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# de l'Accélérateur Laboratoire Linéaire

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### Description and Construction of the Cryostats

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U.M.R  
de  
l'Université Paris-Sud 11



Institut National de  
Physique Nucléaire et de  
Physique des Particules du CNRS

# **ATLAS ENDCAP LIQUID ARGON CALORIMETERS**

## **Description and Construction of the Cryostats**

Guy Macé, Serge Prat and Jean-Jacques Veillet

**Laboratoire de l'Accélérateur Linéaire**  
IN2P3-CNRS et Université de Paris-Sud 11, BP 34, F-91898 Orsay Cedex

All forward calorimeters of the Atlas detector use the same detection technique, energy loss in passive plates, followed by ionisation and charge detection in liquid argon. They are therefore all grouped in the same vessel which must basically support and keep in place the heavy plates and the detection electrodes and maintain liquid argon at cold and stable temperature. Taking into account all the constraints as detailed below, and the overall detector size, 5 meter diameter by 3 meter length this was quite a challenge. The design, construction and tests of these two cryostats, up to their delivery at Cern, are described in this document.

These two cryostats are a joint 'in kind' contribution to the Atlas experiment of LAL (Orsay), Max Planck Institute (München) and Wuppertal University (Wuppertal) and have been designed and built under the responsibility of LAL (Orsay) with contributions of the technical groups of the above institutions and of Atlas-Cern.

We particularly appreciated the contribution of Pierre Pailler (Atlas-Cern) and want to express our gratitude to all LAL people involved, namely Gilles Bellot, Emmanuel Beraudo, Marc Blaquière, Julien Bonis, Frederic Bogard, Christian Bourgeois, Patrick Cornebise, Marc Courtois, Pierre Delebecque, Aboud Fallou, Philippe Jean, Didier Laporte, Patrick Petit, Michèle Quentin, Didier Richard, Alice Thiébault et Emmanuelle Vernay

### **1- Requirements on the cryostat**

Each end-cap cryostat contains an electromagnetic calorimeter, two wheels of a hadronic calorimeter, and a forward calorimeter. For these detectors to give the best performance, the cryostat has the following functional requirements:

- Make the best use of the allocated volume and its partitioning for the different detectors according to the physics simulation results and the boundary conditions of the mechanical implementation.

- Minimize number of radiation lengths (structure of the cryostat and liquid argon) upstream of the detectors.
- Support the detectors by:
  - taking into account their architecture and minimizing the stresses on their structure.
  - ensuring the alignment with respect to the global apparatus and minimizing the variations caused by the different working situations (in particular during cooling-down).
- Provide the appropriate feedthroughs for the various signal, high voltage (HV), and calibration lines.
- Provide a stable, homogeneous and clean (ppm O<sub>2</sub> < 1 ppm) liquid argon bath.

Additional functional requirements are related to the cryostat itself:

- Use double vessel structure for minimal heat leaks.
- Support the internal and external pressures.
- Satisfy the safety requirements due to pressurized vessels, risk of liquid argon leakage, and utilization of materials at low temperature, in accordance with the relevant CERN [1] and CODAP [2] rules.

In order to integrate the end-cap cryostat into the ATLAS experiment one has to:

- Respect the maximum volume envelope as specified by the experiment [5-3] for all operating conditions.
- Provide an opening in the centre of the cryostat for the beam tube and the associated pump station. The choice of materials in the proximity of the beam pipe should also take into account a periodical bake-out of the beam tube (during shutdowns).
- Allow the cryostat to be mounted onto the Tile detector with minimal stresses for both structures.

Furthermore, the choice of materials has been made to minimize activation under radiation. Other constraints include the seismic stresses and those resulting from transportation, handling, and installation at CERN. Finally, to accommodate movements in the ATLAS cavern together with the Tile detector for access to the inner detector and to the barrel calorimeter electronics, all supply lines include a flexible section.

## **2- Engineering design of the cryostat**

The following description refers to the drawings in Figure i, showing the upper half of an end-cap cut vertically, and Figure ii, showing an end view of the end-cap.

The coordinate system used for the two end-cap cryostats is as follow:

- The interaction point is the origin, Y points upwards, X is directed towards the accelerator centre, Z is along the beam.
- End-cap A is defined to be the one at positive Z, end-cap C at negative Z.

## **2.1- General concept**

The cryostat is composed of two vessels made of aluminium alloy 5083. The cold vessel is filled with liquid argon at a pressure defined in § 4.2. The warm vessel is loaded by the external atmospheric pressure. The space in between the vessels is evacuated to at least  $10^{-2}$  Pa and contains multilayer superinsulation.

The cryostat vessels form a cylindrical torus around the beam axis with a flat wall in front (towards the interaction point) and a removable cover plate in the back (away from the interaction point). All cryogenic and electrical feedthroughs are integrated onto the back-end, which as a result extends to a larger cylindrical radius. The outer warm vessel of the cryostat is embedded in the Tile detector, which provides four support bearings (two at each end) slightly below the middle plane OXZ.

The inner warm tube provides space for the beam pipe and an associated pump station. It is bolted to the warm front wall. It is fixed to the warm cover plate at its backend by means of a stainless steel flange. A flexible connection between the tube and the back flange is provided by a seal welded stainless-steel bellows.

The cold inner tube surrounds the inner warm tube. The inner part of it is a double tube, called the FCAL structure. The smaller tube forms the wall of the cold vessel along the axis. The larger tube supports the FCAL detector, composed of:

- the electromagnetic forward calorimeter FCAL1
- the hadronic forward calorimeter FCAL2
- the hadronic forward calorimeter FCAL3
- the copper absorber PLUG3

The outer tube can be separated from the rest of the FCAL structure for the mounting of the FCAL detector. It features a number of holes allowing free circulation of liquid argon.

The FCAL structure is an important element for providing mechanical stiffness of the cold vessel. The conical forward extension of the FCAL structure is bolted to the cold front wall by means of a flange. In the back the FCAL structure is closed by a cover plate. The FCAL outer tube end is bolted onto the FCAL cover plate. This plate is seal welded at its smaller radius to the inner cold tube back-end, using a bellows (equipped with two bi metallic junctions).

The electromagnetic calorimeter (EMEC) and the two hadronic wheels (HEC1, HEC2) are housed in the main part of the cold vessel. The copper absorber PLUG1 is built from segments which are bolted to the inner side of the cold back-end plate. The cold absorber PLUG 2 is fixed on the back end of HEC 2.

A region of the inner front surface of the cold vessel is counterbored to house the end-cap presampler detector (see Figure i, Detail A) covering the pseudo rapidity region 1.4 to 1.8.

Four insulating bearings made of GFRP (Glass Fiber Reinforced Plastic) support the cold vessel within the warm vessel. They are placed such that the forces are transmitted vertically to the supports of the cryostat on the Tile detector (see Figure 1) to avoid geometrical deformation of the warm vessel under loads. In order to facilitate the mounting of the cold vessel, which is covered with multilayer superinsulation, the two front bearings are fixed to the warm vessel and the two back bearings are fixed to the cold vessel. The bearings are equipped with low friction stainless steel pads to allow movement during cool-down and warm-up periods.

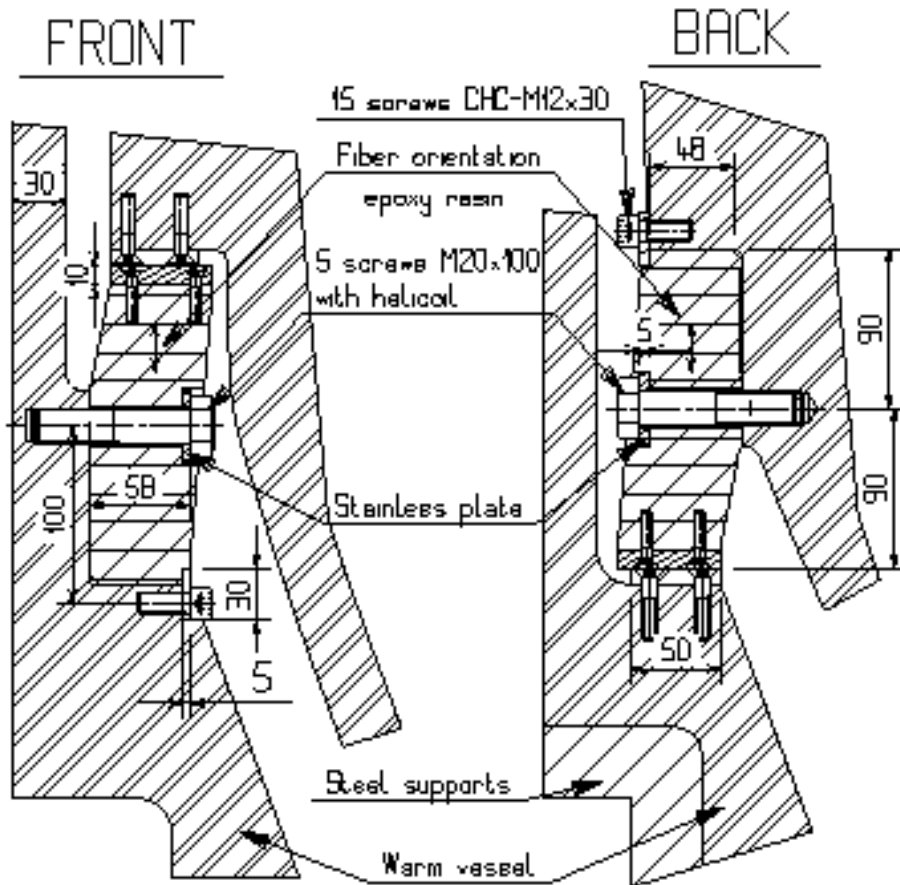


FIGURE 1: Cut showing the insulating GFRP bearings to support the cold vessel within the warm vessel.

The cold vessel positioning within the warm vessel is given:

- in X by four insulating GFRP stoppers placed top and bottom at the front and the back of the cylindrical body (see Figure i Detail B and C).
- in Z the back-end flange of the cold vessel is fixed to the back-end flange of the warm vessel by four GFRP stoppers at the front face of the flange and by GFRP spacers placed between the cold and warm back-end cover plates.

