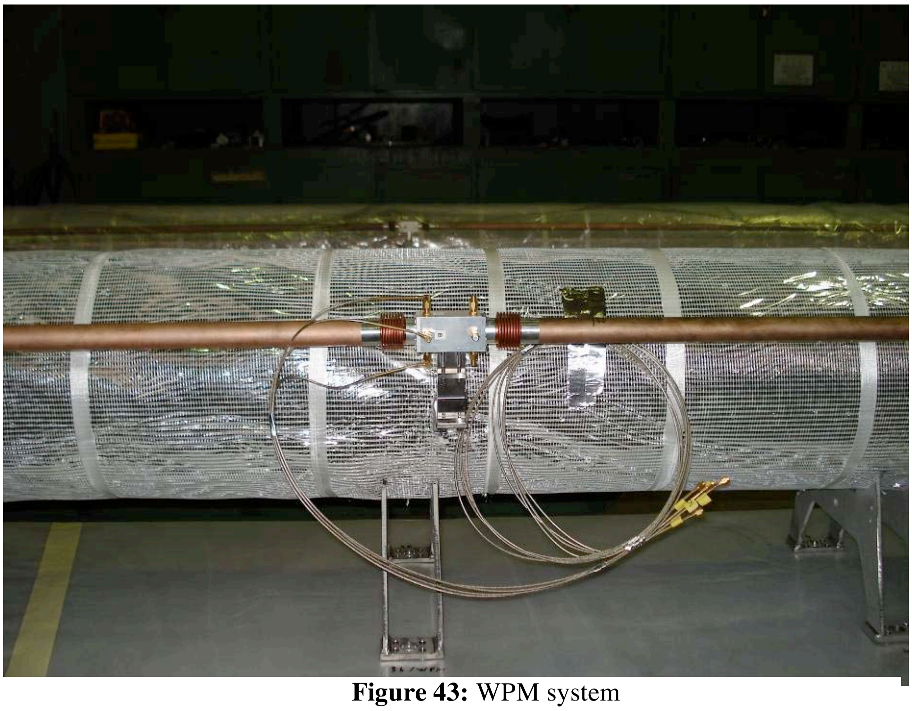


**Figure 43:** WPM system

**Figure 44:** cold mass preassembly

## 4.6 Additional notes

*Superinsulation*

The superinsulation on the 5 K shield is made of 10 layers of Double Aluminized Mylar (DAM) and 10 layers of vitrulan. The whole blanket is assembled in Zanon. The connection between following layers is staggered by about 50 cm. The final closure is done on the coupler side. The connections are done at the DAM layers with mylar tape, at the vitrulan layers with Tesa tape.

The superinsulation on the 70 K shield is made of 30 layers 30 layers of mylar and 30 layers of vitrulan.

In order to simplify the installation of the MLI blankets the double aluminized mylar (reflecting) sheets and the vitrulan spacer nets are prepared in long rolls of 10 layers. The rolls are installed on a scaffolding to the side of the module and the blankets are then easily slid on the thermal shield and cut.

The connections (2 for each layer) are done for the mylar layers with mylar tape, for the vitrulan layers with Tesa tape.

The superinsulation on the He tank shield is made of 5 layers of mylar and 5 layers of vitrulan. The connections are done for the mylar layers with mylar tape, for the vitrulan layers with tesa tape.

The superinsulation on the 2-phase tube is made of 3 layers of two-components sheets. The connections are done with mylar tape.

Before the installation of the layers the mylar roll has to be holed to avoid air trapping while vacuum pumping.

The critical operation during the assembly of the superinsulation is the winding of the first layers: they shouldn’t be too tightened, to avoid breaking of the mylar during cool-down (aluminum and mylar have different thermal shrinkage)

After the assembly of all the layers the MLI blankets are secured with fasteners approximately every meter.

*Helium Gas Return Pipe*

After welding of the shapes, lower post flanges and end flanges, the axis is defined on the milling machine according to the end flange centers and transferred to the lower post flanges. The interconnection bellows, properly fastened, are already included to minimize the intermodule lateral forces. The pipe is then turned and the cavity supports referenced to the defined GRP axis. A similar procedure is also applied to the vacuum vessel to reference the coupler ports and upper flanges to the vessel axis. After welding and before milling, a stress relief is performed on the GRP to avoid permanent deformation induced by thermal cycling.

*Optimization*

The design and production of the cryomodules have been constantly optimized for better performances and cost reduction. Minor manufacture optimizations and cost reduction for large scale production could still be achieved.

