Design of Vacuum Chambers for Experimental Regions of Colliding Beam Machines

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Abstract

During the last twenty years, highly transparent vacuum chambers adapted to the requirements of the detectors have been installed in the experimental regions of the CERN colliders: ISR, SPS and LEP. The general method of design of the chambers is described: criteria for the choice of materials, methods of determining the mechanical parameters, manufacturing methods, environmental constraints, ... An overview of possible future concepts is also presented, in particular the use of new materials.

I. INTRODUCTION

The vacuum chambers for the experimental regions of the colliding beam machines are the main physical interfaces between machine and detectors. Consequently, their design is determined by sometimes conflicting requirements, but drawbacks for the particle detection due to the necessary presence of the pipe could be minimized by a carefully optimized approach. No unique solution exists, but the aim of this paper is to try to give general guidelines based upon experience acquired during the last twenty years on CERN colliders: ISR, SPS and LEP [1], [3], [5]. After recalling the requirements, design strategy will be followed by general hints on shapes and materials and some remarks on manufacturing and an extrapolation to future machines.

II. REQUIREMENTS

General constraints from a collider together with those from an experiment lead to the main design parameters, but more factors specific to the machine type or to the detectors have to be added.

On the machine side, the vacuum chamber should obviously have an aperture large enough to allow the beam envelope, including all running conditions (injection, stable beams, ...), to go through and a sufficient conductance to keep the required ultra-high vacuum. A perfect electrical continuity is also a prerequisite. But one must also add specific requirements such as, for an electron-positron machine:

- protection against synchrotron radiation, either large aperture, in order that no particle hits the wall, or masks, to limit the particle interactions to local zones;
- smooth section transitions to minimize high-frequency losses.

The beam pipe should be compatible with the rapidity coverage of the experiment. The main parameter is its transparency to emerging particles but other phenomena have to be taken into account: shielding against electromagnetic noise, unwanted background created by collisions with residual gases or, in electron-positron machines, by synchrotron radiation photons. A sufficient clearance between the external envelope of the beam pipe and the inner layer of the vertex detector is also very often a prime parameter for the installation.

Finally, it should be borne in mind that adequate supports are of prime importance in the design of a vacuum chamber and that forgetting this fact in the conception of an experiment may lead to rather uncomfortable situations.

III. BEAM PIPE SECTION

Having established the boundary conditions of the design problem, it is now possible to determine the general shape of the beam pipe. A lot of imagination can be incorporated at that stage, but the solutions are usely variants of basics. For example, all the vacuum chamber types ever installed in the ISR have been already determined in the early days of the machine[1].

The first question is the section: either circular or elliptical. An elliptical section can be matched more closely to the beam envelope and allows a minimization of the distance between the first layer of detection and the interaction point. But the increase of the wall thickness, a consequence of a weaker non-circular section, hampers considerably the above advantages and leads usually to the relinquishment of this more complex option.

Circular tubes which could be cylindrical or conical with various wall constructions will be detailed below.

IV. DESIGN

The very large quantity of beam pipe types leads to an impossibility to provide a fully general design method. Guidelines will be given for the simplest beam pipe, a smooth circular cylindrical tube. After definition of the main parameters, it becomes possible to optimise the project in analysing their sensitivity to any variation. Vacuum and mechanical behaviours are treated separately but they interfere one against the other during all the design process.

A. Vacuum

The static pressure in the beam pipe is affected by the outgassing rate of the material, the conductance of the tube and the location and type of the pumps. It can be demonstrated that the pressure difference between the centre (P_{max}) and the extremities (P_o) of a cylindrical tube of a diameter D and of length 2L with two end pumps is independent of the pumping speed. Based upon LEP experience on aluminium tubes, a conservative approximation of this difference is

$$P_{max} - P_o = 1.3 \times 10^{-12}\ (L/D)^2 \quad (P \text{ in Torr})\ .$$

0-7803-1203-1/93$03.00 © 1993 IEEE

The base pressure P_0, dependant of the available pumping speed, is determined by background considerations. Figure 1 shows the pressure curves for two typical values of L. As an example, to run at a maximum pressure of about 10^{-9} Torr, a practical upper limit for the pressure difference would be half of this value.