During cool-down and warm-up, the cold vessel and the detectors remain horizontally centered with respect to the beam axis. However vertically the detectors move downwards by 2 mm. In Z, as the detectors are fixed from the back to the cryostat rails, they move backward proportionally.

Between the front wall of the cold and warm vessels, a set of insulating spacers allows the warm wall, subjected to the external atmospheric pressure, to rest on the cold front wall. The contact between the spacers and the two walls is maintained by both internal and external pressures and by the pre-load resulting from the FCAL structure mounting (see Figure 2).

Warm and cold bottom vessels in working  
 (under pressure and at cold temperature)  
 The representation of the deformations  
 are multiply by 10

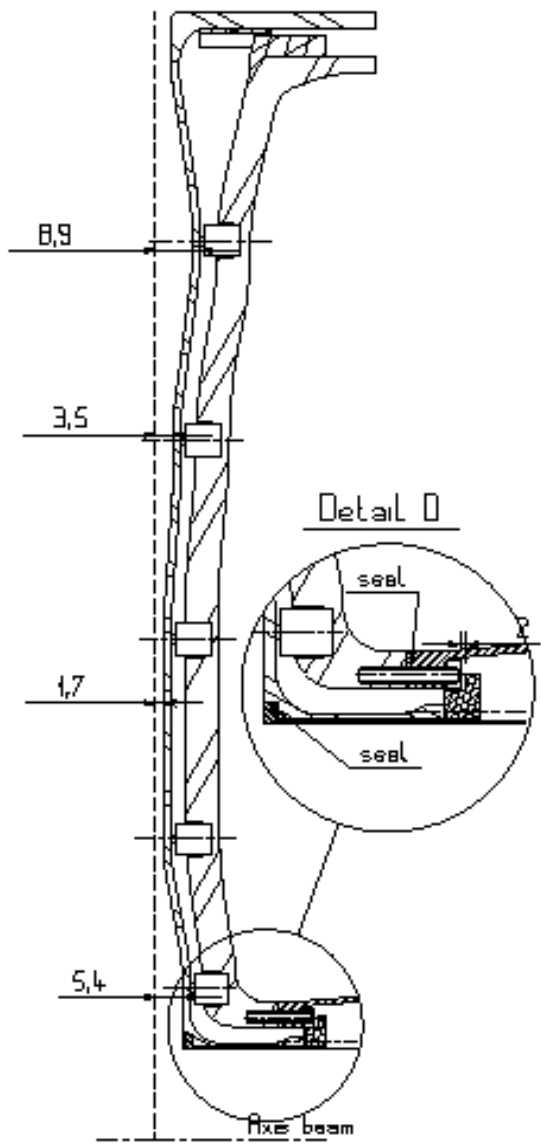


FIGURE 2: deformations of the cryostat front walls under pressure after cool-down.

An inner stopper, made out of two half rings (see Figure 2, Detail D), is positioned during assembly after pre-loading. This stopper maintains the contact between the central part of the two end walls in case of vacuum failure. With this stopper the maximum outward deformation of the warm end wall is considerably reduced and thus stays within the design envelope [3].

The LN2 heat exchanger piping is fixed to the inner cylinder wall of the cold vessel (see Figure 3). The piping consists of two independent parts, one fixed on the lower half cylinder and one in the upper half cylinder. Each of them is connected to feedthroughs for the LN2 inlet and outlet.

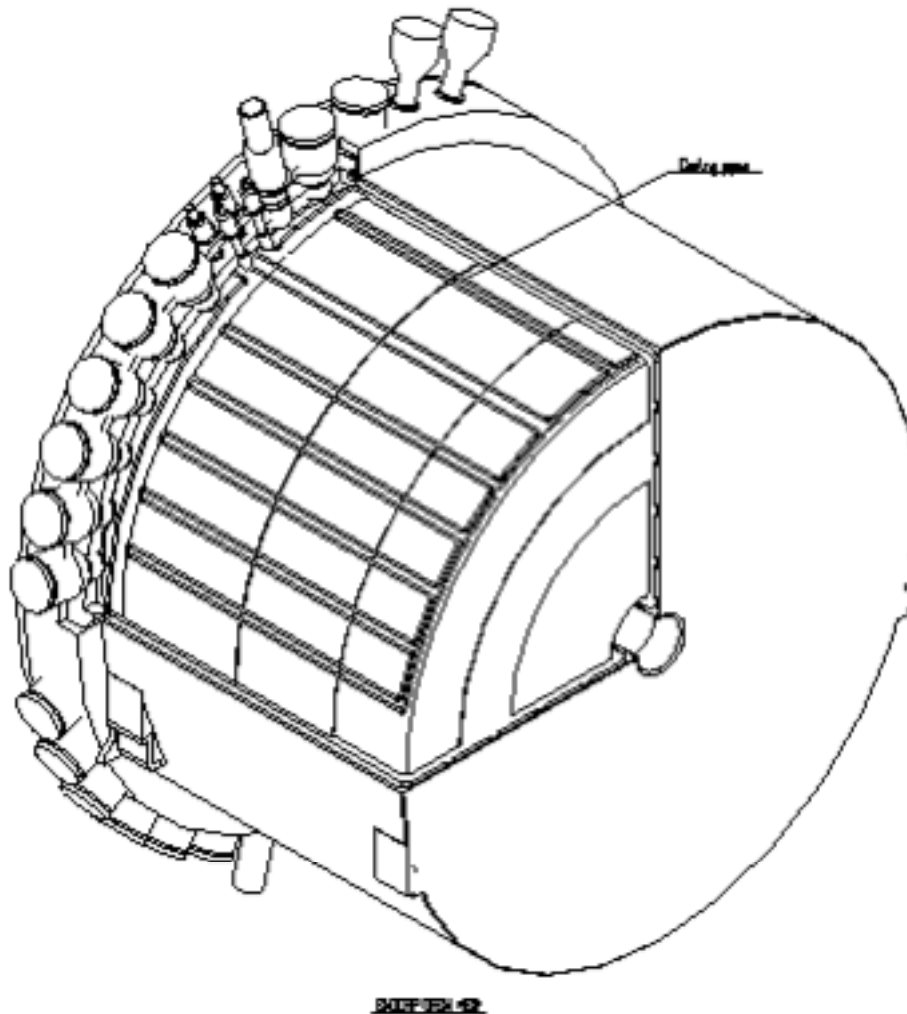


FIGURE 3: Open view of the end-cap cryostat, showing the heat exchanger pipes.

## 2.2- Cryostat interface

### 2.2.1- Mechanical interface to the Tile calorimeter

The cryostat is supported by the Tile detector on four bearings. Assuming the nominal vertical position, the loads are 37 tons per bearing in the front and 83 tons per bearing in the back. However in the case of a vertical misalignment, the stiffness against deformation is such, that a vertical offset of about 0.6 mm of one bearing transfers the load onto three bearings, two in the back and one in the front. The loads are consequently higher than nominal. The two front bearings of 280 x 40 mm<sup>2</sup> surface are free to move horizontally and are supported vertically by the Tile detector modules. These bearings are an integral part of the warm vessel structure. The bearing surface has been machined out to allow the crane adapter to be hooked on. This is secured by lateral fixing screws (see Figure 4).



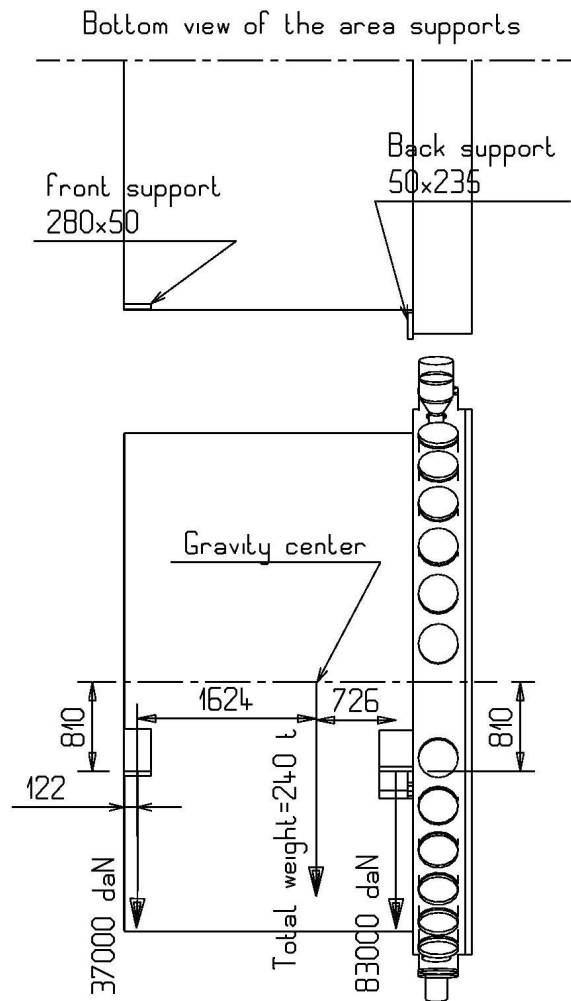


FIGURE 4: Mechanical interface of the end-cap cryostat.

The two back feet are made of aluminium alloy (2024) and bolted to the aluminium warm vessel structure. Their rectangular foot surface of 235 x 70 mm<sup>2</sup> has its longer side aligned along X, corresponding to the support surface of the Tile detector.

The cryostat is locked in Z and X in the horizontal plane on the Tile calorimeter at the location of two bearings in the back

### 2.2.2- Beam pipe interface

The internal diameter of the central tube of the warm vessel is 94 mm. Taking into account imperfections (parallelism, cylindricity, bending), the available diameter for passage of the beam pipe is 92 mm. This diameter does not take into account the geometrical profile defined by beam pipe tolerances, relative alignment tolerances between the beam pipe and the cryostat, and movement tolerances of the Tile-cryostat assembly.

The alignment of the detectors with respect to the beam axis is carried out according to the description given in § 2.3.

## 2.3- Detector interface

All detectors are electrical insulated with respect to cryostat structure by means of G10 pieces at each contact point.