# 5 CRYOMODULE TESTS

## 5.1 Quality control plan for vacuum vessel

Review of the material certificates (tubes, plates, forgings);

100% Liquid Penetrant Test (PT) – 10% Radiography Test (RT) examination of the vessel welds (longitudinal weld of the steel sheets after calendering and tangential weld of the tube pieces);

100 % PT – 100% RT examination of weld crosses;

100% PT examination of the not radiographable sealing welds;

Helium leak test (HLT) of the entire vessel before painting.

Pneumatic test at 1 bar.

## 5.2 Quality control plan for the 5 K and 70 K aluminum cooling pipes

Review of the material certificates (tubes, plates, forgings);

100% PT of the weld connecting the thermocouple;

100 % RT examination of the welds regarding bimetallic joints (weld to stainless steel and aluminum);

Pneumatic test;

HLT of the tubes.

## 5.3 Quality control plan for the 2 K, 5 K and 70 K steel cooling pipes

Review of the material certificates (tubes, plates, forgings);

100% PT of the welds connecting the thermocouple;

100 % RT examination of the tangential welds of the tube pieces (each piece ~6m long);

Pneumatic test;

HLT of the 2 K and 70 K pipes;

HLT of the 5 K pipes.

## 5.4 Quality control plan for the warm up pipe

Review of the material certificates (tubes, plates, forgings);

100% RT of the tangential weld of the tube pieces (each piece ~6m long);

100 % PT examination of the welds connecting the capillaries and ancillary pices;

Pneumatic test;

HLT.

## 5.5 Quality control plan for Helium Gas Return Pipe

Review of the material certificates (tubes, plates, forgings);

100% RT of the welds (longitudinal weld of the steel sheets after calendering and tangential weld of the tube pieces);

100 % RT examination of welds connecting the end bellow (ring + bellow);

Pneumatic test after final machining;

HLT.

## 5.6 Structural tests (pressure tests)

The tube is pressurized up to the pressures in the following table (usually design pressure + 20%).

| Part | Test pressure (bar) |
|---|---|
| Vacuum vessel | 1 |
| HeGRP | 5.2 |
| 5 K, 70 K aluminum pipes | 27 |
| 2 K, 5 K, 70 K steel pipes | 27 |

## 5.7 Quality control plan for the posts

Each support post has been tested by compression-tension cycles to verify the strength of the interference junction. A break test showed that the post break force is about 100 kN: the 300 K steel flange moved a few mm from the nominal position at an applied force of 130 kN

# 6 DIFFERENCES TYPE 3 - TYPE 3+

## 6.1 Cavity spacing

Being cryomodule type 3+ a prototype test cryomodule for the XFEL project, the inter-cavity spacing at cold condition need to be an integer multiple of the reference wavelength of the XFEL (203.6 mm): the cold inter-cavity spacing is than fixed at 1383.6 mm (6 times the wavelength) that corresponds at warm condition to a value of 1384.15 mm. This change influences the position of the shapes, of the coupler openings on the vessel and other parts positions (as, for example, the fiberglass supports of the cooling pipes).

## 6.2 Openings

Here are the openings used in the type 3+ cryomodule:

*Nozzle C*

Nozzle C is dedicated to the magnet: it brings the cooling pipe form the external environment to the magnet. It is a radial nozzle, tilted of 105°. The flange is a standard CF63 flange.

| | |
|---|---|
| Opening diameter (mm) | 64 |
| Nozzle length* (mm) | 78 |
| Nozzle thickness (mm) | 3 |
| Nozzle material | AISI 304L |

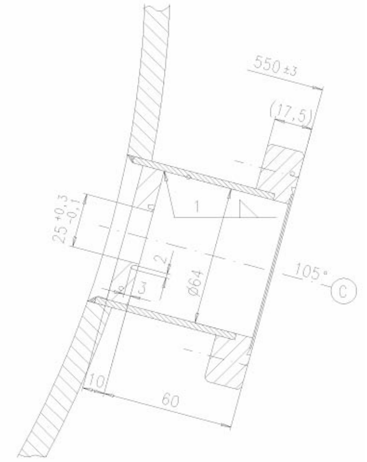


Figure 45: Nozzle C

*Nozzle D*

Nozzles D is dedicated to the tuner: it has 2 feed with 26 pins for the tuner plus 6 feedthroughs SMA. It's a radial nozzle, tilted of 70°. Here are the main parameters:

| | |
|---|---|
| Opening diameter (mm) | 184 |
| Nozzle length* (mm) | 137 |
| Nozzle thickness (mm) | 5.4 |
| Nozzle material | AISI 304L |

