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THE DESIGN AND CONSTRUCTION OF TRANSPARENT VACUUM CHAMBERS FOR INTERACTION AREAS OF COLLIDING BEAM MACHINES

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Summary

The use of modern materials and specialized forming techniques have enabled the ISR Division at CERN to produce very transparent interaction area vacuum chambers. The design and fabrication methods used to conceive and form these chambers are described. Special reference is made to the titanium chamber in intersection 7, the inconel chamber in intersection 8, and the stainless steel chamber in intersection 4. A method is given for rationalising the choice of material for interaction area vacuum chambers for any colliding beam machine.

1. Introduction

The Intersecting Storage Rings (ISR) machine at CERN uses seven of its eight intersection regions for colliding beam physics experiments. In these zones the detection and analysis of emerging particles is hampered by the fact that all emerging particles and electro-magnetic radiation must pass through the vacuum retaining wall and there is therefore a fundamental need to make this as transparent as possible. Over the last few years, by using modern materials, specialised forming techniques and up-date design techniques, the ISR has been able to produce some very transparent interaction area vacuum chambers.

2. Design procedure

a) Space limits

The volume within which the vacuum chamber must be contained has an outer envelope which is that of the surrounding detectors and an inner envelope which is given by the beams.

b) Preferential physics viewing angles

For certain types of physics experiments, the vacuum chamber is often required to have maximum transparency within a stipulated solid angle. Incorporation of such "windows" is usually possible but this inevitably requires the addition of extra material in the less intersecting angles. This dense material although not directly within the acceptance of the detectors is often the source of troublesome background events which shower into the detectors and make subsequent analysis that bit more difficult and expensive.

c) Supporting structure

If the vacuum chamber can be supported from an external structure such as for instance a central analysing magnet, then the chamber can often be made thinner and therefore more transparent than the equivalent self-supporting chamber.

d) Working conditions and safety

All parts of the ISR vacuum systems are subject to a 24 hour bake-out at 300°C in order to obtain an average vacuum of 5×10^{-12} torr. Such a vacuum minimizes the physics background due to gas scattering. The vacuum chamber must therefore be sufficiently strong and stable to resist the external atmospheric pressure at 300°C without collapsing. Factors of safety of 1.3 on yield stress or 2.0 on rupture stress are the values usually applied in the initial design process.

e) Cost and development time

Few vacuum chamber designs are limited by money. Experience at the ISR has shown that the cost of the most expensive modern experimental chambers accounts for less than ten per cent of the total cost of the complete physics experiment.
The time factor is however a very important consideration. Each new intersection chamber has its own particular features incorporated in the design to meet the requirements of the experiment in hand. This often means development of new or existing forming techniques and the production of prototypes. In this case the total time from the initial design study to the installation in the ISR is between 12 and 18 months. If such a time delay cannot be accepted by the experimenters then certain compromises have to be made in the design.
This means use of component pieces of known performance for which tooling exists.

f) Choice of material and shape

Having established the boundary conditions of the design problem, it is now possible to suggest and evaluate certain design solutions. These solutions are frequently variants of basic solutions given in 1971[1].
It is evident that the vacuum chamber material should be as transparent and as stiff or strong as possible. Efficient use of material is reflected in high strength to weight or stiffness to weight ratios. The material requirements are therefore in many ways similar to those required in the aeronautical and aerospace industries.

The gain in transparency obtained by using one material as opposed to another for the same design has been determined in a rationalized way and is reported in reference 2. Eight non-dimensional parameters combining mechanical characteristics with basic physical transparency given by radiation and collision length are used to obtain figures of merit which are independent of thickness. It is assumed that any design is limited by a strength or stability condition which to the first approximation would fall between those for two extreme classical geometries. For stability, for example, it is assumed that the critical external pressure would fall between that for a perfect sphere and that for a long cylindrical tube. The figures of merit for various materials are given in table 1 for 300°C.
It should be emphasized that this table is based on purely theoretical considerations and is therefore only indicative. As an example of the use of this table one can see that a design limited by membrane stresses would be almost 9 times more transparent in titanium than in stainless steel.
Once a preference has been made from this table for a particular material, more practical aspects, such as formability and weldability have to be considered. Formability often limits the use of corrugated forms which in most cases give the most transparent solutions. There is also a practical limitation on thickness, below 0.2 mm fabrication of large components becomes very difficult. The thermal conductivity of the material could also be an important consideration in large e^+e^- machines where higher order losses produce heating wherever there is a change in cross section.

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In the event that several vacuum chamber shapes appear equally attractive after this rather fundamental design sorting operation then a more sophisticated sorting technique which is described later is employed.

Base	Be	B	Al	Ti	Fe	Ni	Cu
Alloy		50%Al	4%Mg	6%Al 4%V	18%Cr 12%Ni	18%Cr 18%Fe	0,6%Cr 0,02%Zr
σ_y	30	120	7	62	20	100	20
E	29000	20000	3800	9100	18250	19250	8500
L_c	300	240	255	176	102	92	93
L_R	353	128	89	37	17.6	15.5	14.3
$L_c\sigma_y$	9000	28800	1785	10912	2040	9200	1860
$L_c\sigma_y^{\frac{1}{2}}$	1643	2629	675	1386	456	920	416
$L_cE^{\frac{1}{2}}$	51088	33941	15719	16789	13779	12847	8574
$L_cE^{1/3}$	9217	6515	3979	3674	2685	2476	1898
$L_R\sigma_y$	10590	15360	623	2294	352	1550	286
$L_R\sigma_y^{\frac{1}{2}}$	1933	1402	235	291	79	155	64
$L_RE^{\frac{1}{2}}$	60114	18102	5486	3530	2378	2164	1318
$L_RE^{1/3}$	10845	3474	1389	772	463	417	292

