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Design of beampipes for LHC experiments

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Abstract

The large hadron collider (LHC) will be a proton–proton collider with a centre of mass energy of 14 TeV presently in construction at CERN. The four colliding experiments will require special vacuum chamber designs to allow the best physics performance. New technologies such as very thin beam pipes to increase transparency, optimised rotatable flanges, wired supports with special layers to reduce dynamic effects, special heating jackets, double wall chambers and mass minimised annular ion pumps are being developed by CERN for this application. © 2002 Published by Elsevier Science Ltd.

1. Introduction

The large hadron collider (LHC), currently under construction at CERN will accelerate and store two counter-rotating beams of protons at 7 TeV. The majority of the 27 km circumference machine contains superconducting magnets operating at 1.9 K to keep the beams circulating. The beams circulate in vacuum chambers, pumped by the cryogenic magnets, to minimise beam loss due to interactions with residual gas. At four places around the circumference, the two beams pass into one chamber at room temperature and are collided at the centre of large high energy physics experiments. Each of these four experiments, ALICE, ATLAS, CMS and LHCb are quite different in design. However, in each case, the detectors require the particles coming from these high energy collisions to pass from the beam vacuum to the detectors with the minimum of interaction with the vacuum chamber.

Apart from the requirement for transparency to particles, these experimental vacuum chambers or ‘beam pipes’ are the main experiment–machine interface and have a number of additional requirements from both sides. They contain ultra-high vacuum, with additional gas load due to the presence of the beam. The electrical impedance of the chamber must be minimised from kHz to GHz range to prevent beam instabilities. The detectors are some 40 m long and 20 m in diameter, so access to the beam pipe will be difficult and time consuming. This can be seen from Fig. 1, which shows the beam pipe in the CMS experiment.

The environment of the detectors is also difficult due to the large flux of particles which pass through the vacuum chamber. At nominal operation two of the detectors will see a luminosity of $10^{34}\,(\mathrm{cm}^2\,\mathrm{s})^{-1}$. This corresponds to a radiation dose of up to 10^6 Gy per year of operation.

This paper describes some of the principal requirements of these experimental beam pipes, and the development either complete or under way to fulfill them.

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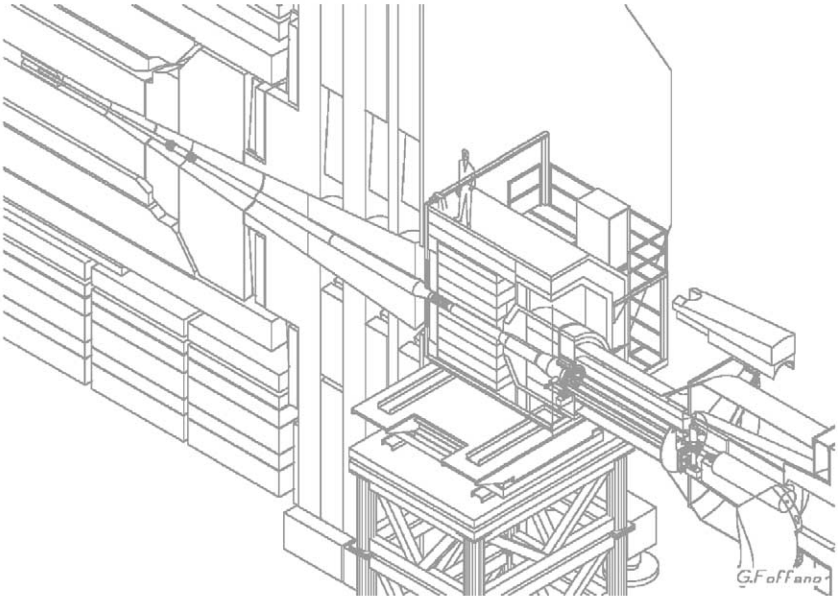

Fig. 1. Half section through the CMS detector showing the experimental beam pipe.

2. Vacuum chambers

2.1. Geometry

Beam pipes for the LHC experiments will be either thin walled cylinders with diameters from 50 to 400 mm or conical sections with opening angles 10 to 25 mrad and diameters up to 400 mm. Cylindrical chambers are used where the surrounding detectors need to be slid into place very close to the beam pipe, typically close to the centre of the experiment. However, further from the centre, they become progressively less and less transparent, as the particles pass through at smaller angles, and hence see more material. This problem is overcome by making these 'forward' chambers from conical sections with the cone pointing close to the particle collision point. Most of the particles then only traverse the 'window' at the end of the cone at close to a right angle. These two types of chambers can be seen in Fig. 1.