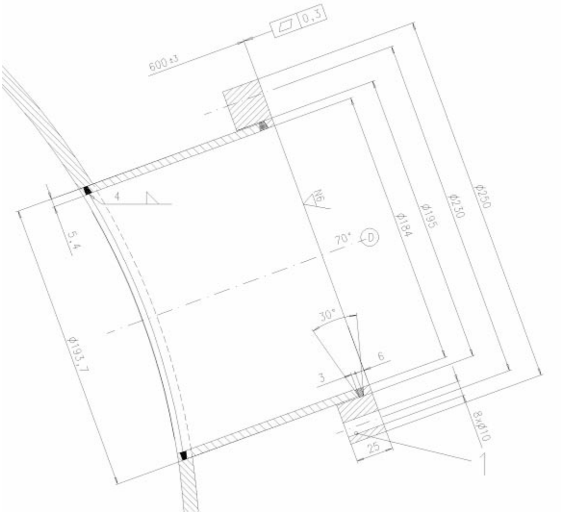


**Figure 46: Nozzle D**

*Nozzles F*

There are two openings named F, perpendicular to each other. These nozzles are dedicated to an “ad-hoc” laser interferometer dedicated to vibration measurements of the magnet. In the final cryomodule design the interferometer will be removed. The two nozzles aren’t radial, they are shifted respect to the vessel axis: the horizontal one is shifted of 378 mm under the vessel horizontal line, the vertical one is 185 mm away from the vertical line. The flanges are standard CF100 flanges.

| | |
|---|---|
| Opening diameter (mm) | 100 |
| Nozzle maximum length (mm) | 295 / 135 |
| Nozzle thickness (mm) | 2 |
| Distance of the horizontal nozzle axis to the horizontal axis of the vessel (mm) | 378 |
| Distance of the vertical nozzle axis to the vertical axis of the vessel (mm) | 185 |
| Nozzle material | AISI 304L |

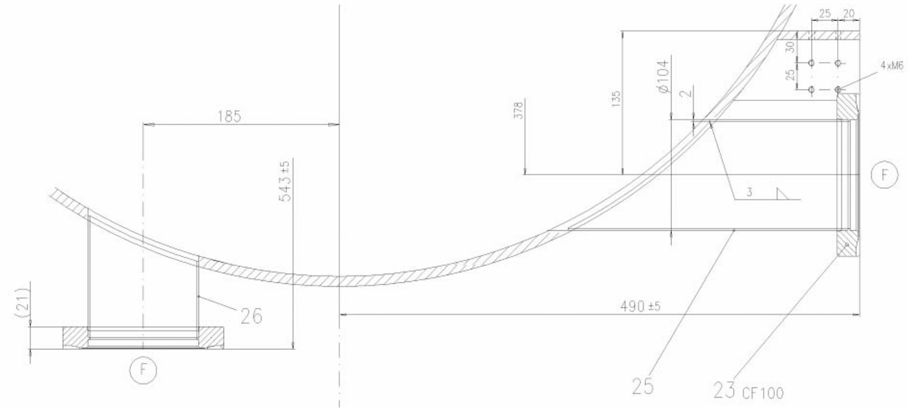


**Figure 47: Nozzles F**

*Nozzle G*

Nozzle G is for the magnet current leads, it is at ambient temperature. It’s a radial nozzle, tilted of 30° respect to the horizontal axis.

| Opening diameter (mm) | 100 |
|---|---|
| Nozzle length* (mm) | 35 |
| Nozzle thickness (mm) | - |
| Nozzle material | AISI 304L |

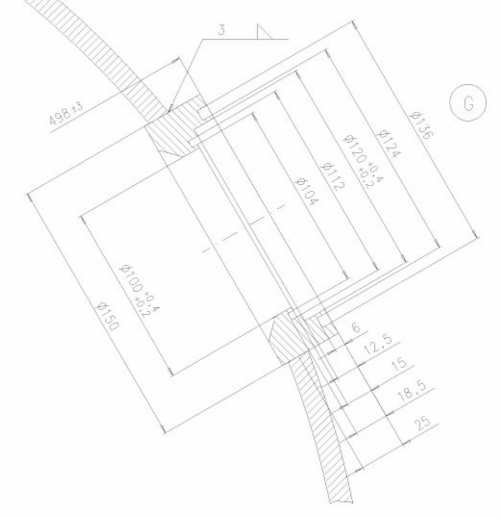


**Figure 48: Nozzle G**

*Nozzles K3 – K1*

Nozzle K3 is positioned over the first coupler opening and is the opening dedicated to temperature sensors. Nozzle K1 has the same configuration as nozzle K3, but it’s positioned at the other end of the vessel on the rear side; it is for spare service. Both the nozzles are axial nozzles, tilted of 70° (K3) and 225° (K1).

| Opening diameter (mm) | 158.3 |
|---|---|
| Nozzle length* (mm) | 104 |
| Nozzle thickness (mm) | 5 |
| Nozzle material (mm) | AISI 304L |