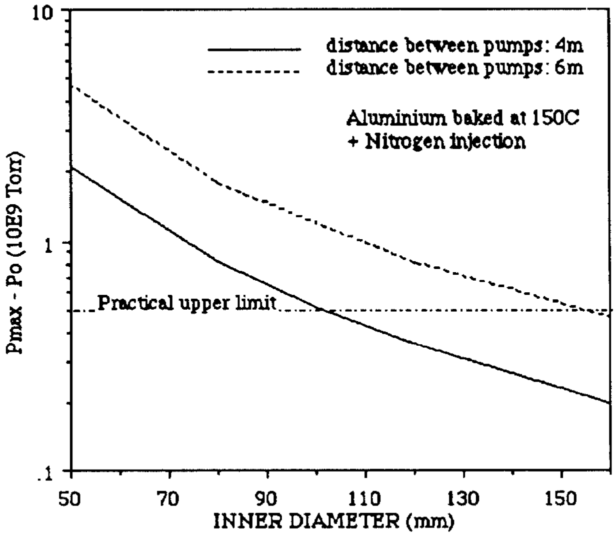

Figure 1. Pressure difference between interaction point (Pmax) and pumps (Po)

B. Mechanical behaviour

The main loads applied on a beam pipe are the external pressure due to vacuum and the own weight of the tube. They lead to buckling and bending.

For a long smooth cylindrical tube, the minimum thickness t required to avoid linear buckling (non-linear bifurcation before yielding) under vacuum is

$$t = 58 \sqrt[3]{\frac{1-\nu^2}{E}}\, D,$$

with a safety factor of 4, E and ν being respectively Young's modulus and Poisson ratio of the material (S. I. units).

But too long a distance between supports may cause a coupling between buckling and bending (ovalisation called the Brazier effect) leading to an earlier failure. Bending behaviour depends considerably upon the supporting method; an example is given below to illustrate this phenomenon. For a beam pipe simply supported only at the level of the pumps, assuming that the maximum deformation should be less than the wall thickness, the minimum value of t is

$$t = \frac{5}{3}\frac{\rho g}{E}\frac{L^4}{D^2}$$

where ρg is the specific weight.

Figure 2 summarizes the application of this method to cylindrical beryllium tubes. However, it should be noted that this is the worse supporting case and that an extra support point improves significantly the situation.

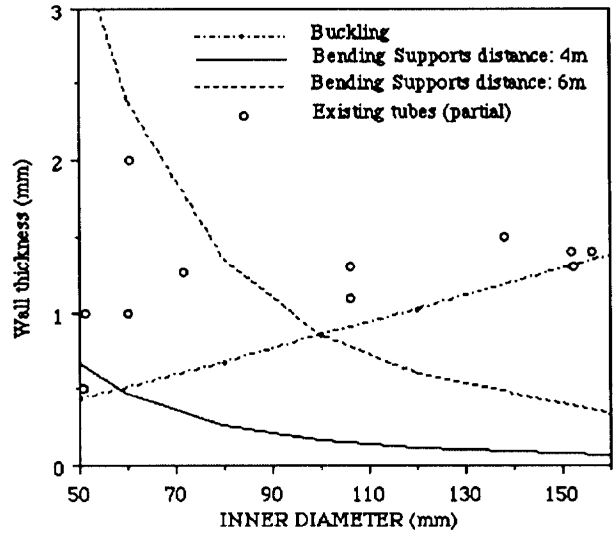

Figure 2. Geometry of beryllium beam pipes

Therefore, after having defined the vacuum pressure in running conditions based upon background considerations and after having defined the location of the pumps and the support points, geometrical and material parameters can be discussed.

V. SHAPES

A circular tube could be, in the order of manufacturing complexity, smooth, ring-stiffened, conical (simple or multiple), corrugated, a skin in tension between rings, ... The transparency of the first three options is compared in Fig. 3. (The ring-stiffened tube is a 0.5mm thick cylinder reinforced by ribs 0.5mm thick, 4.5mm in height, evenly spaced by 60mm).