2.2. Choice of material

Table 1

Material	Be	CFC	Al-Be	Al	Ti	Fe
E (GPa)	290	200	193	70	110	210
X_0 (m)	0.353	0.271	0.253	0.089	0.036	0.018
$X_0E^{1/3}$	2.34	1.58	1.46	0.37	0.17	0.11

The general requirement for materials for experimental beam pipes is that they cause the minimum of interference with the particle detectors. The inherent transparency of materials is quantified either by their radiation length, X_0 (for elastic collisions) or the interaction length, λ (for inelastic collision of hadrons). In addition, a certain thickness of material is required to fulfill the mechanical function, i.e., resist the pressure loading for the chamber wall, or bending stresses for a flange. For typical cases of external pressure load or bending, this is quantified by the elastic modulus, E.

From these criteria, a number of merit for vacuum chamber materials can be established [1]. For the case of a chamber under external pressure, this has been shown to be $X_0E^{1/3}$. Table 1 gives the order of merit for some materials used in experimental chambers. Beryllium is the best material by these criteria, and is used in the most critical parts of the beam pipes. However, its use is restricted by very high manufacturing costs and the fact that it constitutes a toxic material. Until recently, beryllium chambers have been constructed by furnace brazing using aluminium based brazes. These brazed joints have proved to be the weakest point in terms of both mechanical strength and leak tightness. Recent developments have opened up the possibility to manufacture beryllium chambers by welding. If prototypes prove successful there are significant advantages, not only in terms of reliability, but improved mechanical tolerances and overall diameter requirement. Carbon fibre composites also rank high in Table 1, and they are used in some accelerators. However, they are not inherently UHV compatible, and so require a leak tight liner made out of an electrically conducting material. Resin systems in the composite also limit the maximum temperature of the system, which is critical in this application (see Section 4).

Aluminium–beryllium is easier to machine and weld than pure beryllium. Complex chamber such as that in the KLOE experiments at INFN have been made in this material [2]. However, it has the same restrictions as pure beryllium, and finished cylindrical chambers have a similar cost to the pure metal. As a consequence it is currently not planned to be used in the LHC.

The majority of the experimental chambers will be made in aluminium alloys and stainless steel for reasons of economy and ease of manufacture.

2.3. Flanges

The LHC experimental chambers are 40 m long. A fragile chamber of this length cannot be manipulated safely, so chambers are installed in lengths of up to 8 m. Although it is possible to weld chambers in situ, the very strict cleanliness requirements, use of surface coatings and limited access make this difficult to achieve. The alternative is to use highly optimised UHV bolted flanges.

A bolted flange has been specially developed for this application using the Helicoflex® sealing system. Two and three dimension finite element analysis of the flange-bolt-seal assembly was performed to optimise the design. This analysis was performed both at room temperature and bakeout temperatures of 250°C (for aluminium 2219) and 300°C (for stainless steel). For a nominal bore of 58 mm, the optimised flange has an outside diameter of 86 mm, and a thickness of 14 mm. This represents only 30% of the mass of the standard 63 mm bore Conflat® flange. A photograph of a transition between these two flanges is given in Fig. 2. Prototype assemblies using these flanges have been manufactured and tested with 10 bakeout cycles. No leaks greater than $10^{-12}\,\mathrm{Pa\,m^3\,s^{-1}}$ were detected. Longer term testing is now in progress.

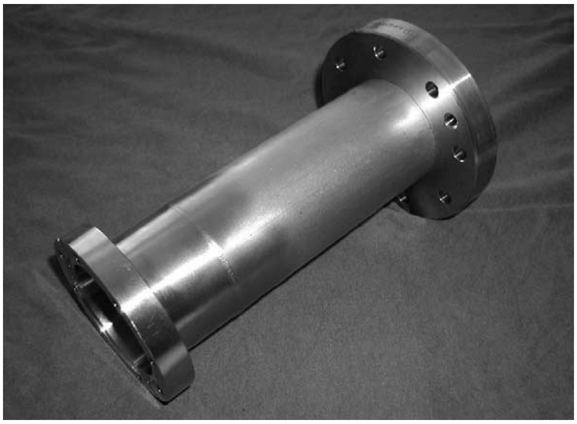

Fig. 2. 58 mm bore vacuum chamber with DN 63 Conflat flange and optimised flange.

2.4. Supports

Vacuum chamber supports inside detectors cause interference with physics performance and detector layouts. Each support must therefore be optimised. The primary function of the supporting system is to ensure that the chamber does not encroach on the aperture of the beam. In addition, it must ensure the mechanical stability of the chamber. Bending of the chamber leads to ovalisation of the section, which in turn will reduce the critical pressure. This phenomenon, known as the Brazier effect, can determine the support requirements [3]. Large spans between supports also give low eigenfrequencies for the structure and potentially large amplitudes of harmonic vibration. These can lead to stress and fatigue in the chamber. Where possible, support conditions giving natural frequencies above 50 Hz are chosen to avoid direct coupling with mains driven mechanical devices. Where this cannot be achieved, the use of high damping coefficient polymers are under consideration to minimise the amplitudes of vibrations and reduce the damping time of oscillations following impacts.