### 2.3.1- Forward calorimeter (FCAL)

It is mounted within the FCAL tube and supported directly by the inner cylindrical surface of the tube. In fact the outer diameter of the detectors almost fits the inner diameter of the tube. The difference in diameters gives space for mounting and for the shrinkage differences between the detectors and the tube. The positioning and fixation in Z is given by two pins (top and bottom) for each detector (see Figure 5).

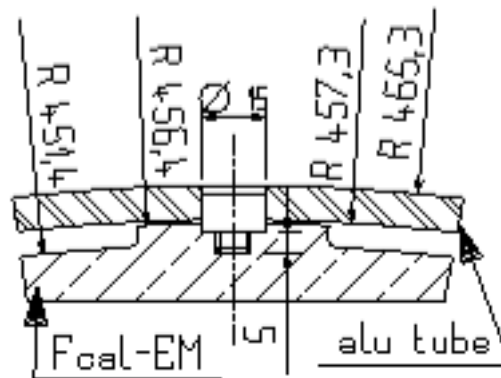


FIGURE 5: FCAL detector locking mechanics.

The detectors have longitudinal grooves in their outer surface to give room for the cables running along the FCAL tube. These cables exit the back-end between the tube and the FCAL cover by notches in the flange of the tube (see Figure i Detail E) to allow the tube to be attached onto the FCAL cover plate. The cables are terminated by connectors.

With the back-end cover of the cold vessel mounted and the FCAL assembled (structure, detectors and PLUG3), the FCAL can first be moved into the cryostat through the back-end to about 500 mm of its final position. In this position the cable ends coming from the detectors can be connected to the corresponding ones fixed on patch panels all around the circumference of PLUG2. After this operation the assembled FCAL can be pushed into its final position, where it is centred and fixed to the front and back plates of the cold vessel structure.

The FCAL structure coordinates are surveyed and referenced to alignment markers on the external part of the cryostat. The Tile-cryostat assembly will then be positioned in Z and adjusted in X and Y within the ATLAS experiment by using the reference markers on the outside of the cryostat, such that the FCAL detectors are centred on the beam.

### *2.3.2- Electromagnetic (EMEC) and hadronic (HEC1, HEC2) calorimeters*

At 75 mm below the middle plane OXZ, the cold vessel is equipped with a rail along the inner wall on both sides which serves as support for the feet of the EMEC and HEC detectors (see Figure ii Detail F). The lateral positioning (centring in X) is provided by a guiding rail fixed to the top of the cold vessel (see Figure ii Detail G). The Z position of the detectors is given at their backend face by stoppers in Z.

Prior to their mounting into the cryostat, the detectors are equipped with their cables, which are terminated by their connectors mounted on patch panels. Each detector slides in, is positioned in place, and fixed by two stoppers. Its cable harness is mounted from the front to the back onto the cold vessel and guided towards the feedthroughs. Shields are mounted to protect the cables. The patch panels are then fixed into place in the proximity of their corresponding feedthrough.

The alignment of the EMEC, HEC1 and HEC2 detectors is given by the mechanical positioning within the cold vessel, which in turn is aligned in reference to the FCAL structure, positioned on the beam axis, as described in §.2.3.1.

## **2.4- Mechanical structure response under load**

The cryostat is subjected to the following pre-loads:

- internal and external pressures,
- weight of the different elements,
- assembly pre-load corresponding to an extra length of 15 mm of the FCAL structure,
- the loads on the spacers and stoppers between the vessels and between the detectors and the cold vessel, including the tangential friction forces due to the retraction and shrinkage differences during cool-down and warm-up phases,
- the loads on the four insulating support feet between the vessels, including the tangential friction forces on the support surfaces,
- handling and transportation loads,
- seismic stresses.

The design principle followed is to minimize the number of structural parts which are affected by the transfer of the detector loads onto the supports of the Tile detector. This was carried out allowing for thermal retractions and shrinkage differences:

- The support feet of the principal detectors are positioned in the same vertical planes as the feet on either side of the cold vessel. The detectors sit on reinforced zones of the cold vessel. These zones bend without torsion moments. In addition, the ovalization of the back flange when the back-end cover is removed, is practically zero. This in turn allows to mount the cover without difficulty.

- The support of the FCAL detector within a tubular structure, whose ends are embedded into the front and the back of the cold vessel, also minimizes the deformation caused by the weight within the structure.

Non-negligible stress-induced displacements come from the pressure loads, because of the large dimensions. In order to minimize displacement without increasing the thicknesses excessively, which would contradict the request of transparency to particles, the following principles have been adopted:

- Linkage of the front-end to the back-end of the cold vessel by means of the FCAL structure.
- Support of the end plates of the warm vessel by those of the cold vessel by means of insulating spacers. This consequently reduces the thickness of the front warm end plate to 15 mm.
- Application of compression pre-load of about 30.000 daN to the FCAL structure, due to the mechanical assembly of the FCAL structure. This pre-load reduces the final pull stress in the FCAL structure.

## ***2.5- Electrical and cryogenic feedthroughs***

There are four kinds of feedthroughs for which the repartition is given in Figure ii:

- Twenty five feedthroughs for the measurement and calibration signals coming from the different detectors. One of them dedicated to FCAL detectors is at the top of the cryostat and 24 of them are grouped into four sectors of six feedthroughs each which are pairwise connected to 12 standard electronic boxes (identical to the ones used for the Barrel cryostat), using a special pedestal base as an adapter. One special electronic box is use for FCAL feedthrough.
- Two HV feedthroughs, integrated in the upper part of the cryostat near the top.
- Feedthroughs for the cryogenic lines:
  - One of large diameter to connect the cryostat with the overflow vessel. This is mounted near the top of the cryostat.
  - One LAr feedthrough connected to the bottom and used to empty the cryostat by means of gravity.
  - Two inlets and outlets of LN2 connected to the two heat exchangers are positioned on one side of the cryostat.
  - The evacuation flange of the warm vessel is positioned in the bottom part. A safety relief valve, which opens at 50 mbar overpressure, is mounted in the upper part of the cryostat.

The cryogenic feedthroughs are all fixed to the cold and warm vessel side in the same way as for the signal feedthroughs. A bellows is integrated into the structure which allows shrinkage. On the outside of the cryostat the cryogenic feedthroughs are equipped with a double wall insulated by vacuum, which interfaces to the external transfer lines (see Fig. 6) .

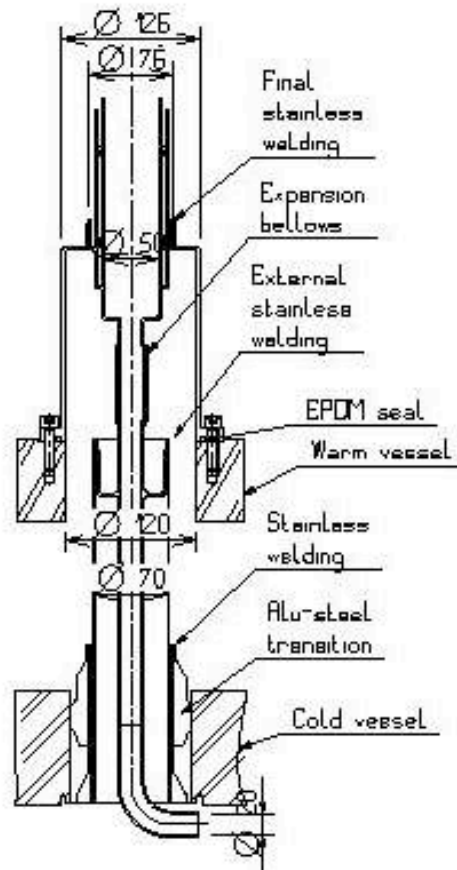


FIGURE 6 : Cryogenic feedthrough (LN2 outlet).

All feedthroughs are linked to the cold vessel by means of bi metallic junctions and designed in such a way that only the aluminium weldings have to be done at the workshop, and that the stainless steel weldings can be carried out in the assembly hall at CERN. The latter kind of weld can be milled and redone several times if necessary for installation and maintenance.

## 2.6- Cryogenic and thermal considerations

With the vacuum multilayer superinsulation placed between the warm and the cold vessel (nominal heat transfer  $5 \text{ watt/m}^2$ ), the insulating performance is mainly determined by the number of thermal bridges between the two envelopes and by the imperfections they introduce in the superinsulation coverage. The thermal bridges, which are the support feet, the spacers and stoppers, and the electrical and cryogenic feedthroughs, constitute heat sources (warm points) for the cold vessel. The cold preamplifiers of the HEC1 and HEC2 detectors also introduce heat sources within the LAr bath.

The total heat flux has to be globally compensated by the two heat exchangers inside the cold vessel. The layout of the heat exchanger, within which a nitrogen gas/liquid mixture is circulating, has been chosen in accordance to [4]. Also the cooling has to be managed in such a way, that the heat sources taken

individually do not create bubbles of argon gas, which are likely to produce short circuits between the detector electrodes. The local compensation without bubbling is based on the following features:

- The heat leaks through the supports, the spacers, and stoppers is distributed over a large effective exchange surface with the LAr because the structure aluminium is an excellent heat conductor.
- Effective local convection takes place within the subcooled (overpressured) liquid argon in the neighbourhood of the internal electronic heat sources, given that enough global cooling power is provided by the heat exchanger
- The heat sources caused by the feedthrough cables are in an area which, if necessary, can be separated from the detectors by a shield, keeping potential bubbles in the zone at the extreme back-end.
- The heat exchange and temperature homogeneity of the LAr bath, specified to be better than 0.66 K, can be improved by convection which is introduced by an appropriate cooling capacity difference between the upper and the lower heat exchangers.

In order to avoid condensation on the external surface of the warm vessel, some printed circuit heaters are glued on this surface and monitored, in running situations, by temperature sensors.

In order to quicker warming up the cryostat, some thermocoax or printed circuit heaters (total power 8kw) are fixed on external surface of the cold vessel and have to be monitored by temperature sensors during this stage.