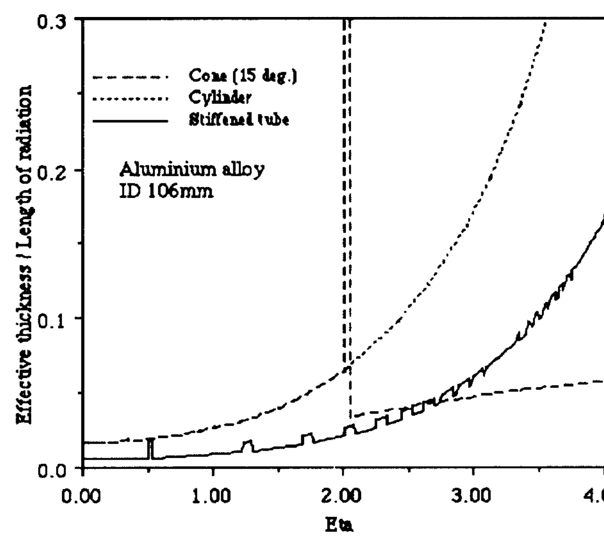

Figure 3. Transparency versus pseudo-rapidity

The smooth circular tube is the simplest beam pipe but its performances at high rapidity are very poor. The ring-stiffened tube is a way to minimize the wall thickness while keeping the smoothness of the internal wall. A way to open a window at high rapidity is a cone but the allowable transition angles are limited in some machines (15° at LEP) and the path length inside the conical wall (corresponding to the big jump) becomes arbitrarily large; the latter drawback is even amplified by the fact that the interaction zone is not a point but finite and that charged particle tracks are curved in a magnetic field. A corrugated tube is an elegant way to minimize the wall thickness at low rapidity but at higher rapidity the number of wall crossings becomes prohibitive and this sort of tube is unacceptable in electron-positron machines. All attempts to manufacture a skin under tension have shown that the ring mass becomes prohibitive and the transfer of the large forces involved to the supports is a problem, especially with nowadays light trackers.

VI. MATERIALS

For the same design, the gain in transparency obtained in using one material instead of another can be determined in a rationalized way [2]. Considering the elastic buckling as usual failure mode of a circular tube loaded by an external pressure, it can be shown that if X_o is the radiation length and E the Young's modulus, a non-dimensional parameter $X_oE^{1/3}$ gives a figure of merit of materials. Table 1 allows to compare the principal ones.

Material	Be	CFC	Al	Ti	Fe
E (GPa)	290	200	70	110	210
Xo (m)	0.353	0.27	0.089	0.036	0.018
Xo $E^{1/3}$	2.34	1.58	0.37	0.17	0.11

Table 1

Beryllium gives uncontestably the best performance but tube geometry has been limited up to now to smooth cylindrical shapes. It has three major drawbacks: safety hazards, manufacturing difficulties and, consequently price. Beryllium particles, generated in the case of an implosion or a fire, is highly carcinogenic. Obtained only through powder metallurgy, beryllium is considered not to be weldable at UHV standards. Tubes are presently produced from a hot formed sheet brazed on a longitudinal splice joint (Figure 2 shows dimensions of the longer vacuum tubes produced). Extruded tubes, proposed but not yet qualified, would permit more complex shapes. Heavy transition ends, either in aluminium or stainless steel, have to be brazed at both ends for welding to the other tubes.

A large number of wall constructions can be called composite [4]. Only two families will be mentioned: sandwich and carbon fibre reinforced plastics (CFRP).

A honeycomb sandwich made in Nomex honeycomb glued to two aluminium skins has been installed in a collider and further development work has shown the viability of this option, unfortunately presently asleep.

CFRP tubes have been used with more or less success. The composite structure itself was always up to the expectations and new fibres arriving on the market next year will double the Young's modulus value of Table 1, therefore superseding beryllium. When a problem appeared, it was always caused by the inner metallic liner and its connections to the transition end pieces. But, if this continuous liner can be replaced by a sputtered metal, then fully reliable optimized vacuum chambers could probably be obtained at a very competitive price.

Aluminium alloys are light metals which provide the best cost-effective solutions. Almost any shape can be produced by precise machining, in particular ring-stiffened tubes as thin as 0.5 mm, which could be adapted to any detector acceptance. Their design is complex but present day analysis programs are able to handle any buckling problem. However, a great care is required to successfully weld thin aluminium alloy parts to UHV standards.

Titanium or stainless steel tubes could only be competitive with a very thin wall. The common solution is therefore to corrugate them but then a lower bending rigidity means more supports and, at high rapidity, the number of wall crossings increases quickly above an acceptable level. If the vacuum bake-out temperature can be limited to 150°C, then aluminium alloys are preferable.

VII. FUTURE COLLIDER BEAM PIPES

Beryllium is still considered to be the best option, especially for the central part, but carbon fibre reinforced plastics become very competitive with the arrival of new rigid fibres and reliable enough with the development of new resins and coating methods.

A cheaper option is to choose parts with fancy shapes machined in aluminium alloys, especially for the forward parts: ring-stiffened or cone, the latter being more transparent at high rapidity at the expense of an important "shadowed" zone.

But other ideas should not be forgotten, even if they need more development: honeycomb sandwich or even machined beryllium-aluminium alloy, ... once tubes become available.

VIII. REFERENCES

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