9. VACUUM TANK

This system constitutes the external part of the solenoid cryostat. The vacuum tank, made of stainless steel, is cantilevered from the central ring of the barrel yoke. It houses and supports the superconducting coil, and must resist the unbalanced magnetic forces due to centring faults or misalignment of the solenoid, with respect to the return yoke. The inner cylinder, equipped with two horizontal rails, supports the weight and induced moments of the inner detectors, mainly the hadronic calorimeter barrel (HB). The outer shell is also used as a support for the cabling and piping of the inner detectors.

The vacuum tank consists of two concentric cylindrical shells connected through structural welds by two end flanges. Two chimneys are situated near the top of the vessel, on each side of the central ring of the barrel yoke. Their purpose is the following:

i) the vertical chimney contains the cryogenic lines, maintaining the solenoid at 4 K during operation,
ii) the second one, inclined at 30° to the vertical, contains the electrical leads, and is also used as the main pumping and venting line.

The design of the vacuum tank is made in such a way that the connection of the thermal shields with their pipework, and the tightening of the suspension and tie rods, remain possible even though structural welding must be performed to close the vessel.

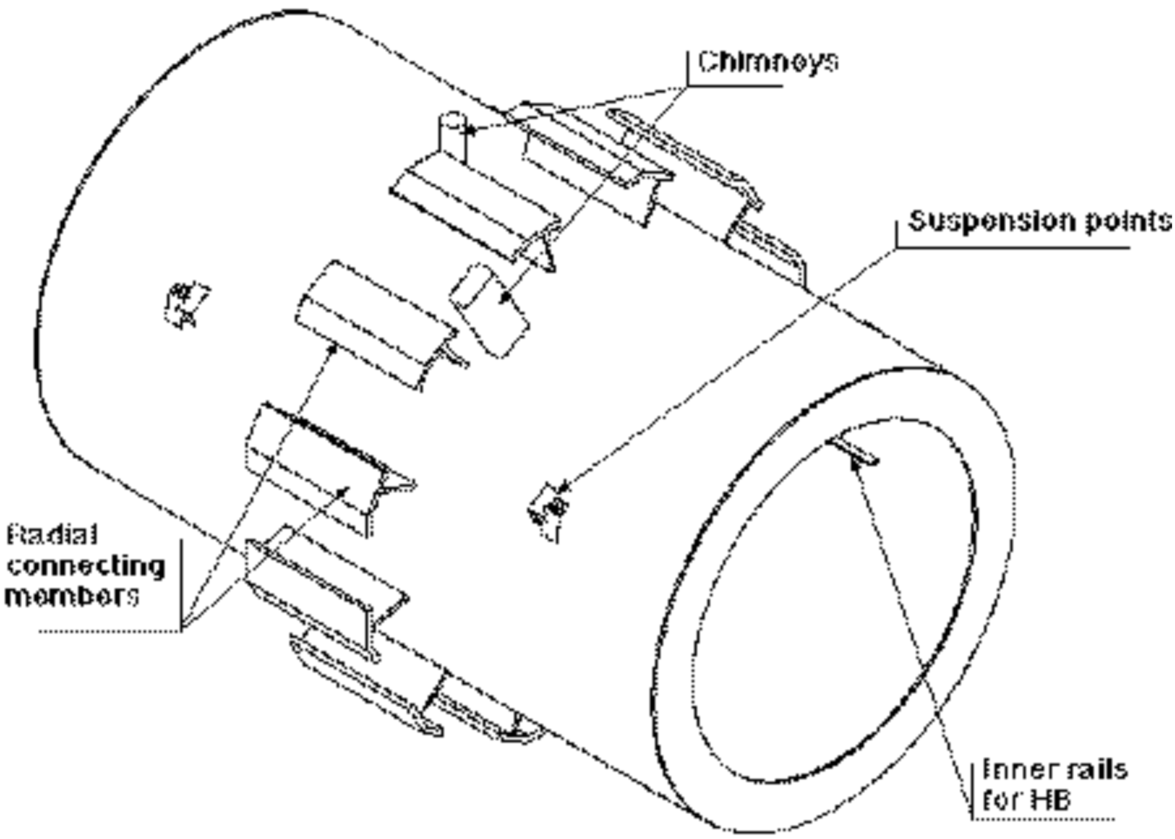

Fig. 9.1: Vacuum Tank general overview.

9.1 STRUCTURAL ANALYSIS OF THE VACUUM TANK

9.1.1 Introduction

Three independent Finite Element Analyses (FEA) of the vacuum tank have been performed, at CERN, FNAL and CEA Saclay.

