DEVELOPMENT OF COMPOSITE TUBES FOR EXPERIMENTAL VACUUM CHAMBERS OF COLLIDERS

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Abstract

Interaction region vacuum chambers should be as transparent as possible to minimize the background on the detectors. Beryllium vacuum chambers are, so far, the most transparent, but development work to obtain composite tubes of the same performances is being carried out for LEP.

Two new types of tubes have been produced : carbon fiber composite and honeycomb sandwich tubes. The design method together with the fabrication procedures and the test results of these high technology products are presented in this paper.

General

The vacuum chambers of the detectors installed around the interaction regions of the colliders are the main physical interfaces between machine and experiments. Consequently, their design is determined by the sometimes conflicting requirements of the surrounding detectors, developed to do the best possible physics, and the machine, feeding particles at optimum conditions. A synoptic table of the parameters resulting from both parties is given below.

MAIN DESIGN PARAMETERS

COLLIDER	EXPERIMENT
	Transparency
Beam Envelope	Detectors acceptance
Synchrotron Radiation	Detector internal diameter
Ultra High Vacuum	Background
Electrical Continuity	Beam Shielding
Low RF losses	Temperature Variations
External mechanical forces	External mechanical forces
	Beam pipe supports

Table 1

Present experiments are designed to detect emerging particles in an angle of almost 4π. Consequently all heavy parts such as vacuum equipment have to be pushed far from the interaction point to improve acceptance.

The very sensitive vertex detector must be as near as possible to the initial interactions (small diameter) and loses its usefullness if the vacuum chamber material produces too many secondaries (transparency).

Unwanted background is also created by synchrotron radiation photons in electron-positron machines and by collisions with residual gases inside the vacuum pipe.

Shielding against electromagnetic noise is provided by a continuous metallic wall with smooth section transitions to minimise heating by high-frequency losses.

Finally a long light tube must be adequately supported by the central detectors.

A typical vacuum chamber, like the ones designed for LEP [1], is a cylindrical tube with vacuum equipment (pumping and controls) located at both ends. To tackle the design parameters enumerated above, the beam pipe has an internal skin metallic (light material), thin, smooth and continuous (welded).

Towards an optimal design

The main mechanical loading on vacuum chambers is the external pressure, generally 1 bar, but may be higher if the beam pipe is also the internal envelope of a detector. One has also to take into account other loads : thermal stresses occuring during the 150°C bake-out of the vacuum conditionning and inadequate supports generating bending forces.

The usual failure mode of a cylinder subjected to external pressure is buckling. This corresponds to a non-linear bifurcation in the elastic behaviour before yielding of the wall material.

It has been shown in [2] that, if L_R is the length of radiation and E the Young's modulus, a non-dimensional parameter $L_R\ E^{1/3}$ indicates on a rationalised basis the gain in transparency for an "infinite" smooth cylinder, one could expect by changing from one material to another one. Beryllium gives uncontestably the best performance, but it is so expensive to manufacture into a tube that its use is limited.

To approach the transparency of beryllium tubes, more complex shapes and materials must be considered. However, modifying the geometry to increase the inertia (ondulations, stiffening rings,...) leads to a loss of space for the central vertex detector : the distance between the internal skin and the external overall dimension is denoted ΔR in what follows.

To create some sort of guidelines, a scatter of points shows relative positions of present manufacturing possibilities according to the two main parameters : space taken by the vacuum pipe ΔR and "transparency" (minimum thickness/radiation length). Figure 1 shows, as an example, points for LEP vacuum chambers of first generation (internal diameter 156 mm).

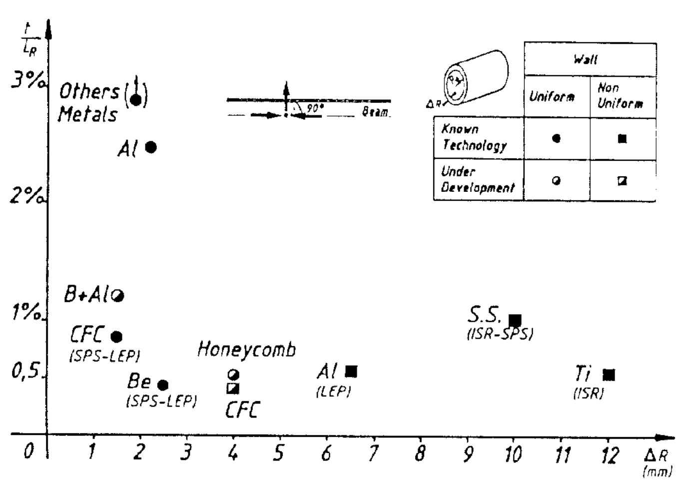

Fig. 1 : Transparency versus space loss

The optimum point lies on the lower left corner. Besides the afore mentioned beryllium, two types of structures are found around this point : carbon fiber composite (CFC) and honeycomb sandwich composite. They are considered good and, a non-negligible aspect, cheaper alternatives to beryllium. High technology development work for LEP is being carried out to produce reliable vacuum chambers and enhance their performances.

