DEVELOPMENT OF BERYLLIUM VACUUM CHAMBER TECHNOLOGY FOR THE LHC

R. Veness, CERN, Geneva, Switzerland
G. Simmons, C. Dorn, Materion Electrofusion, Fremont, CA, U.S.A.

Abstract

Beryllium is the material of choice for the beam vacuum chambers around collision points in particle colliders due to a combination of transparency to particles, high specific stiffness and compatibility with ultra-high vacuum.

New requirements for these chambers in the LHC experiments have driven the development of new methods for the manufacture of beryllium chambers.

This paper reviews the requirements for experimental vacuum chambers. It describes the new beryllium technology adopted for the LHC and experience gained in the manufacture and installation.

INTRODUCTION

In particle colliders such as the LHC, two beams of particles counter-rotate inside a continuous vacuum chamber ring. For the LHC, this ring is some 27 km in circumference. At four locations around the ring, the two beams are steered into head-on collisions in the centre of high-energy physics experiments inside 'experimental beampipes'. These beampipes represent perhaps the most intimate interface between machine and experiment. The two beams collide inside this chamber producing secondary particles, and (unless detectors are placed inside the machine vacuum) all secondary particles detected by the experiment must first pass through the beampipe.

Particles interact with the material of the beampipe, causing unwanted signals in the detectors and activation of the beampipe material. These interactions can be characterized by the property of 'radiation length' (X_0), which is the distance a charged particle travels before losing 1/e of its energy [1]. To a first order, this distance is inversely proportional to the product of density (ρ) and atomic number (Z) so materials with low Z and ρ are required to minimize interactions. Thin-walled chambers with few mechanical supports also minimize these interactions, so a material with a high elastic modulus is an advantage. A figure of merit can be established for these parameters to rank materials for this application [2]. Considering a cylindrical, simply supported, vacuum chamber, this is equal to $X_0E^{1/3}$. Table 1 shows these values for some candidate materials, where CFC is a typical high modulus carbon-epoxy composite and Be-Al is a commercial 62% beryllium alloy. It can be seen that the material of choice for these chambers is beryllium. However, beryllium is expensive to produce, and has safety restrictions in usage, so applications are limited to the most critical areas around the 'vertex' where the two beams collide.

Table 1: Figures of Merit for Transparent Beampipes

Material	E (GPa)	X_0 (m)	X_0 $E^{1/3}$
Be	290	0.353	2.34
CFC	200	0.271	1.58
Be-Al	193	0.253	1.46
Al	70	0.089	0.37
Ti	110	0.036	0.17
Fe	210	0.0018	0.11

TECHNOLOGICAL CHOICES

Beryllium vacuum chambers assembled by furnace brazing have been used in a number of colliding beam experiments, such as the Large Electron-Positron collider (LEP) [3]. However, new detector designs and the use of sputtered NEG coatings [4] in the LHC required chambers with a smaller 'envelope' (i.e. maximum outer radius minus minimum inner radius) and with higher temperature resistance. This led to a proposed design with long, thin-walled tubes, machined from block, with steel or aluminium flanges electron-beam welded or vacuum brazed on the ends. A chamber made entirely of beryllium, including flanges was considered, but rejected due to concerns over 'repairability' in case of damage to the seal surface.

This new design required the development of four technologies: machining of long beryllium tubes; electron-beam welding of beryllium; vacuum brazing of beryllium and use of high-temperature aluminium alloys. Although not new technologies *per se*, they had not been used before on this scale, or in this environment.

MACHINED TUBES

Machined tubes of ~30 cm in length have been used in the past to manufacture chambers for the Cornell Electron Storage Ring (CESR) [5]. However, the LHC requires longer sections in order to assemble the 7 m long chambers envisaged for the project.

The manufacturing of the tubes began with the sawing of oversize pieces of vacuum hot-pressed beryllium block from a qualified billet of structural-grade material. These pieces were then gun-drilled to the required inner diameter, and subsequently turned on a lathe to the required outer diameter and wall thickness, while maintaining the vacuum integrity of each piece. Beryllium's low coefficient of thermal expansion compared to aluminium permits tighter dimensional tolerances to be achieved in conventional machining operations than would be possible with aluminium.

A technology test piece was manufactured using this method, and it was shown that tubes of 1 m in length and

0.8 mm wall thickness could be manufactured in the required 58 mm inner diameter, meeting a straightness tolerance of 0.3 mm or better.