The results are very similar and a combination of the three studies is presented in this report.

9.1.2 Material properties and allowable stresses

The material proposed for the vacuum tank components is stainless steel. A common steel used for such vessels is SA-240 SS304. The ASME Code is used throughout to verify the integrity of the vacuum tank components.

Table 9.1
Material properties used for the vacuum tank.

Material	SS304
Young's modulus	190 GPa
Poisson's ratio	0.3
Density	8000 kg/m^3
Elastic limit	205 - 230 MPa
Ultimate Tensile Strength	670 MPa
Allowable stress intensity	138 MPa

9.1.3 Dimensions and loads

The main geometrical dimensions of the vacuum tank are given in Table 9.2.

Table 9.2
Main geometrical dimensions of the vacuum tank.

Length	13000 mm
Outer shell external diameter	7600 mm
Inner shell inside diameter	5940 mm
Length of HB supporting zone	8864 mm
Inner shell thickness	60 mm
Outer shell thickness at z < 2300 mm z > 2300 mm	 60 mm 30 mm
End flange thickness	50 mm

The loads acting on the vacuum tank are the following:
i) The external atmospheric pressure (103 kPa),
ii) the weight of HB, electromagnetic calorimeter EB, and the Tracker for a total of

1050 tonnes,

iii) the reaction forces of the cold mass supporting and preloading system, including maximum unbalanced forces, as shown in Fig. 9.2. This situation exists at two locations (see Z-coordinates of Table.9.3).

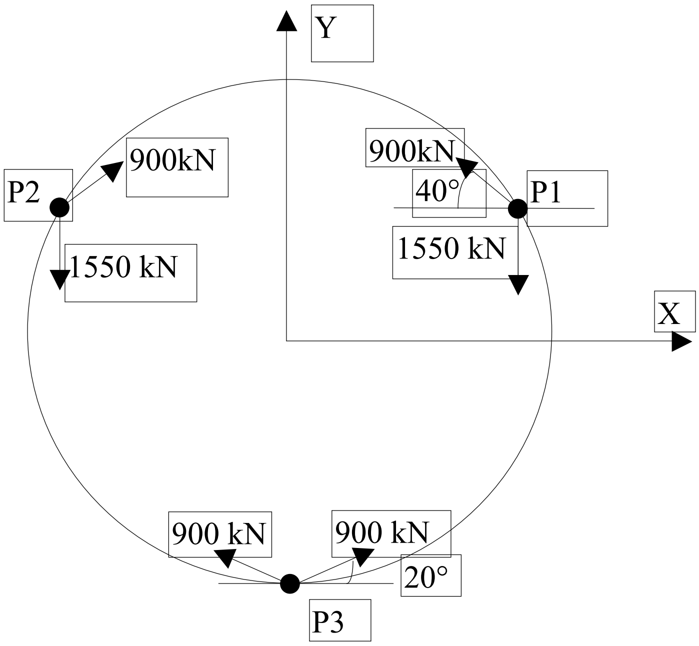

Fig. 9.2: Reactions of the cold mass supporting system.

Table 9.3
Coordinates and values of the reaction forces of the cold mass supports.

	Coordinates in mm (origin at interaction point)		
Point	X	Y	Z
P1	3265	1885	± 4000
P2	-3265	1885	± 4000
P3	0	-3770	± 3750

9.1.4 FEA Models and Results

Several independent models have been made to prove the sound design of the vacuum tank. Whereas the CERN/CEA analysis [9-1] aimed to verify the total integrity of the chosen wall thicknesses and the buckling safety, the more detailed FNAL study [9-2, 9-3] concentrated on the design of the rails which support the hadronic calorimeter barrel and the impact of the suspension points that house the coil suspension bars and the coil prestressing belt system.