## ***2.7- LAr and vacuum tightness***

The sealing of the cold vessel is performed in different ways, depending on the location:

- by aluminium welds for the structural parts and for the connection to the different bimetallic junctions
- by stainless steel welds for the connection of the bimetallic junctions to the different feedthroughs and bellows.
- by the bimetallic junctions stainless steel - aluminium themselves.
- by metallic HELICOFLEX, seals for the bolted structural link between front part of the FCAL structure and the cold vessel and, in addition, by welding structural parts in this area.
- by double metallic omega seals in the two other structural parts of the cold vessel (FCAL and cold vessel bulkheads). These structural parts have also finally been welded together (see Fig 7 a and b).

The fixture of these omega seals uses stainless steel bolts and Invar rings, which by their small expansion coefficient, allow differential shrinkage between the stainless steel and the aluminium to be compensated during and after cool-down. In front area however, in order to have a better transparency, the fixture of the Helicoflex seal use aluminium alloy studs with stainless steel nuts and no Invar rings are needed.

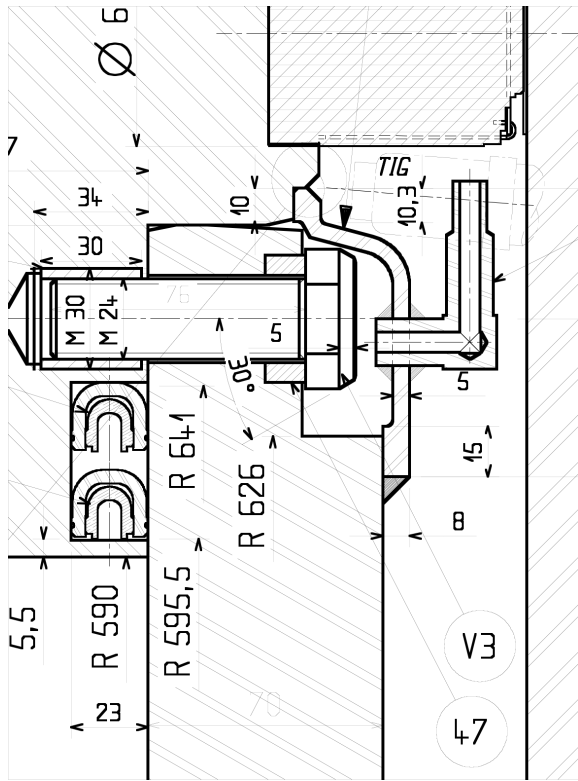


FIGURE 7a : Fixture and sealing of the Fcal plate on the cover plate.

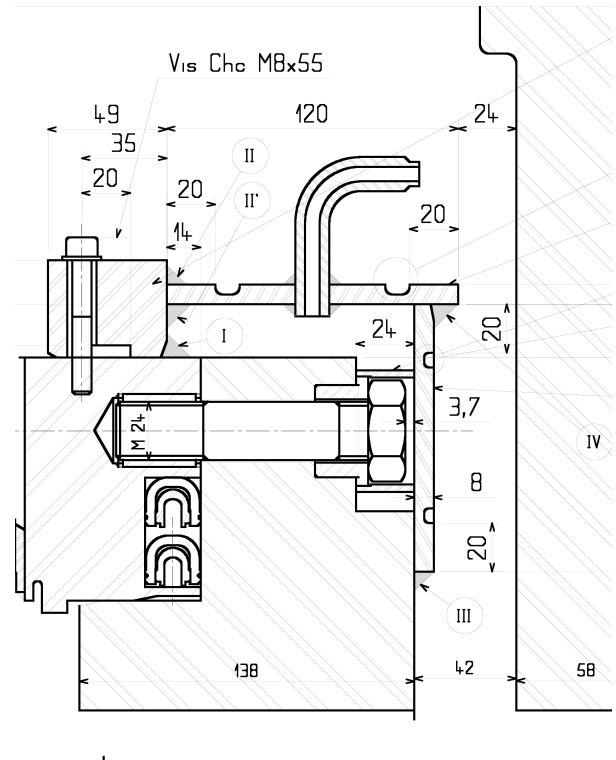


FIGURE 7b : Fixture and sealing of the cover plate on the cold vessel.

The seal for the warm vacuum vessel are always done by using EPDM O-ring seals.

## 2.8- Monitoring equipment

The equipment foreseen to monitor the cryostat during the various working situations consists of different sensors for the measurement of pressure, temperature (in CERN stage), stress and position (during industrial stage). These are installed in the inter-vessel and cold vessel spaces.

The stand-alone vacuum of the feedthroughs will be monitored in order to be able to detect any possible leak of liquid argon coming from their cold flange.

## 3-Design of the electrical feedthroughs

The feedthroughs for the signal and calibration lines are the same as for the barrel calorimeter. They consist of a cold flange (in contact with the LAr) and a warm flange (in contact with the external cryostat) which are separated by a monitored vacuum, which is independent of the envelope vacuum and have a pumping flange connected to the warm flange. The connection on the cold side is made by a stainless steel weld to a bimetallic junction, which is in turn welded to the cold vessel side by an aluminium weld.

The link to the warm vessel is made by means of a chimney with one end bolted to the warm flange of the feedthrough. The leak tightness is provided by an elastomeric joint. The other end of the chimney is bolted to the warm vessel, again using an elastomeric joint to seal the connection.

The internal cables, coming from the feedthroughs, are terminated by connectors and are long enough to allow placing them outside of the cold vessel towards the backend during the mounting of the detectors, and then connecting them to the detectors. The cables are identical, apart from some connected to the FCAL, which need to be longer.

The HV feedthroughs are built according to a different principle. They have a single warm flange, which is insulated from the liquid argon by a layer of argon gas, created by heating the liquid argon in contact with the warm flange. This works, unlike the other feedthroughs, by positioning the two HV feedthroughs on top of the cryostat. The connection to the cold and warm vessels is made in the same fashion as for the feedthroughs described previously: by a stainless steel weld to a bimetallic junction on the cold side and by a bolted connection with an O-ring seal on the warm side.

The HV and signal feedthroughs will also be equipped with printed circuit heaters, to prevent condensation and icing, which might cause O-rings leaks and bad contacts.

## 4-Working situations and load cases

### 4.1- Specifications and mass table of cryostat materials

The total mass of the cryostat of 23.6 tons plus the mounted detectors of 218.6 tons (without liquid argon) amounts to  $242 \pm 2$  tons. For the crane load one has to add the mass of the crane adapter of  $10 \pm 2$  tons. The mass of the liquid argon filling is 26 tons. A detailed list of the masses is given in Table 3 for the detector masses and in Table 4 for the cryostat masses. All materials used to build the cryostat are given in Table 5.

TABLE 3 : Detector masses (in tons).

Qty	Detector Part	Material	Mass (tons)
1	EMEC Electromagnetic calorimeter	Lead - stainless steel	24.2
1	HEC1 hadronic calorimeter	Copper	69.4
1	HEC2 hadronic calorimeter	Copper	92.2
1	Absorber (PLUG1 fixed on the cold end cover)	Copper	19
1	FCAL1	Copper	2.8
1	FCAL2	Tungsten	4
1	FCAL3	Tungsten	4
1	FCAL absorber (PLUG3)	Copper	2.5
1	FCAL absorber (PLUG2)	Copper	0.5
	<b>Total mass of detectors without LAr</b>		<b>218.6</b>



TABLE 4 : Cryostat masses (in tons).

Cryostat masses (in tons)			
Qty	Cryostat Part	Material	Mass
1	Cold vessel (feedthrough interface and welding seams included)	Alu 5083	7.3
1	Warm vessel (feedthrough interface and welding seams included)	Alu 5083	5.3
1	FCAL structure in two parts + cover	Alu 5083	0.45
1	Cold cover plate	Alu 5083	3.6
1	Warm back cover plate	Alu 5083	3
1	Warm inner tube	Alu 5083	0.019
28	Electrical signal feedthrough		0.04
28	Cable harness		0.054
2	HV feedthrough		0.04
1	Cryogenic safety feedthrough	Stainless steel	0.02
2	Return feedthrough for liquid and gaseous N2	Stainless steel	0.02
2	N2 input feedthrough	Stainless steel	0.02
1	LAr emptying feedthrough	Stainless steel	0.02
1	Vacuum pumping feedthrough to the inter vessel volume	Stainless steel	0.02
1	General nuts and bolts (about 500 all diameters)	Stainless steel/ Alu 2219	0.5
	Miscellaneous		0.5
1	Cooling pipes (total length = 170 m)	Stainless steel	0.08
	<b>Total cryostat mass without detectors and without liquid argon</b>		<b>23.6 + 2</b>

TABLE 5: Cryostat materials

Cryostat materials.							
Material	used for	Rultimate in MPa 300 K/87 K	R0.2 in MPa 300 K/87 K	A in % 300 K/87 K	E in MPa	Thermal conductivity in W/m K 300 K/87 K	Performance under 20 years radiation load at $10^{12}$ to $10^{16}$ Neutrons/cm <sup>2</sup> /year
Aluminium 5083 H111 (AlMg 4.5 Mn)	the structure of the cold and warm vessel	275/390	125 / 140	16 / 34	71,000/78,000	150/80	good
Stainless Steel 304L (Z 2 CN 18-10)	nuts and bolts	600/1320	210 /350	60 / 40	200,000/210,000	17/9	good (activates)
Stainless Steel ASTM XM14	cryostat support	805/1644	430 / 955	59 / 33	200000/210000	17/9	good (activates)
Aluminium alloy 2219 T 851 or T 6	insert bolts	410/610	300 / 300	10 / 12		- / -	good
cryogenic INVAR	fitting rings	470/980	280 / 680		14,500/13,800	10	good
GFRP STESALIT 4411 W	spacers and insulating supports	410 under compression 270 under traction			24,000/-	0.8/0.4	
EPDM	warm seals						good
HELICOFLEX (Alu + Inconel 600 + NIMONIC 90)	cold seals						good (activates)
Superinsulation (aluminized Polyester + Polyethylene Terephalate)	filling of the inter vessel space					average value 6 W/m <sup>2</sup>	good
Copper	absorber	23/37	7 / 12	- / -	12,500 / -		good

## ***4.2-Description of situations and load cases***

The operation of the cryostat can be described in terms of different working situations given in the following list. The situations are put, according to the CODAP rules, into the three categories: normal situation, exceptional situation and test situation.