Carbon fiber composite tubes

The high rigidity of new fibers has recently attracted many designers. Composite tubes may be manufactured with various technologies but fibers in light materials (boron and carbon) are the best candidates for transparent vacuum chambers.

Tests with boron embedded in aluminium have been successfull at temperatures up to 300°C but, if the bake-out temperature is limited to 150°C, carbon fiber-epoxy compounds have better relative performances and are easier to manufacture.

Manufacturing
A carbon fiber composite tube is the overlapping of a series of layers (fig. 2). An aluminium skin has been chosen as the first metallic layer. Contrary to previous designs, it presents no discontinuities neither along the cylinder nor at the end connections. This aluminium wall is machined by honing and outside turning down to 0.1 mm from a AA 5052X seamless thick tube. It provides good electrical characteristics and vacuum performances equivalent to plain metallic parts.

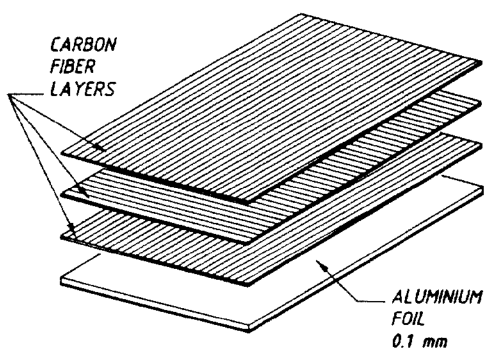

Fig. 2 : Carbon fiber composite structure

After etching, carbon fiber composite is layered either by wrapping or filament-winding, the latter being generally preferred, wherever possible, because it gives larger fiber content and better product quality. The fibers are impregnated with high temperature epoxy resin just before winding. Many fiber qualities are available on an industrial basis but the more rigid (and fragile) should be preferred. High modulus (HM) (40'000 kg/mm^2) fibers give a composite with an axial Young's modulus of about 25000 kg/mm^2 but an almost nul transverse one. Ultra High Modulus (UHM) fibers are 15% better. Composites with a 30'000 kg/mm^2 modulus are now produced with new fibers arriving on the market. The performances of the latter type become comparable with beryllium ones. If a detection window is needed, a smooth tube is replaced by a stiffened one with thinner zones (figure 3). The stiffening rings are wound as before but cracks during curing in transition regions are avoided only by a careful study.

Adherence between layers and bubbles content are main concerns, especially between aluminium and composite. The first test is visual : a human eye is very sensible to any default on a brilliant aluminium surface. Ultra-sonic and X-rays tests are systematic but thermography and holography also give good results. Gas permeation measurements have shown that this phenomenon is not negligible and that pressure build-up in bubbles between aluminium and composite may lead, under the worst conditions, to long-term delamination.

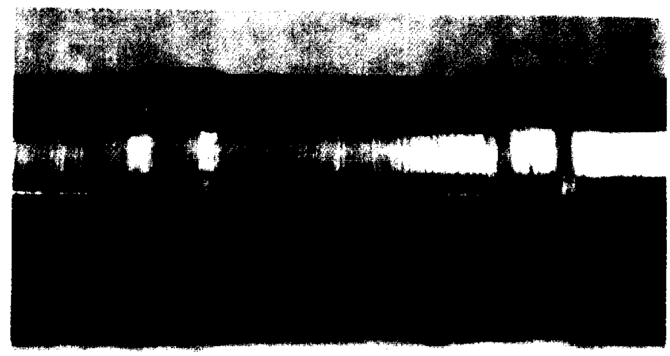

Fig. 3 : Ring-stiffened carbon fiber tube

Tubes are assembled by temperature-controlled automatic welding of thicker aluminium ends. Transitions between aluminium and carbon fiber composite behave badly under temperature : the thermal expansion coefficient of carbon fiber is around zero and interlaminar shear is avoided only by choosing an adequate winding orientation of the successive layers.

Design
Design of orthotropic tubes versus buckling is done either by approximation to close-form isotropic formula or using a more complex computer program BOSOR4 [3]. This second and precise analysis consists in evaluating equivalent moduli for the material treated as orthotropic. A good correlation is found between experimental and analytic buckling values, even in the case of stiffened tubes subjected to general and local modes of failure.

All the tubes described above have been carefully manufactured by industry [4] under CERN specifications.

Availability of new rigid carbon fibers will probably "beat" beryllium in some years but they are very fragile and therefore difficult to proceed. To produce reliable vacuum pipes, severe material quality control and high quality manufacturing are compulsory.

Honeycomb sandwich tubes

Instead of working with a stiffer material as above, it is possible to increase the inertia by using the skins of the wall as a rigidifying structure and keeping a low density core in-between.

Manufacturing
A honeycomb sandwich structure is composed of three element types (fig. 4) : two thin aluminium foils and an internal honeycomb core glued together by two layers of film adhesives.