The FNAL analysis has been performed using ANSYS; the CERN/CEA one was done with CASTEM 2000. Figure 9.5, p. XX shows the 3-D model of the vacuum tank. Around the suspension points a reinforced area of 45 mm thickness has been meshed with a finer grid. In Fig. 9.6 only the external part (30 mm) of the outer vacuum tank shell is shown. The deflection values are given in millimeters and indicate that the prestressing and suspension forces acting on the suspension shoulders create an inward-outward oscillation of radial displacement. The maximum inward deflection at the location of the shoulders is of the order of 9.5 mm. The points of maximum outward deflections are situated at an angle of + and -30 degrees in azimuth from the shoulders. It is of the order of 5.5 mm. To calculate the stresses in the rail that is welded to the inner vactank shell, the following approach has been made:

A coarse model of 1/4 of the vacuum vessel and rail was created in which the rail and inner vactank shell were modelled with solid elements while all other components were modelled with plate/shell elements. The welds were not explicitly modelled but considered only as line contact between the rail and vacuum tank. The hadronic calorimeter (HB) was modelled as a perfectly rigid plate acting on the vacuum tank through 40 spring elements. A refined submodel with explicit weld modelling was created with its center at the location of highest stress as indicated by the coarse model. The coarse model displacements were used for the displacements at the outer boundary of the submodel.

Finally, rail, weld and inner vacuum tank stresses were extracted from the submodel and compared to allowable stresses for SS 304 weldments.

Figure 9.7, p. XX shows the peak stresses at z = 4432 mm, i.e. at the end of the hadronic calorimeter loading. Assuming fully radiographed weld and primary membrane and bending stresses, ASME Section VIII, Div. 2 gives the following criteria for stress intensity:

- Primary membrane stress intensity limit = 138 MPa (20 ksi).
- Primary membrane + bending stress intensity limit = 205 MPa (30 ksi).

When the stresses in the most highly stressed region of the submodel are linearised to eliminate peak stress contributions, the following values are found:

- Primary membrane stress intensity = 113 MPa, therefore < 138 MPa.
- Primary membrane + bending stress intensity = 160 MPa, therefore < 205 MPa.

These values are clearly inside the target values. Nevertheless, full radiography of the welds is mandatory due to the high loading and disastrous consequences of failure.

In Figure 9.8 the sum of Ux and Uy displacements is plotted. The maximum displacement of the inner shell is + and -12 mm due to the bending moment induced by the hadronic calorimeter.

The complete deformation of the vacuum tank can be seen in Fig. 9.9, p. XX where the undeformed shape is shown in blue and the deformed in red. Amplification factor is 50.

The overall Von Mises stresses in the vacuum tank are shown in Fig. 9.10, p. XX. The highest value of only 102 MPa and the very low stress gradients prove the well designed distribution of material thicknesses in this highly loaded system.

To check if stability, i.e. collapsing of the vacuum tank, could be a problem, a buckling analysis on the base of eigen-values has been undertaken. The obtained values are 6.4 for the first and 7.7 for the second mode of buckling. Multiplying the actual loads by these values would lead to buckling. The buckling modes occur at the pre-stress locations due to the fact that the forces are applied very locally. The safety value against buckling is thus 6.4 for the lowest mode.

9.2 CONSTRUCTION CONCEPT

9.2.1 Transportable components

Due to its size and overall dimensions (13 m long x 7.6 m diameter), the vessel must be fabricated in transportable sections which will be assembled by structural welds after delivery to the CERN site.

The outer shell, which has a diameter exceeding transport limitations, will be split in three longitudinal sections (a central one about 4.6 m long, and two outer ones slightly shorter), each section being again split into two half shells (see Fig.9.3, items 1-6).

The inner cylinder which has a diameter within the transport limitations will be transported to CERN in the form of two half-length sections each 6.5 m long and 5.9 m in diameter (see Fig.9.3, items 7 and 8).