### **Normal situation:**

1. Standard run condition (including a deregulation up to 1.7 bar of the nominal expansion vessel pressure of 1.25 bar)
2. Purging (successive application of 0 to 1 bar argon pressure in the cold vessel in order to purge it before cool-down and filling with LAr)
3. Cool-down with argon / warm-up with argon
4. Filling with LAr / purging LAr

### **Exceptional situation:**

5. Transport of the empty cryostat from the factory to the assembly hall at CERN
6. Mounting / dismounting of the different detectors
7. Surface transport at CERN from the assembly hall to the pit (warm cryostat with mounted detectors)
8. Lowering by crane into the pit
9. Displacement for access of the complete cryostat filled with liquid argon and hooked to the cryogenic lines
10. Rupture of the inter vessel vacuum with the pressure maintained at about atmospheric pressure
11. Leakage of liquid argon into the insulating vacuum space

### **Test situation:**

12. Helium leak test under vacuum of the cold vessel with its bimetallic junctions welded in at the aluminium end and obturated at the stainless steel end.
13. Helium leak test under vacuum of the warm vessel with obturated feedthroughs and the cold vessel mounted inside to hold the cover.
14. Helium leak test under vacuum of the assembled cold and warm vessel equipped with cabled feedthroughs.
15. Hydraulic pressure test.

With regard to the mechanical stiffness and taking into account the safety factors corresponding to the different situations one can cover the situations by five different load cases described in Table 6. Each of these load cases was verified by structural calculations. To be on the safe side, situation 1 was validated

with only one front foot in contact with its Tile support and in addition under consideration of seismic stresses specified by 0.15 g in all directions.

TABLE 6: Load cases, referring to the situations described on the text

Load cases, referring to the situations described in the text					
Load case	Ptotal (bar)	Inter vessel Pressure (bar)	T cold vessel (K)	T warm vessel (K)	Detectors mounted?
<b>Normal situation</b>					
1 + one front foot without contact	1.7 + 1	0	87	300	yes
2	0 to 1	0	300	300	yes
<b>Exceptional situation</b>					
1 + one front foot without contact + seismic effects	1.7 + 1	0	87	300	yes
11	1.7 + 1 + 0.2	1.05	87	300	yes
<b>Test</b>					
12	0	1	300	-	no
15	3.1 / 4.05 [14]	0	300	300	yes

[14]  $P_{test\ hydraulic} = 1.3 \times P_{ns} \times f / ft = 1.3 \times 2.7 \times 78/87.5 = 3.1\ bar$  with  $P_{ns}$  = maximal calculated pressure in the normal situation according to CODAP and with  $f, ft$  = admissible calculated stresses in the normal situation at 300 K and at 87 K respectively

$P_{test\ hydraulic} = 1.5 \times P_{ns} = 4.05\ bar$  according to TIS

## 5-Structure analysis

### 5.1-Calculations based on dedicated models

In order to validate the design principles adopted and described in §2.4 (stopper support of the warm front cover on the cold front cover, application of pre-loads) and in order to optimise the structure thickness and reinforcements with spacers, dedicated models were used.

- 2D axi-symmetric model of the two vessel envelopes for the pressure calculation.

The model is used to validate the following design principles:

- support of the thin warm front cover on the cold front-end of enhanced thickness. In fact, the results show, that on one hand the warm front end is subjected to small stresses only and on the other hand reduces the stresses in the cold front end by transmitting the outer atmospheric pressure onto it.

- pre-load of the FCAL structure at time of assembly. In fact, this pre-load reduces the stresses in the FCAL structure (zone 2, 3, 4 and 5), at the cost of zone 1 (see Fig.8).
- holding the warm front end by the front spacers (in the case of situation 11 of over pressure in the inter vessel space) within acceptable limits.
- simplified 3D model of the cold vessel

This was used to evaluate the cold vessel ovalization with detectors and without bulkheads.

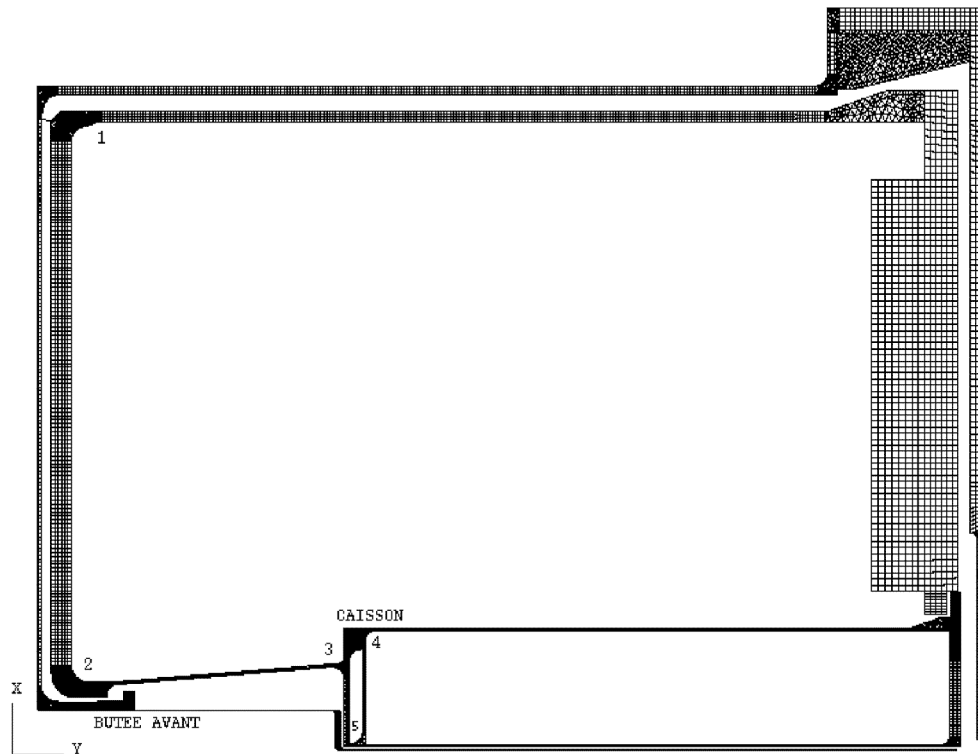


FIGURE 8: Dedicated axi-symmetric 2D model for calculation of the cryostat under pressure load only.

## 5.2 finite element analysis

A finite element model as shown in Figure 5-iii has been established using the SYSTUS program package. This allows a simulation of both vessels with the different stoppers and spacers between them with the consideration of the corresponding tolerances. It has the possibility to load the structure with all kinds of stresses to which it is subjected: pressure, weight, pre-load and seismic stress.

The shell model approach was used to determine deformations and reaction forces on bearings and fixations. The reaction forces are used as boundary conditions in local 3D models, which was used to calculate stresses in zones under high loads.

Main calculations made are listed in annex 1

## 6- Safety considerations

### 6.1-Risk cases

The risks are of different nature and origin owing to:

- the fact that the structure is pressurized
- the behaviour of the different materials at LAr temperature
- the use of liquid argon and nitrogen, which can be dangerous to people in case of spill out
- the aging of materials submitted to high doses of radiation, which can compromise their mechanical performance
- the activation of materials by radiation, which presents a hazard to the maintenance personnel.
- the use of specific components and materials as conception choices.
- the quality of industrial procurement, fabrication, transport and tests, for cryostats and tools.

### 6.2-Treatment of risk cases

#### 6.2.1-Mechanical stiffness

The end-cap structure has been checked with respect to its behaviour under load by reference to the CODAP rule C10 for all the operational situations.

The finite element calculations have been done using two different program packages:

- SYSTUS (ISO 9001 certified), which allows on one hand the pre-dimensioning and optimisation of the structure by means of shell elements of the 3D type or the simplified axi-symmetric type, and on the other hand the validation of the structure by means of a combination of shell elements and volume elements .
- ABACUS (ISO 9001 certified), which is used for a second calculation and independent validation).

The safety coefficients between maximal stresses and admissible stresses are taken in accordance to the CODAP safety code and are different for the normal and exceptional situations. In addition all aluminium welds will be certified according to the CODAP rules (see Table 7).

TABLE 7: CODAP criteria for admissible stresses depending of the type of situation.

CODAP criteria for admissible stresses depending on the type of situation.		
Situation	Structure parts	Nuts and bolts
Normal situation	$\text{Min}(R0.2/1.6 , R_{ultimate}/3)$	$R_{ultimate}/5$
Exceptional situation	$\text{Min}(0.95 \times R0.2 , R_{ultimate}/2)$	$R_{ultimate}/3$

All materials used are cryogenic compatible, even those of the warm vessel.

The different loads was established, the variations of the stresses was measured and checked in place by means of the stress gauges installed on the structure. The measured values was compared with the results of the calculations.

#### *6.2.2-Leakage of cryogenic liquid*

There are three possible causes of leakage:

- porosity of the material
- defective welding
- leaking seal

The non-porosity of the materials (grain size, cracks, etc) was assured by specifying the supply and by the global leak test once the assembly is finished.

The design of the aluminium and stainless steel welds as well as that of the bimetallic junctions, was subjected to development tests.

The structural welds, and all knot welds, was X- rayed, 100%.

Tests of the cold seals was done to justify the reliability of these solutions.

#### *6.2.3-Radioactivity*

The materials have been chosen by considering their satisfactory behaviour under long term irradiation. With reference to maintenance, the problem of residual radiation needs further studies. However, a first qualitative study has been done.

#### *6.2.4-components and materials validation*

All along development stage (including procurement and fabrication) components and materials was tested to validate choices of conception. They concern, Russian bi metallic junctions, bolts and nuts, friction material (PERMAGLIDE), bellows, composite feet and stoppers, HELICOFLEX and omega seals. These tests are listed in annex 2.

#### *6.2.5-Quality of industrial work*

See §7 “Industrial fabrication”

## 7- Industrial fabrication

### 7.1- Introduction

The manufacturing of the 2 cryostats was awarded through a European call for tenders to the Italian company SIMIC located in Camerana – Piemonte (northern Italy). The contract started on 1/01/1999 and lasted 53 months.