In the most restricted areas, supports consist of thin wire crosses under tension between the detector structure and vacuum chamber.

3. Vacuum pumping

3.1. Requirements

Ultra high vacuum is required in experimental regions of the LHC for a number of reasons. Avoiding unacceptable loss of the beam due to beam–gas interactions requires a local pressure better than $\sim 10^{-5}$ Pa. However, in many cases the experiments require a lower pressure, down to 2×10^{-9} Pa to minimise background due to beam–gas interactions. Calculation of pressure profiles must take into account the presence of the beam (dynamic pressures). Indeed, the main gas sources are due to beam-related effects rather than static outgassing. The principal phenomena are ion induced desorption [4] and electron multipacting [5]. In both cases, charged particles (either electrons or ionised residual gas) accelerated by the electric field of the beam, impact on the walls with sufficient energy to desorb gas molecules. In extreme conditions, these phenomena can lead to uncontrolled pressure rises, such as the ion induced desorption instabilities that were seen in the ISR machine at CERN [6]. Both effects will be controlled in the LHC by a combination of adequate cleanliness (implying a fully baked system), adequate pumping and surface coatings. Specifically, surface coatings are required which give low yields of gas when bombarded by ions (quantified by the ion desorption yield, η) and by electrons (quantified by the secondary electron yield, SEY).

3.2. Getter pumps

The design of the experimental chambers plans to take full advantage of new non-evaporable getter films (NEGs) developed at CERN that can be sputtered directly onto the chamber surface [7]. When activated, these coatings combine the advantages of high distributed pumping speeds, low values of η and SEY and practically negligible mass, being only a few μm thick. Due to their relatively limited pumping capacity, the entire surface of the vacuum chamber will be NEG coated. The getter films are activated by heating the coated chamber to between 200°C and 300°C for a few hours. Equipment developed specially to achieve this is described in Section 4.2.

3.3. Ion pumping

The NEG pumps have a high specific pumping speed for all active gases. However, any vacuum system requires a finite pumping speed for inert gases. Small annular triode ion pump elements with $16\,\mathrm{l\,s^{-1}}$ nominal pumping speed have been developed in collaboration with Varian Spa. The cells of the pump are distributed around the vacuum chamber in an annulus. This shape takes the minimum of space around the chamber and gives a high effective pumping speed due to the proximity of the elements to the chamber. The elements sit in an optimised vacuum envelope developed in collaboration with LAPP[1]. The pump assembly is shown in Fig. 3. A high voltage feedthrough of 6 kV is needed by the pump. The magnetic field will normally be supplied by a large superconducting solenoid magnet which is part of the experiment. Permanent magnets can be added if the pump needs to operate with the detector solenoid switched off.

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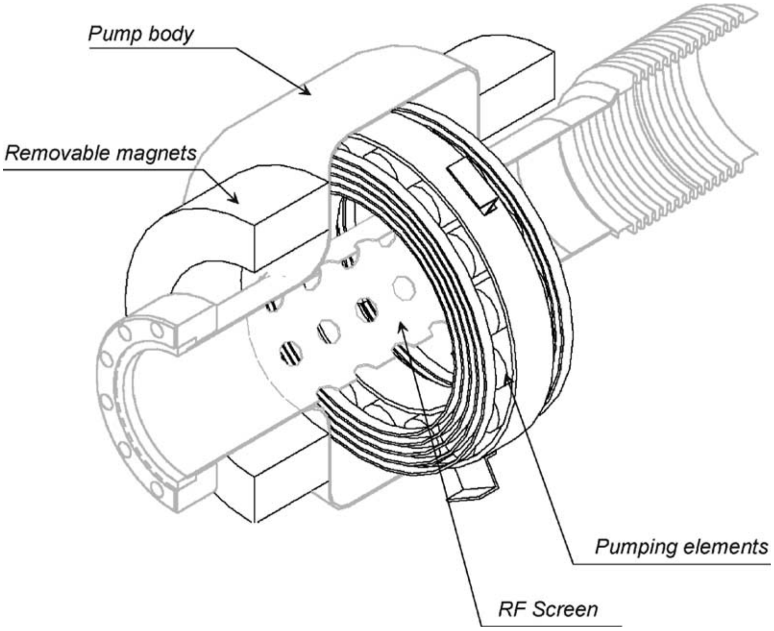

Fig. 3. Section through annular ion pump.