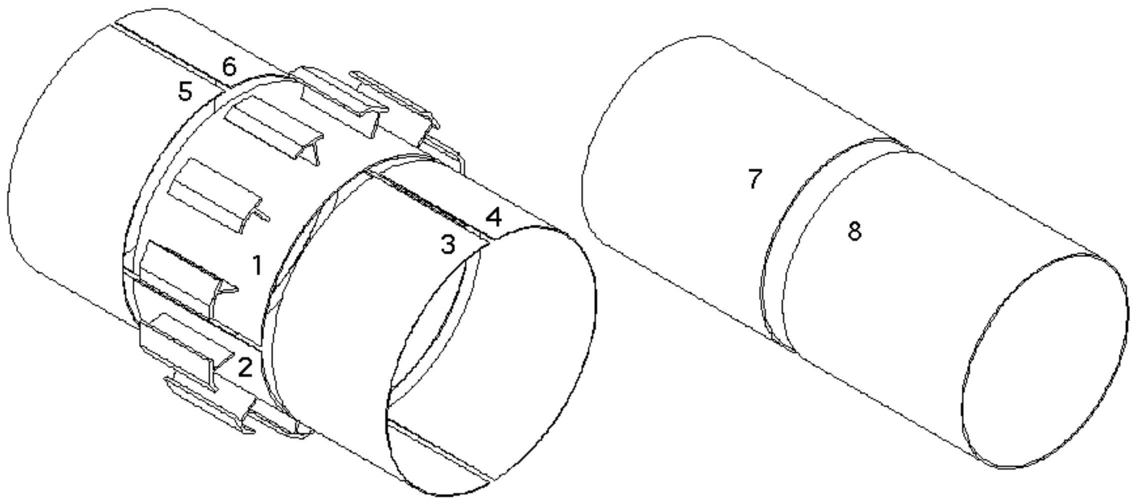

Fig. 9.3: Split outer and inner shell.

9.2.2 Manufacture of the outer shell

The central section of the outer shell is used for the pre-assembly of the central barrel wheel as it is described in Chap. 7.2. Hence its manufacture will be different from the two outer sections.

An internal structure acting as reinforcement and skeleton for the jig will be produced in two halves, each one comprising six radial webs converging onto a corresponding split bushing. Each half internal structure will be accurately machined on its mating surfaces in order that they assemble together precisely.

A previously rolled half-cylinder will then be fitted and mechanically constrained onto the pads of the half jig by tack welding. Once this operation has been repeated for the other half shell, the two components will be assembled together, precisely checked for geometry, then provisionally welded at the diametrically opposite seams using temporary straps.

The twelve outer radial connecting members will be fitted and welded to the shell in correspondence with the reinforcing webs. After stress relieving heat treatment, the complete structure will be placed on a vertical lathe and the corner pieces, situated at the extremities of the connecting members, accurately machined to provide a perfect dodecagonal profile for the trial assembly at the factory, (see Fig. 9.4).

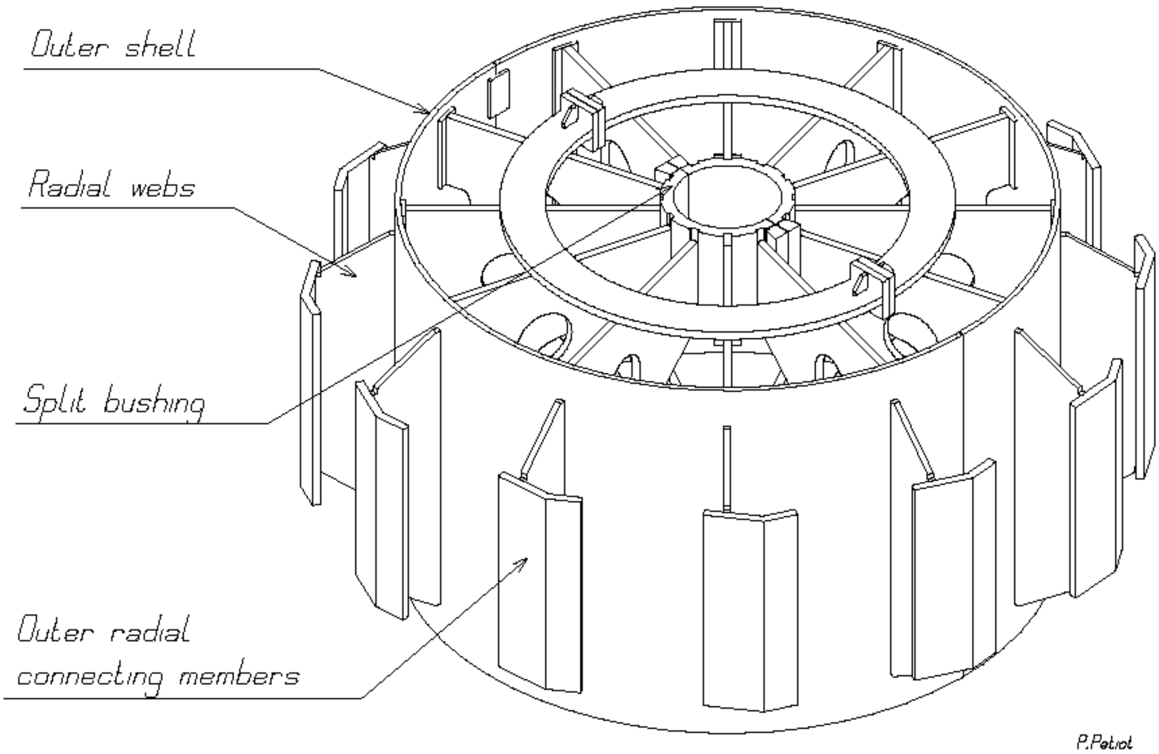

Fig. 9.4: Central section of the outer shell. This will be used as assembly jig in the Ferris Wheel for the central barrel yoke.