Cryostat C:

- was delivered to CERN on 20/03/02
- the reception leak test was performed by CERN on 30/05/02
- an additional cold test was performed by CERN on 20/06/02

Cryostat A:

- was delivered to CERN on 4/06/03
- the reception leak test was performed by CERN on 16/06/03

The manufacturing scheme followed as closely as possible the contractual documents:

- the CCTP (Cahier des Clauses Techniques Particulières), which describes what had to be done (list of deliverables, list of qualification tests to perform)
- the STP (Spécifications Techniques Particulières), which describes the manufacturing processes

### 7.2- Manufacturing files

To each cryostat is attached a manufacturing file which describes the specific fabrication processes and provides all tests results. The detailed content of each file is the following:

- Material documents:
  - Part list with supplier name for raw material
  - Raw material certificates according to EN 10204 3-1 B standard
  - Bolts and nuts supplier list
  - Welding material certificates
  - Bellows: material certificates and supplier's calculation design reports
  - Axial stops: qualification tests
  - Cold vessel supports: supplier certificate and qualification compression test
  - Specification for gluing
  - Cryogenic feedthroughs provided by ISN Grenoble: drawings
- Welding documents:
  - Welding principles
  - Welding procedures approval records (Italian Institute of Welding)
  - Welding seams: definition, specifications and drawings
  - Welding Procedure Specifications for production
  - Non-destructive control of welds



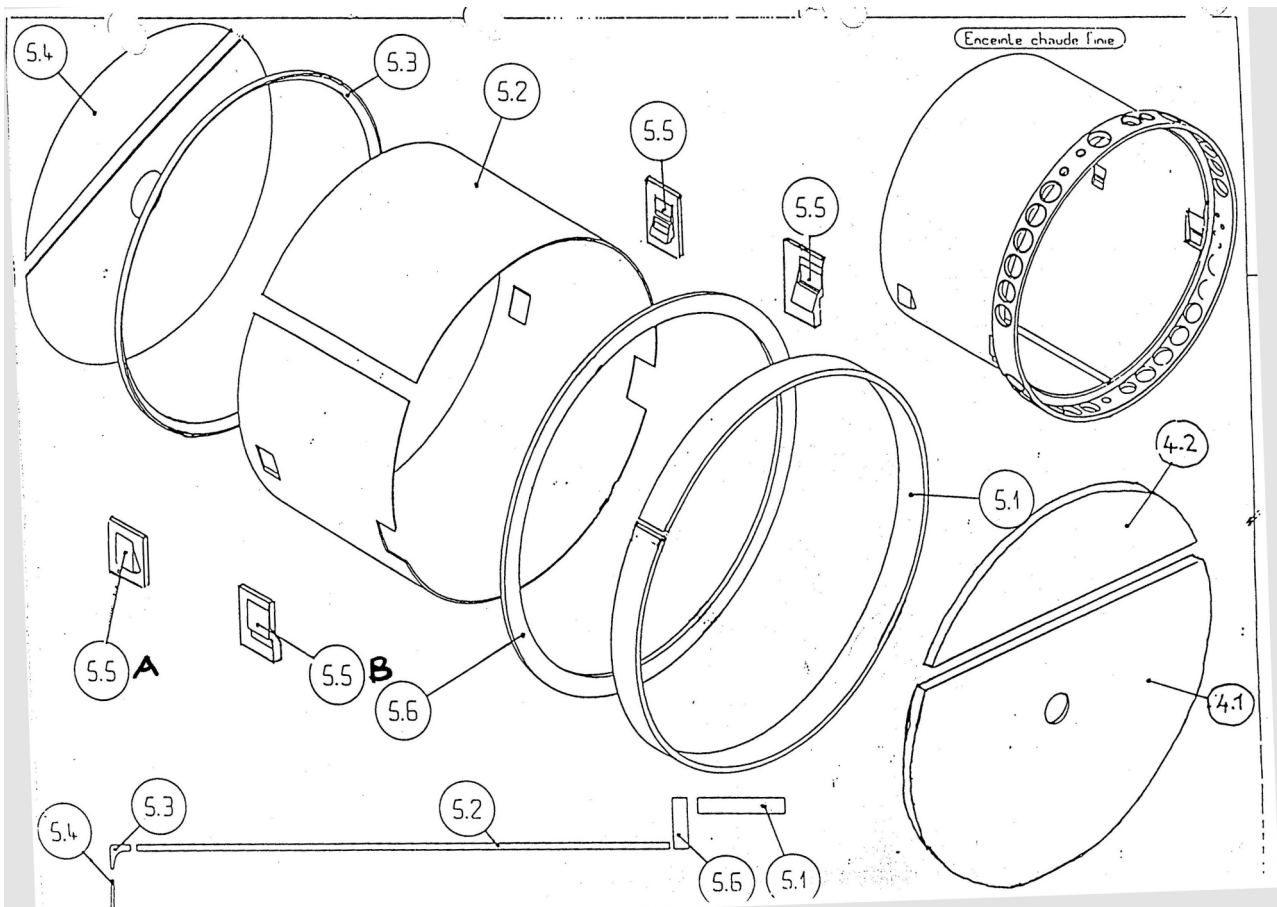
- Welding coupons qualification test reports
- Thermal treatment for stress relief: procedure and recordings of thermocouples
- Welders qualification certificates
- Welding quality plan and list of operations
- Tests records:
  - Load test of the warm vessel
  - Hydraulic test of the cold vessel: procedure and records
  - Procedures for leak tests
  - Leak tests reports:
    - Extensions for feedthroughs
    - Warm vessel
    - Warm tube
    - Cold tube
    - Cold vessel
    - Global leak test at 300K
    - Global leak test at 80K
  - Cryogenic test: procedure and records
- Non-conformance reports:
  - List of n-c
  - Reports explaining how each n-c was solved
- Quality plan and list of manufacturing and control operations (LOFC)
- Control documents:
  - RX and LP control of welds in the heat exchanger
  - Dimensional control reports for cold vessel
  - RX examination reports of welds for the cold vessel
  - Dimensional control reports for warm vessel
  - RX examination reports of welds for the warm vessel
  - Dimensional control reports for the cold and warm tubes
  - RX examination reports of welds for the cold and warm tubes
- Calculation reports and tests done by LAL:
  - Joints froids OMEGA
  - Joints froids HELICOFLEX
  - Température de surface pendant le test cryogénique
  - Températures internes lors du test cryogénique
  - Besoins thermique de réchauffage du tube chaud
  - Fluage du PEEK
  - Réponse des cryostats aux secousses sismiques
  - Série de tests effectués par LAL
  - Essais mécaniques des matériaux composites époxy / fibre de verre
  - Test d'un pied composite arrière
  - Essais en compression des butées axiales
  - Calcul de la pression dans l'espace inter-enceintes
  - Tests de frottement
  - Essais de qualification des rails en PERMAGLIDE
  - Couples de serrage des vis : essais et spécification
  - Note de calcul préliminaire globale

- Subcontracted items:
  - Chemical cleaning of warm and cold vessels
  - Procedure and drawings of super-insulation
  - Active carbon material
  - Specification for gluing
  - THERMOCOAX heaters
  - ALODINE treatment of rings for warm vessel
  - Bi-metallic transitions
  - Bellows
  - Hydraulic jacks for tightening nuts
  - Handling and transport

## 7.3- Welded assemblies

### 7.3.1- Warm vessels

Warm vessels and covers are made of several elements assembled and welded together according to the following figure:



The manufacturing process consisted in:

- assemble and weld together elements 5.1, 5.6, 5.2, 5.3, 5.4
- heat treat the assembly for stress relief
- cut 4 openings in the wall of 5.2
- weld the 4 feet 5.5 to 5.2
- final machining of the holes in the flange
- RX control of all welds
- Dimensional control to verify that the tolerances are met

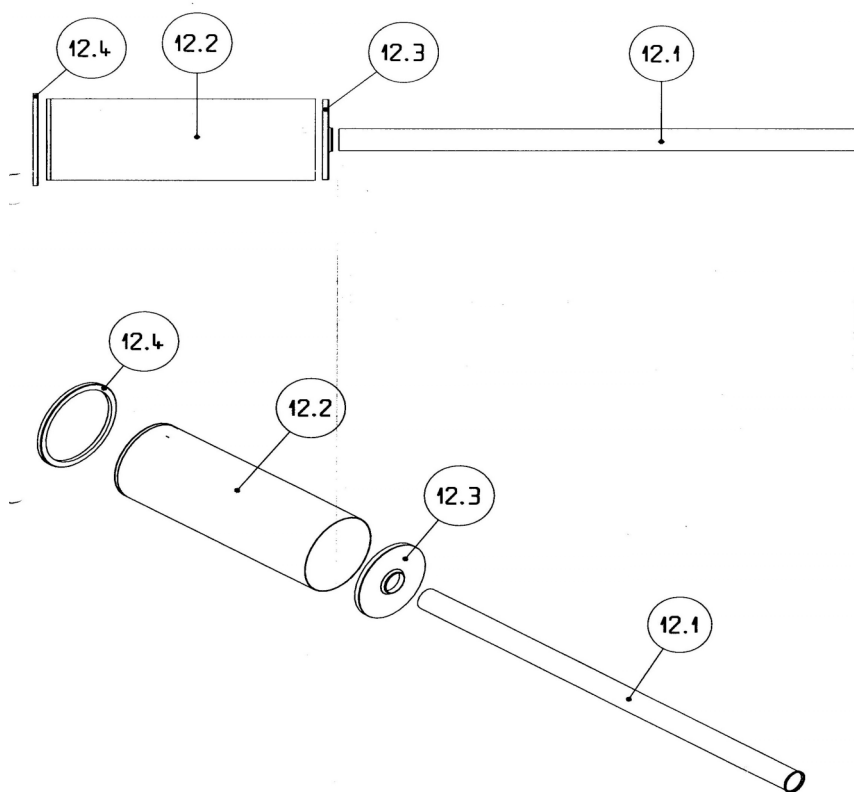
Outside rings with ALODINE treatment (surface treatment to improve electrical conductivity) were welded on each signal port, and covers with O rings were installed to close the vessel.