4. Vacuum conditioning

4.1. Requirements

The getter coating on the beam pipe needs periodic reactivation at a temperature between 200°C and 300°C, depending on the gas load. This implies an in situ heating of the whole 45 m long sector of chamber between valves. In the accessible parts of the sector this can be achieved using conventional removable bakeout jackets. However, in certain areas, the detectors cannot be opened to access the beam pipe, so NEG activation heaters and insulation must be left in place. The integration of such equipment into the chambers has been studied, taking into account the special requirements of maximised transparency, minimum diameter and resistance to radiation.

4.2. Heaters

Conventional bakeout heaters such as heater tape and coaxial heater wire represent too much material for certain areas of the beam pipe. Therefore, a number of special heaters were investigated for this application. Clearly, the best in terms of transparency would be to heat the chamber directly by passing a current through the wall; the Joule effect. This has been demonstrated as feasible for very thin walled steel chambers. However, the materials shown to be the most transparent (beryllium and aluminium), also have a very low electrical resistance. Implementing joule heating in these chambers would imply currents of more than 250 A, which proved prohibitively difficult in practice.

An alternative technique tested was to deposit strips of resistor onto the outside of the chamber by vacuum plasma spraying. First an insulating layer of 0.1 mm alumina ceramic was sprayed on to the chamber. Then strips of 316L steel, 0.05–0.65 mm thick and 5–8 mm wide were sprayed on the ceramic (see Fig. 4). These strips were connected to form a heater circuit. This thickness and width was considered the minimum necessary to achieve a uniform heat distribution along the tube, avoiding potentially dangerous hot spots. The final (optional) layer was 0.1–0.2 mm of alumina to provide electrical and some thermal insulation. A

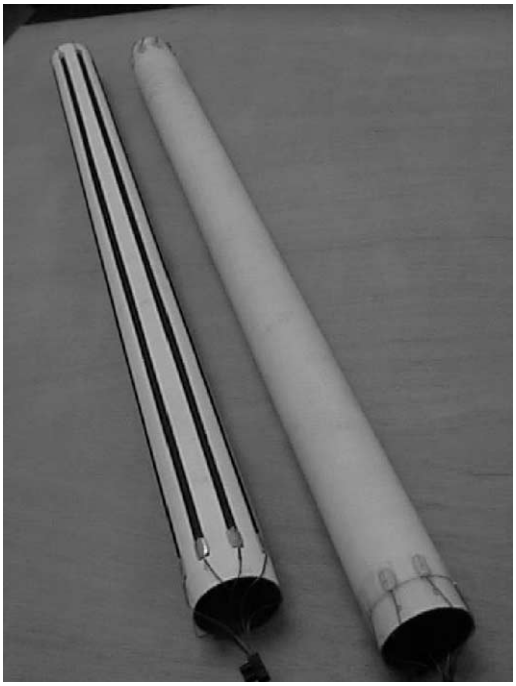

Fig. 4. Tube with plasma sprayed heater strips (left) and with additional alumina insulation (right).

number of chambers have been equipped with this system. Tests have been performed with numerous thermal cycles up to 350°C, without failure. This technology is likely to be applied in areas where the access and space requirements are very limited, and NEG activation temperatures are required.

The third heating method considered is that of a polyimide (Kapton®) heating foils. They are made from a thin metal foil circuit laminated between two polyimide foils. The thickness of the assembled foil is 0.13 mm. This foil is then bonded to the vacuum chamber using Kapton glue. The chambers have been equipped with these heaters and tested extensively at 300°C without failure. However, it is known from manufacturers literature that time dependant degradation of the material in air starts at 280°C. Care was taken in the selection of products to avoid glues containing PTFE and other products known to be prone to radiation damage. Irradiation tests of heater assemblies will be required before these heaters can be used. As they represent in terms of radiation length only a quarter of the beryllium thickness, they can be used in the most sensitive areas. However, the maximum service temperature and time may be limited and hence redundant circuits must be provided to increase reliability.

4.3. Insulation

The quantity and type of thermal insulation depends mainly on the space available and heat input that can be tolerated by nearby detectors. Wherever possible, high performance commercial insulators such as ceramic fibre blankets are used. Tests have shown that approximately 250 W m^{-1} is required to maintain a 60 mm diameter tube at 300°C using a 5 mm thick ceramic powder insulation.

Where there is a lack of space for adequate insulation, the insulation is replaced by a second chamber wall, maintaining an insulation vacuum in the range 10^{-2}–10^{-4} Pa. This vacuum serves to avoid losses by conduction and convection. Thermal radiation losses are reduced by sputtering a thin ($\sim$100 nm) reflective coating on the inside of the insulation tube. Using this system, heat losses can be reduced to approximately 30 W m^{-1}.

5. Conclusions

Special requirements on vacuum technology are imposed on the design of experimental beampipes for the LHC. New technologies used include welding of beryllium, miniaturised ion pumps as well as bakeout and NEG activation equipment. The functioning of these new developments has been demonstrated in the laboratory. Full scale testing is now proceeding.

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