9.2.3 Manufacture of the outer shell end-sections

The 30 mm thick plates of the end-sections will be rolled to the specified radius. An internal structure will be inserted, to provide the rigidity during transport and machining.

The mating surfaces of each half shell, together with their internal structures, will be accurately machined. The two halves will then be assembled, checked for geometry, and provisionally welded at the diametrically opposite seams using temporary straps. The complete structure will be placed on a vertical lathe and precisely re-adjusted. It will then be separated again in two halves for transport.

9.2.4 Manufacture of the inner shell

The inner shell will be constructed as two complete cylinders, 5.9 m in diameter and 6.5 m long. Some temporary internal structural reinforcement may be added to maintain geometry.

The pre-machined support rails will be attached to the inside walls by structural welding. The temporary internal reinforcement will be completed, nevertheless leaving sufficient space for the insertion of a dedicated milling machine tool head. The complete assembly will be placed on a vertical lathe and the rail bearing surfaces and cylinder end faces machined to the required tolerances. The use of the temporary internal reinforcement will ensure geometric integrity and maintain the rail system tolerances.

This internal reinforcement will remain in place until the final welding of the inner shell to the end flanges at the CERN site.

It should be noted that as each hadron calorimeter half-barrel will be inserted from the corresponding end of the vacuum tank (see Chapt. 26), there is no strict geometrical relationship to be maintained between the rail system of one half-shell and its counterpart.

9.2.5 Trial Assembly

Before transportation the main components will be presented together at the factory, as if to be welded, to check the general geometrical conformity. Due to the presence of the inner reinforcement structures which maintain cylindricity, it will not be possible to perform the trial assembly of the full vacuum tank. However meaningful checks are still possible.

In particular, the two inner shell sections will be properly aligned to check the rail system and the interface with the end flanges.

Similarly, the outer shell end-sections will be presented to the outer shell mid-section, during trial assembly of the central barrel wheel.

9.2.6 Transport

Transport from the factory to the CERN site of the main items (8 in total for a gross weight of about 240 tonnes) will require road transportation for the last leg of the journey and sizes of pieces to be transported are very important.

All parts will include reinforcing structures to ensure geometrical stability and subsequent precision during final assembly. The maximum overall dimensions given below take into account this reinforcement; some protection should also be accounted for.

– outer half shell centre section:	(2 off)	4.5 m by	5.5 m by	11.0 m
– outer half shell end section:	(4 off)	4.3 m by	4.5 m by	9.0 m
– inner half-shell:	(2 off)	6.0 m by	6.0 m by	6.5 m

Each item will be transported with its axis of revolution horizontal. The first two columns above are thus showing either the width or the height of each transported item.

9.3 FINAL ASSEMBLY

9.3.1 Reconstruction of the shells on the CERN Site

The two vacuum tank outer half-shells will first be mounted on the Ferris Wheel and welded together thus providing the assembly jig to be used for the central barrel ring (YB0) construction, as described in Chapt. 26, and as can be seen in Fig. 26.13-A, p. XX. When the assembly of YB0 is finished, the internal structure will be removed.

The four outer half-shell end sections will then be welded to the central section and the internal reinforcement structures will be removed completing the outer shell assembly. It may be possible that external reinforcement will be required, before the removal of the internal structures to maintain cylindricity near the end flanges. The outer shell of the vacuum tank will then be ready to receive the coil as seen in Fig 26.14, p. XX.

The two sections of the inner shell of the vacuum tank will be welded together on the turning system used previously to place the coil in the horizontal position. The same system will be used to place the inner shell in the horizontal position, ready to receive the coil itself as described in Chapt. 19 and 26, before closing the cryostat.

9.3.2 Closing of the Vacuum Tank

The vacuum tank must be closed around the coil by structural welding in the region of the end flanges, to transfer the loads generated by supporting the inner detectors. To allow disconnection of the coil from the turning device, and to allow completion of the coil ends as described in Chapt. 19, the inner shell will initially be connected to the outer shell by radial beams thus providing the structural integrity, but nevertheless allowing access to the inside of the vacuum tank. This access is needed for removal of the welding thermal protection and the completion of the thermal shield and super insulation facing the end flange regions.

The openings between the radial beams will then be closed by welding on thin closing plates.