ASSEMBLY

Electron Beam Welding

The 1m long tube sections needed to be joined together to form leak-tight, mechanically strong tubes. In addition, the long, small diameter LHC chambers require as a good straightness tolerance as possible on the joints to maximise available beam aperture. Electron-Beam (EB) welding, with its low energy deposition, fulfils these functions. However, the beryllium material is manufactured by a hot-pressed powder metallurgy process, so re-crystallisation leading to embrittlement was a concern.

To obtain good quality, UHV-tight EB weld joints in beryllium, the importance of weld joint design should be noted. Other principles common to EB weld joint design such as the close dimensional tolerancing of mating component parts is also important. To address the concern about re-crystallisation of the beryllium in the weld joint, an intermediate aluminium shim was used. This material was chosen for its weldability by EB, its compatibility with beryllium, and its suitability for use in the UHV environment. The weld joints were all subsequently helium mass-spectrometer leak tested to a rate of 2.6×10^{-10} mbar.l.s^{-1} or better. A micrograph of a beryllium-beryllium EB weld developed for this application is shown in Figure 1. Tensile testing of two preliminary tube samples with EB welds gave failure stresses of 94.5 and 93.6 MPa.

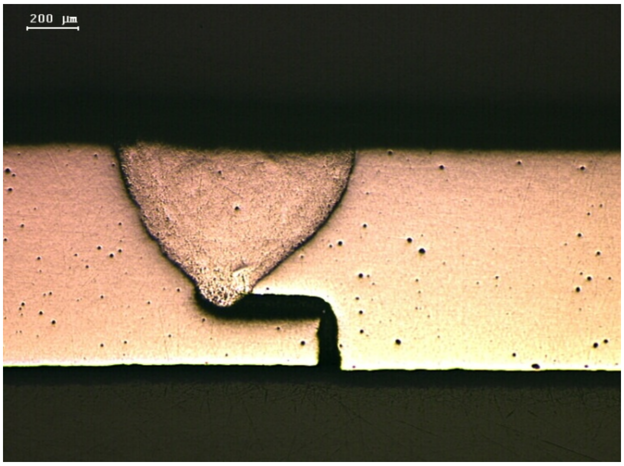

Figure 1: Micrograph of a Be-Be EB weld.

Vacuum Brazing

Due to the large difference in fusion temperature and relative immiscibility, beryllium and stainless steel cannot be joined by welding. In order to avoid the use of active brazing fluxes a vacuum brazing process was developed for this application.

As with EB welding, good joint design is likewise important to obtain high quality, UHV-tight vacuum brazed assemblies in beryllium. A silver-based braze alloy was selected which would allow the brazing process to take place at a temperature which would minimize re-crystallisation of the beryllium. This braze alloy was also chosen for its compatibility with beryllium, its suitability for use in the UHV environment, and its ability to ultimately withstand a 300ºC bakeout. The braze joints were all subsequently helium mass spectrometer leak tested to a rate of 2.6×10^{-10} mbar.l.s^{-1} or better.

Figure 2 shows a micrograph of a brazed joint. The 0.8 mm thick beryllium wall is on top. Tensile testing of two vacuum brazed samples gave failure stresses of 203.5 and 177.0 MPa.

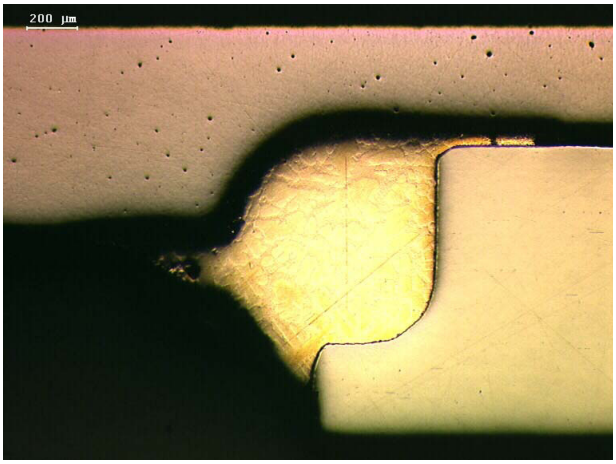

Figure 2: Micrograph of a Be-Stainless steel vacuum brazed joint.

TRANSITIONS AND FLANGES

Following the decision not to adopt beryllium flanges, alternative interface sections at the end of the beryllium chambers were required. Aluminium alloy is a good material for 'transparent' chamber construction due to its relatively low density and atomic mass. However, standard weldable alloys such as AA5000 and AA6000 series are generally limited in temperature to less than 200°C to avoid annealing. AA2000 series alloys have higher service temperatures, but are difficult to weld. However, the AA2219 alloy provides a combination of a service temperature of 250°C+ and good weldability. This alloy was qualified at CERN for weldability and corrosion resistance. Mass-minimised flanges were also developed using Helicoflex joints for this application [6].