The warm vessel was leak-tested under vacuum, and for that a special steel frame was inserted in the vessel to hold the atmospheric pressure acting on the bottom and on the cover.

The warm vessel was cleaned according to step 1 only of the cleaning procedure, consisting of degreasing with “Clinox 30” liquid.

After that a complete dimensional survey was done by SIMIC, first on a vertical lathe, secondly in the assembly hall using a theodolite. Besides, for the endcap “C” an independent dimensional survey was done by the CERN survey team which issued a control report (CERN document N° EDMS 309779), measurements which are in a very good agreement with SIMIC’s results. Consequently it was not repeated for endcap “A”.

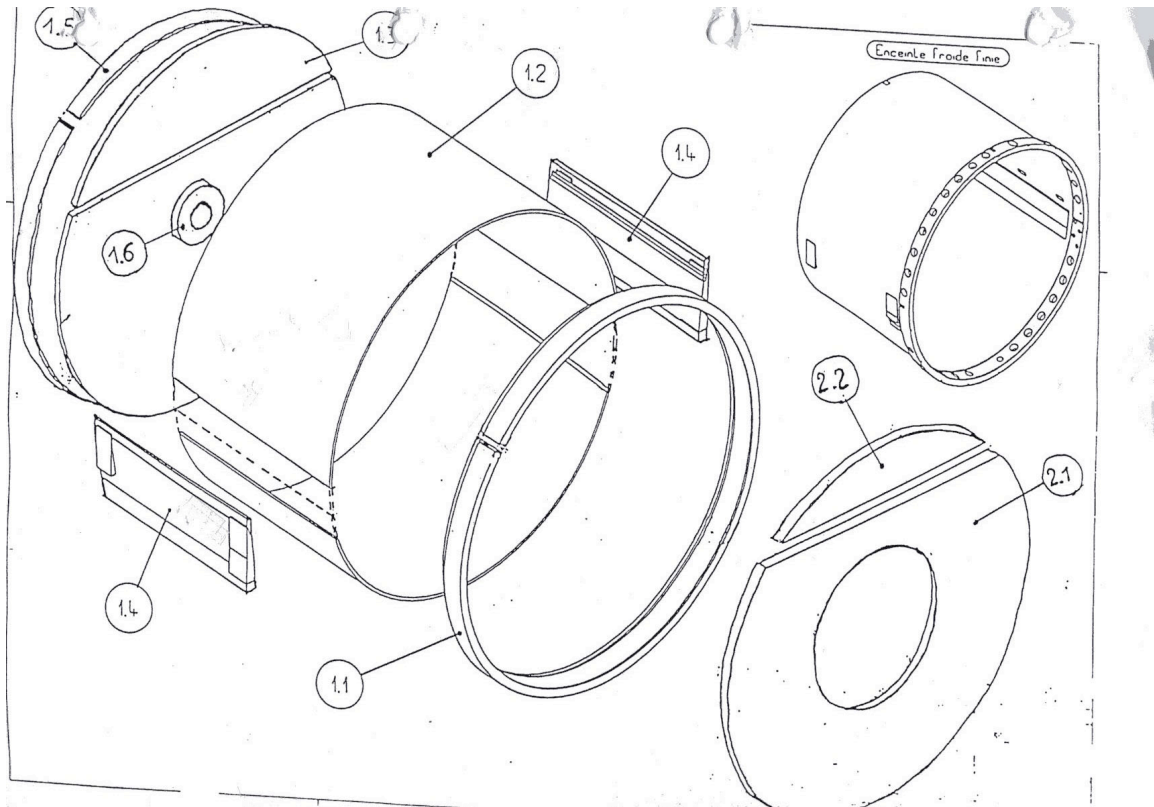
### **Welding assembly of the warm tube:**



this shows all elements which were welded together.

### 7.3.2- Cold vessels

Cold vessels are made of several elements assembled and welded together according to the following figure:



The manufacturing process consisted in:

- assemble and weld together walls 1.2 to the 2 beams 1.4
- heat treat this assembly for stress relief
- weld separately 1.3, 1.5, 1.6
- weld all parts together
- heat treat the whole assembly for final stress relief
- final machining of the holes in the flange
- RX control of all welds
- Dimensional control to verify that the tolerances are met

The bi-metallic transitions were welded at each signal and cryogenic port.

The 2 LN2 heat exchangers were assembled and welded, installed on the inner walls of the vessel and welded to the 4 bi-metallic transitions.

The cold vessel was leak-tested by pressurizing the internal volume at 1.5 bars absolute (1 bar N<sub>2</sub> + 0.5 bar He). Specification of leak < 10<sup>-8</sup> mbar was met for both cold vessels.

The 2 LN2 heat exchangers were leak tested by pressurizing them at 9 bars with He, leak value was measured < 5 10<sup>-8</sup> mbar.

The cold vessel was then cleaned according to steps 1, 2 and 3 of the cleaning procedure, consisting of degreasing with “Clinox 30” liquid, acid etching with fluophosphoric acid, passivation with nitric acid and rinsing with demineralised water.

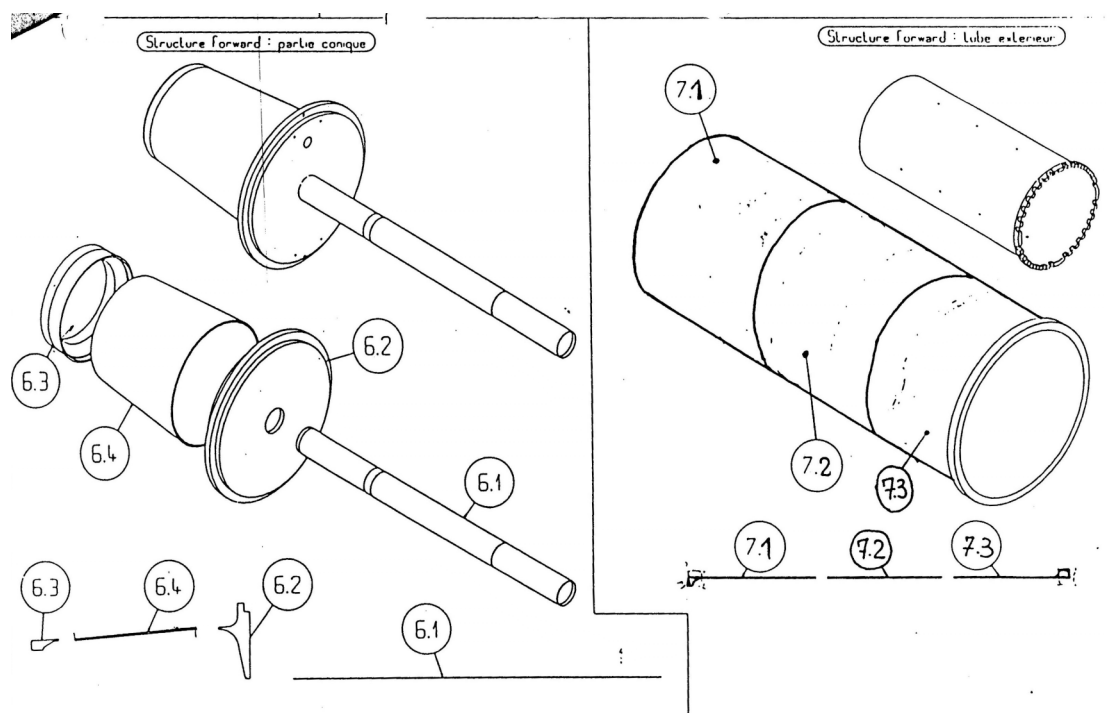
A hydraulic pressure test was performed up to 3.4 bars absolute pressure measured at the bottom:

- for endcap C this test was done after insertion in the warm vessel, and was repeated 2 more times due to leaks first of OMEGA seals and later of HELICOFLEX seal. These leaks caused moisture of the super-insulation, which was very difficult to get rid of: multiple flushing of the inter-vessel space with warm N2 was done in a lengthy process.
- For endcap A, it was decided to perform the hydraulic test on the cold vessel as stand alone before installing the super-insulation, in order to avoid the same moisture problems in case of a leak. A mechanical study justifies the validity of this test compared to the original configuration.

The 8 THERMOCOAX heaters were welded on the outside wall of the vessel.

After that a complete dimensional survey was done by SIMIC, first on a vertical lathe, secondly in the assembly hall using a theodolite. Besides, for the endcap “C” an independent dimensional survey was done by the CERN survey team which issued a control report (CERN document N° EDMS 319255), measurements which are in a very good agreement with SIMIC’s results.

### **Welding assembly of the FCAL structure (conical tube and external cylinder):**



### **7.4- Inter-vessel spacers**

Spacers have 2 functions : one is to sustain the weight of the loaded cold vessel and the axial load due to vacuum, the other is to limit the thermal losses by conduction.

#### *7.4.1- Cold vessel supports*

4 support bearings hold the weight of the cold vessel, with a nominal load of 70 Tons per support. They are made of several layers of glass fibers oriented in specific directions and bonded in epoxy. This material was specially manufactured according to the design specifications by STESALIT in Switzerland. Samples were tested to qualify the material. After manufacturing, an additional support was load tested until 210 Tons showing a linear deformation and no degradation. This support resisted without collapse until the maximum feasible load of 500 Tons.

#### *7.4.2- Axial spacers*

There are 40 axial spacers on the rear end between the 2 covers and 51 on the front between the 2 bottoms. They consist of several cylinders interlaced, made alternatively of stainless steel and glass-epoxy material. Each glass-epoxy cylinder was qualified by compression tests.

In the original design, the front contact surface was a disk of PERMAGLIDE material, but it was found after the cryogenic reception test that these disks produced deep indents in the mating surface of the warm vessel, and some parts were unglued . A new design was produced and all the spacers were modified to suppress one intermediate glass-epoxy cylinder and with a front contact disk made of PEEK, while thin stainless steel plates were fixed on the mating warm surfaces.

The relaxation coefficient of PEEK was measured experimentally and a global load test qualified the resistance of the axial spacers.

There was a trial insertion of the cold vessel in the warm vessel after mounting all the inter-vessel supports, prior to installation of the insulation, to validate the assembly dimensions.