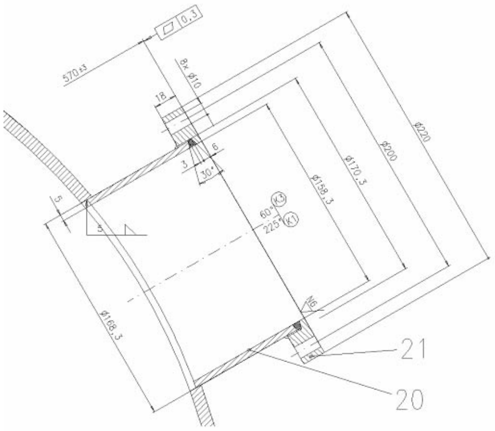


**Figure 49: nozzles K1 - K3**

## 6.3 ASME computations

Being the opening and nozzles different, also the ASME computations changed. We resume here the main changes.

[...]

*Geometry*

[...]

Nozzles

| Parameters | Nozzles K1 – K3 | Nozzle C | Nozzle D | Nozzle F_hor | Nozzle F_vert | Nozzle G | Coupler nozzle | Post opening |
|---|---|---|---|---|---|---|---|---|
| $D_i$ - internal diameter (mm) | 158.3 | 64 | 184 | 100 | 100 | 100 | 278 | 394 |
| d – max opening dimension[*] | 158.3 | 64 | 184 | 180 | 113 | 100 | 329 | 394 |
| $t_s$ (mm) | 5 | 3 | 5.4 | 2 | 2 | 25 | 5 | 123 |
| $P_d$ (bar) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $L_n$ – length (mm) | 104 | 78 | 137 | 295 | 135 | 35 | 200 | 183 |
| Cylindrical tube with longitudinal joints – Uncorroded geometrical characteristics | | | | | | | | |

*Verification of pressure and thickness requirements for main body and nozzles*

[...]

Nozzles

| Parameters | nozzles K1-K3 | nozzle C | nozzle D | nozzle F_hor | nozzle F_vert | nozzle G | coupler nozzle | post opening |
|---|---|---|---|---|---|---|---|---|
| A[8] | 1.27e-2 | 1.13e-2 | 1.00e-2 | 1.07e-3 | 2.80e-3 | 30e-3 | 4.35e-3 | 3e-3 |
| B[9] (kPa) | 89.0e3 | 88.3e3 | 87.6e3 | 58.4e3 | 72.8e3 | 99.9e3 | 78.9e3 | 103.4e3 |
| P[10] (bar) | 35.26 | 50.43 | 32.38 | 8.47 | 16.60 | 277.79 | 18.27 | 344.57 |
| t[11] (mm) | 0.50 | 0.25 | 0.75 | 0.75 | 0.40 | <5 | 0.85 | <10 |

Results

As in ASME 2001 sect. VIII div. 1 part UG-28 (c) (1) step 8, being for main body and nozzles $P_d < P$ AND $t < t_s$, the thickness and operating pressure of the vacuum vessel and nozzles are satisfactory.

*Verification of opening reinforcements*

[...]

| Parameters[24] | nozzles K1-K3 | nozzle C | nozzle D | nozzle F_hor | nozzle F_vert | nozzle G | coupler nozzle | post opening |
|---|---|---|---|---|---|---|---|---|

---

[*] d = $D_i$ for radial openings

[24] ASME 2001, sect. VIII, div. 1, part UG-37 (d) (1)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $A_1$ (mm$^2$) | 446.41 | 180.48 | 518.88 | 282.00 | 282.00 | 282.00 | 783.96 | 1111.08 |
| $A_2$ (mm$^2$) | 109.87 | 40.29 | 122.61 | 12.31 | 15.63 | 929.73 | 141.85 | 5252.98 |
| $A_3$ (mm$^2$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_{41}$, $A_{42}$, $A_{43}$ (mm$^2$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $A_1+A_2+A_3+A_{41}+A_{42}+A_{43}$ available reinforcing area | 556.27 | 220.77 | 641.49 | 294.31 | 297.63 | 1211.7 | 885.28 | 6364.06 |
| A/2 (mm$^2$) – required reinforcing area, external P | 530.31 | 214.40 | 616.40 | 335.00 | 335.00 | 335.00 | 931.30 | 1319.90 |
| Cylindrical tube with longitudinal joints – Uncorroded geometrical characteristic | | | | | | | | |

Results

As in ASME 2001, sect. VIII, div. 1, part UG-37 (d) (1):

- being for nozzles C, D, G, K1-K3 and post opening $A/2 <= A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43}$ these openings are adequately reinforced;
- being for coupler openings and nozzles F $A/2 > A_1 + A_2 + A_3 + A_{41} + A_{42} + A_{43}$ these openings aren’t adequately reinforced and need stiffeners or increased thickness.

[...]

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