The thicknesses of both skins are identical. Two types of foils were used : a 0.1 mm thick AA 5454 alloy and a 0.23 mm thick AA 5052. A leak-tight internal skin is obtained by TIG welding but it can also be envisaged to use the same technique as for the CFC pipe : machining from a thick tube. Two flexible Nomex^R honeycombs were available with densities of respectively 0.029 (type 1) and 0.048 (type 2). Bonding between core and skins is done with a high temperature epoxy film adhesive. Polymerisation is performed under pressure at 175°C during one hour.

The bonding procedure, in particular surface preparation, was the most critical operation of the

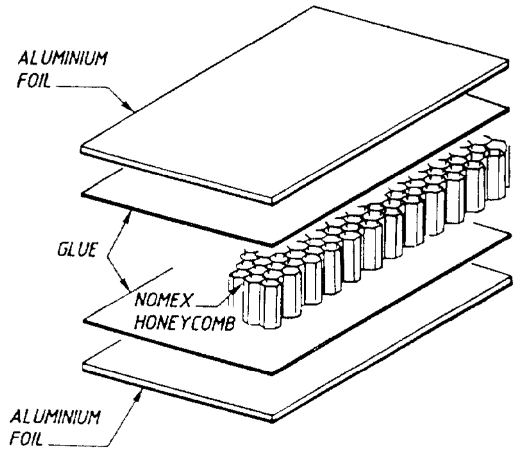

Fig. 4 : Sandwich structure

whole assembly. The adopted etching technique was based on a mixture of hydrochloric, nitric and hydrofluoric acids. Peel tests have been used to determine the best surface preparation and, during subsequent manufacturing, to check all steps systematically with a control sample. Further qualification tests have shown that no damages are noticed up to 10^8 rad irradiation, neither after a 200 hour bake-out at 150°C.

Design

Failure modes of a honeycomb structure is not only a general buckling. Various local bucklings and yielding may also limit the performances. A systematic approach of all these phenomena has been carried out to try to optimize the design. Figure 5 gives, as an example, theoretical curves corresponding to a 156 mm internal diameter, 500 mm long and 4 mm thick. Critical pressures are plotted versus skin thickness.

Skin elastic limit :
If the two skins of a tube of radius R are very thin, the membrane stress under pressure p may reach the elastic limit of the material. A fairly accurate approximation is $\frac{pR}{2t}$.

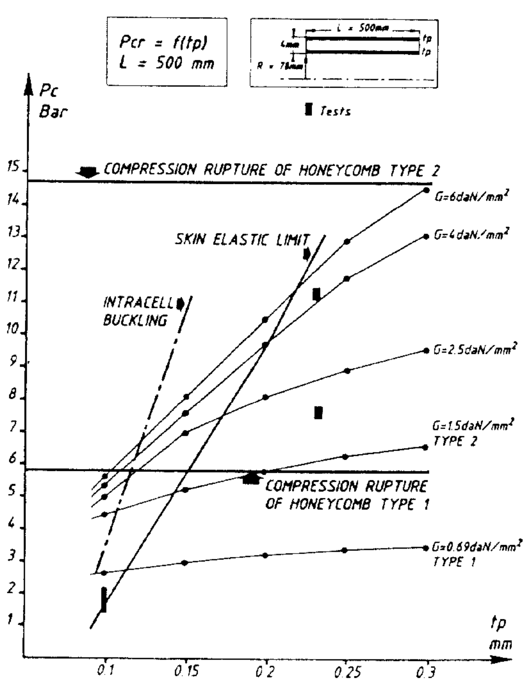

Fig. 5 : Design curves for a honeycomb tube

General buckling :
This critical pressure is computed as the value minimizing a function of buckling mode and geometric and mechanical characteristics of the tube. This complex approach was computer programmed. It was found that the shear modulus of the honeycomb core G has a large influence on the general stability as shown by plotted curves.

Local bucklings :
A honeycomb structure is composed of a multitude of sub-structures, each of which could be subjected to local instabilities. Two types of instabilities occured in the present tubes : intracellular buckling and core compression rupture.
Intracell buckling :
Skins are subjected to compressive forces. Being only supported on the edges of cells, they may buckle like plates. With the present parameters, intracellular buckling always occurs after yielding but if the adherence is bad due to poor bonding conditions, propagation of intracell buckling causes destruction at a very low pressure.

Core compression rupture :
Honeycomb is made of a 50 μm thick Nomex[R] material arranged in cells with dimensions of many millimeters. Therefore, even if the forces due to pressure are low, they may destroy the structure. Nominal values given by the manufacturer are plotted.

Test points are indicated in figure 6. All the tubes with 0.1 mm thick skins failed around 2 bars irrespective of their honeycomb type. This has been explained by premature yielding of the weak aluminium alloy foils. Trials with 0.23 mm thick skins gave better results than expected : about twice as good. Too conservative values of the shear modulus and core crushing of the honeycomb are suspected.

All the tubes described above have been manufactured at CERN. The transparency achieved is not far from the beryllium one but some limited space is lost due to an increase in thickness.

Conclusion

Development of composite vacuum chambers have led to very transparent pipes, almost as good as beryllium, but at a much lower price. Their vacuum performances are equivalent to those of fully metallic tubes. However, they are highly technological products and great care should be taken during the whole manufacturing process to obtain reliable finished products.

References

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