2219 flange sections were EB welded to the beryllium tubes for the ATLAS chamber.

DEVELOPMENT PROCESS

In order to qualify these technologies, a test piece was manufactured by Materion Electrofusion for CERN. It consisted of a 1 m long beryllium tube, 58 mm bore and 0.8 mm thick, electron-beam welded to a 0.1 m long beryllium tube of the same section. At one end a 316L stainless steel tube was vacuum brazed and at the other an AA2219 aluminium tube was EB welded. Mass minimized flanges were welded on each end. The total 'envelope' of the chamber was 1.8 mm, limited by the thickness of the braze joint. This compares with 4.5 mm for the LEP chamber designs and permitted experimental PIXEL detectors to approach closer to the vertex.

The straightness of the Be-Be weld was measured to be 0.1 mm/m. The chamber was thermally cycled to 250°C and then overpressure tested to 1.5 bar.

In order to qualify the vacuum performance, the chamber was baked to 300°C (for the stainless steel parts) and 250°C (for the beryllium and aluminium). The chamber was pumped from a stainless steel measuring dome through a conductance of 9.13 $l.s^{-1}$ (for air). Residual partial pressures after 117 hours of pumping were 1.3×10^{-11} for H_2 and 1.5×10^{-12} for CH_4 with all other species below 1.3×10^{-13}. The N_2 equivalent outgassing rate was measured to be 6.7×10^{-13} $Torr.l.cm^{-2}$, very similar to the background rate of the stainless steel measuring dome. No sign of air permeation was detected.

SERIES PRODUCTION

A series of three chambers were manufactured for the LHC start-up. All three chambers used the same basic design with a 58 mm ID and 0.8 mm wall. This allowed the production of a series of machined tubes along with common tooling and weld parameters. The longest chamber was for the ATLAS experiment [7] with 7.3 m total length, composed of 7 m of beryllium with short aluminium extensions. Both ALICE and CMS experiments used 4 m long beryllium sections with stainless steel extensions and flanges.

The quality of production was generally good, with series weld samples giving failure loads consistently above 150 MPa for Be-Be welds and an achieved straightness of better than ±0.4 mm over the 7.3 m ATLAS chamber length.

Two problems were identified and resolved during the production process. Firstly, two leaks were identified through the machined wall of the tubes after final assembly, in the 10^{-6} and 10^{-12} mbar ranges respectively. The smaller leak was considered acceptable for operation. The section containing the larger leak was cut and removed. Secondly, EB weld arc instabilities caused a number of weld failures. This was corrected be improving the power supply control of the EB welder.

The chambers were NEG coated at CERN, then installed in the experiments [8] and commissioned without problem.

SUMMARY AND CONCLUSIONS

A new compact, NEG-compatible design of beryllium vacuum chamber for collider experiments was proposed. Technology for machining thin-walled chambers from block, EB welding and vacuum brazing were developed and confirmed to be compatible with the ultra-high vacuum, accelerator and detector environment.

The few problems encountered during production suggest that the design is close to practical wall thickness limits, both coming from material inclusion levels and control of EB welding parameters.

A series was produced for the LHC at CERN and is now operating successfully.

ACKNOWLEDGEMENTS

The microscopic analysis was performed by A. Gerardin and S. Sgobba. Vacuum testing was performed by B. Versolatto. C. Conolly, J. Villanueva and P. Murphy (Materion Electrofusion) participated in the detailed design and manufacture of the test piece. P. Lepeule assisted with the specification of the LHC chambers.

REFERENCES

[1] European Physical Journal C 15(1-4) (2000) 166.

[2] J-C. Brunet et al., "The Design and Construction of Transparent Vacuum Chambers for Interaction Areas of Colliding Beam Machines", IEEE Trans. Nuc. Sci. NS-26(3), June 1979.

[3] O. Grobner, C. Hauviller, "LEP Vacuum Chambers for Experimental Regions: Experience with the First Generation, Prospects for the Second Generation", EPAC 90 Proceedings, Nice, 12-16 June 1990.

[4] C. Benvenuti et al., Vacuum 60(1-2) (January 2001) 57-65.

[5] S.D. Henderson, "The CLEO-II SVX Water-Cooled Beryllium Beampipe", Proc. 8th Meeting Div. Part. Fields of the APS, Albuquerque 1994, p. 1480.

[6] R. Veness et al., Vacuum 64 (2002) 467-473.

[7] R. Veness "The ATLAS Beam Vacuum System", PAC '09.

[8] R. Veness et al., "Installation and Commissioning of Vacuum Systems for the LHC Particle Detectors", PAC'09.