### ***7.5- Super-insulation***

The installation of the super-insulation is described in the procedure. In addition, a layer of active carbon was installed between the cold vessel and the insulation. The cold vessel was inserted definitively in the warm vessel after completion on the insulation.

### ***7.6- Cryogenic feed-through***

There are 4 LN2 feed-through and one LAr feed-through including expansion bellows. They were assembled and welded in place after insertion of the cold vessel into the warm vessel.

### ***7.7- Cold seals***

During the 1<sup>st</sup> and 2<sup>nd</sup> hydraulic tests of endcap C leaks occurred on the OMEGA cold seals. It was found that the elastic deformation of the cold cover was bigger than the elasticity of the seals themselves, so it was decided to re-machine the main and small covers in order to increase the compression of the OMEGA seals. This improved the tightness and the next hydraulic test was successful on this side of the endcap, while a leak occurred in front at the HELICOFLEX seal. It was found also that the elasticity of the seal, of thickness 5.1 mm, was too small. It was then decided to increase the thickness of the seal to 7.1 mm and consequently to re-machine the FCAL cone. The 3<sup>rd</sup> and last hydraulic test on the endcap C was then successful.

The hydraulic test on the endcap A was successful on the 1<sup>st</sup> time.



## 8- REFERENCES

- 1) CERN Safety Code D2, Issue 1988.
- 2) CODAP, Code Français de Construction des Appareils a Pression non soumis a l'Action de la Flamme, Edition 1995, SNCT AFIAP.
- 3) Space occupied by the end-cap in ATLAS: CERN drawing AT280151PL, 24/01/1996.
- 4) Caractéristiques de l'installation cryogénique, Technical Specifications, Note CEA ref.: 5 C 5720 T 00795 A.
- 5) D.H. Jung, H. Laskus, H. Stenzel, Atlas Internal Note LARG-049, 1996.







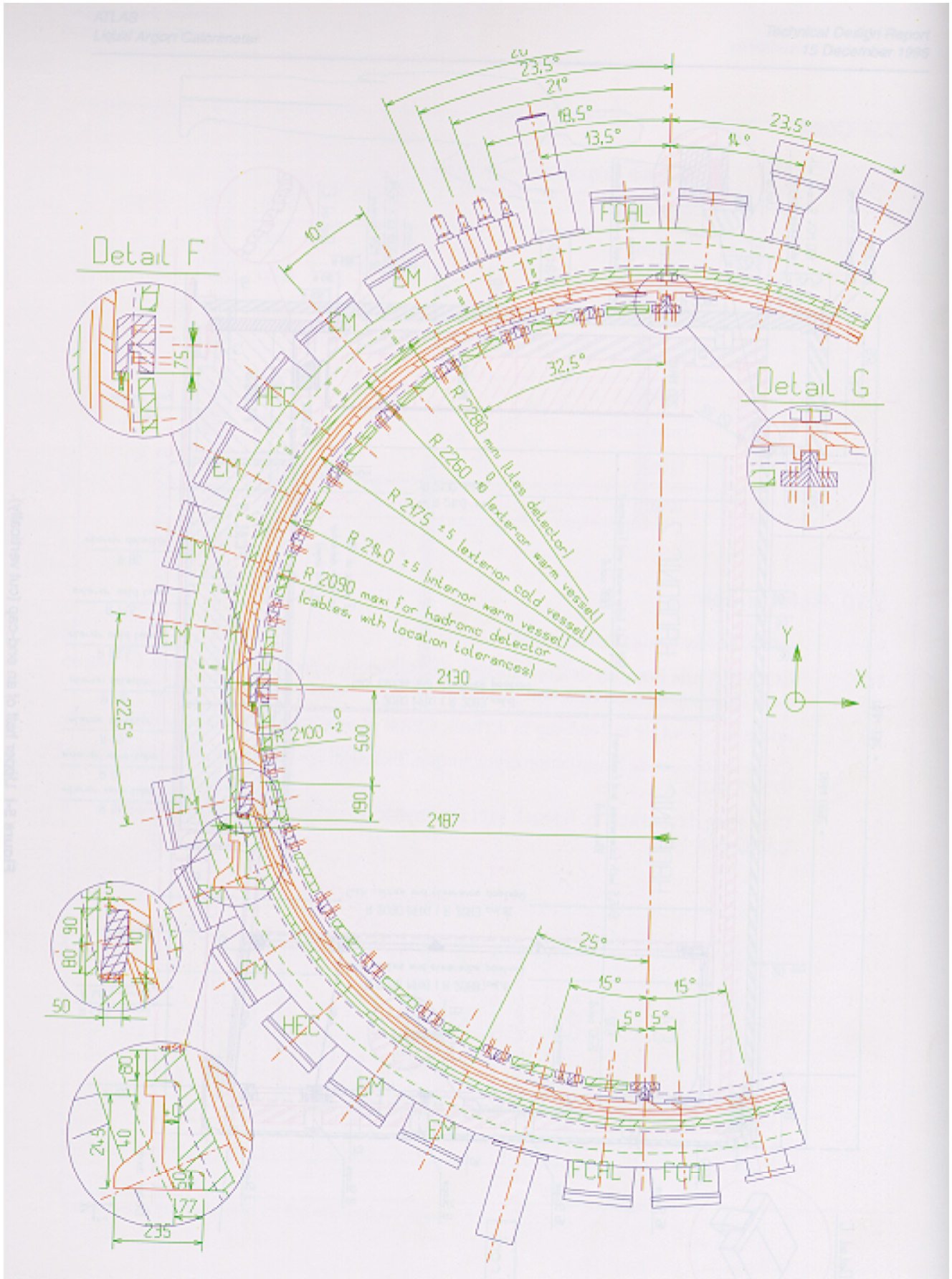


FIGURE ii : End view of the end-cap calorimat.

# Annex 1

## Liste des notes de calculs

- Note de calcul préliminaire  
Réf.: SECAP/97.94/GM.MA du 16/07/97  
But: dimensionnement général, structure, visserie, appuis.
- Complément sur la structure forward  
Réf.: SECAP/97.116/GM.EV.AM du 24/10/97  
But: calcul de la structure forward dans sa définition définitive
- Complément concernant les pieds supports arrières sur le détecteur tuiles - version 2  
Réf.: SECAP/98.97/GM.EV du 22/10/98  
But: calcul des appuis arrières du cryostat
- Complément concernant les pieds inter-enceintes arrières  
Réf.: SECAP/98.17/GM.EV.AM du 23/02/98  
But: calcul des pieds composites
- Calcul couvercle enceinte cryogénique  
Réf.: 99/061PD du 02/06/99  
But: calcul des assemblages couvercle froid - virole et couvercle froid - couvercle forward
- Réponse des cryostats EC à une secousse sismique  
Réf.: 2001.068 du 12/07/01  
But: Evaluation des efforts latéraux sur les butées inter-enceintes  
Détermination des coefficients de rigidité pour calculs CERN sur le système global.
- Calcul du forward avec les détecteurs FCAL et tube T2  
Réf.: 2001.034 du 01/03/01  
But: justification de la structure forward lors des manutentions
- Weight et Gravity Center of End Cap Calorimeter  
Réf.: ATL-AE-EP-0002 du 31/10/00  
But: Donner les poids et C dG ainsi que les efforts aux appuis.

# Annex 2

## Liste des tests réalisés au LAL

### 1 – Jonctions bimétalliques russes

- Note réf.: SECAP/RetD/EC/97.1 du 04/04/97  
But: tests de validation du choix en étanchéité
- Note réf.: SECAP/RetD/EC/97.5 du 08/10/97  
But: note de synthèse sur les jonctions bimétalliques russes.

### 2 – Tests visserie

- Note réf.: SECAP/RetD/TB/97.1 du 15/10/97  
But: validation de l'assemblage vissé pour matériaux, lubrification sèche par microseal, couple de serrage.
- Note réf.: SECAP/RetD/EC/98.3 du 04/05/98  
But: résistance à la traction et couple de serrage pour les goujons V2 en 2024.T4 traité MOS2.
- Note réf.: Essais sur machine de traction du 26/07/01  
But: Essais à rupture sur prélèvement de production pour toutes les vis.
- Note réf.: 2001.103 du 22/11/01  
But: maîtrise de l'effort de traction dans les goujons V2 (2024.T4) par utilisation de Téflon en bombe.

### 3 – Test de frottements pour le cryostat EC

- Note réf.: 99152 du 01/10/99  
But: validation du Permaglide pour les différentes surfaces frottantes dans le cryostat.

### 4 – Tests rails Permaglide P11

- Note réf.: ATA-AE-TR-001/EDMS id 113142 du 28/07/00  
But: déterminer le coefficient de frottement des rails dans les conditions nominales et extrêmes.

### 5 – Test soufflets azote des cryostats EC

- Note réf.: AT/2001.042/Cryostat EC du 14/03/01  
But: validation des soufflets azote avec coefficient de sécurité suffisant.

### 6 – Essais en compression des butées télescopiques des cryostats EC

- Note réf.: AT/2001.54/Cryostat EC du 06/04/01  
But: validation des butées pour la charge nominale maximale et avec un déplacement latéral.

### 7 – Tests matériaux et pieds composite

- Note réf.: 2001.057 du 18/04/01
- Note réf.: 2001.059 du 09/05/01
- Note réf.: 2002.009 du 19/06/01
- Note réf.: 2001.081 du 14/09/01  
But: validation du matériau et des pieds composites sous charge nominale avec coefficient 3 et après mise en froid, sous charge à rupture.

8 – Essais mécanique du matériau composite ME730 (Permal) des butées inter-enceinte

- Note réf.: 2001.056 du 04/01/01

But: tests en compression et cisaillement pour validation du matériau.

9 – Essai joint Helicoflex

- Note réf.: 2001 du 20/11/2001

But: réparation de fuite sur joint hélicoflex et cyclages autour d'une valeur d'écrasement nominale pour tester l'élasticité de ce type de joint.

10 – Tests sur cryostat effectués chez SIMIC

- Note réf : 2002-008 du 04/01/02

But : validation mécanique globale du cryostat.