Table 1

g) Theoretical design calculations

Having determined one or several design possibilities, the next step in the design process is to carry out a detailed theoretical stress analysis using finite element techniques. In-house mesh generation programs are used to generate the finite element computer models and also to produce a plot of total thickness seen by particles coming from the interaction diamond and traversing the vacuum chamber within a particular solid angle.[3] By comparing the plots for the various designs proposed the experimenters are able to give a preference for a particular design. This is the final sorting operation.

h) Detail design

This is the final stage of the main design process. The details of fixation, internal accessories and supports are incorporated into the main study and the fabrication drawings are prepared.

3. Fabrication of prototypes

a) Forming

Considerable use is made of thin-walled corrugated structures in ISR vacuum chambers because they have a high stiffness to weight ratio. Specialised equipment has been developed in the ISR main workshop to form these corrugations on both circular and elliptical cross-sections. The working principle of the forming tool is shown in Fig. 1.

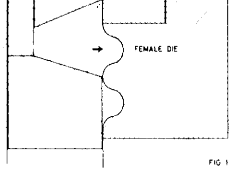


FIG 1

A smooth thin walled tube of the metal is fed corrugation by corrugation through the forming tool. Hydraulic jacks displace two wedge shaped rings which force the rubber radially outwards into the required female form.

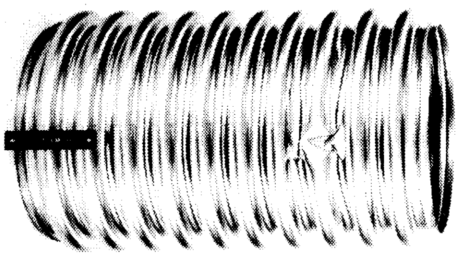
b) Welding

Fabrication of sheet metal structures for use in an ultra-high vacuum environment requires very high quality welding. These welds must have good elongation for formability, they must be as strong as the parent metal so as not to limit the design and they must be leak tight at 300°C. These requirements are in general easily met for stainless steel. For some new materials, welding thin sheets (0.15 mm to 0.70 mm) can prove difficult unless special precautions are taken or special techniques are employed.
For titanium and titanium alloys for example brittle or porous welds are obtained if the surfaces to be welded are not rigorously degreased and cleaned and the surface oxyde layer not removed. For all titanium welding high quality inert gas protection as found in modern glove box facilities is essential. Any titanium welds other than bright silver in colour are systematically refused by the ISR. It has been found[4] that manual TIG welds made on 0.6 mm thick sheets of the 6Al-4V titanium alloy have only about 2% elongation in the as-welded conditions. This near brittle condition can be returned to the more normal ductile conditions by the use of heat treatment cycles.

Inconel 718 in the aged condition becomes very brittle after welding and is susceptible to hot cracking whereas aged welds have a good ductility. Fabrication can therefore be difficult and delicate. Although the ISR has built a very transparent chamber in inconel, welding problems associated with the material need careful study for each design.

4. Testing

The strength and stability of complete vacuum chamber assemblies are determined by laboratory tests on prototype chambers. The position and magnitude of maximum stress levels at room temperature are determined by the use of brittle lacquer and strain gage analyses. Collapse pressures are determined by over-pressure testing in either air or water tanks. The use of water has the advantage that the chamber after collapsing remains intact and post buckled deformations can be studied, see figure 2.



With air the stored energy is so large that the chamber is completely destroyed.

5. Examples

Three vacuum chambers which have resulted from the application of the above design approach are described as follows.

a) The titanium chamber in intersection 7

This is the most transparent self-supporting vacuum chamber ever installed in the ISR, see fig. 3. It is bigger than other ISR chambers because it was foreseen that it be used in a steel low-beta intersection where the beam width was large.

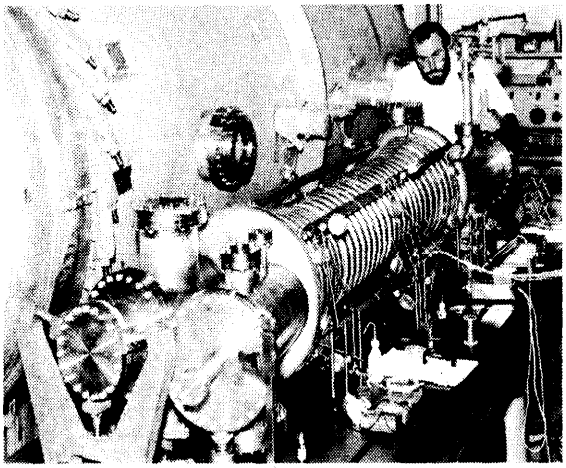


FIG.3

The large angle window consists of a 300 m diameter corrugated cylindrical tube of 0.3 mm wall thickness. The longitudinal joint in the cylindrical tube was made by electron beam welding, the other welds were either made by TIG hand welding in the ISR glove-box facility or on automatic machines with a good inert gas protection. Every millimeter of every weld was X-rayed to determine the level of porosity. During laboratory testing the collapse pressure at 300°C of the center tube of this chamber was found to be 2.9 atmospheres.

b) The stainless steel chamber in intersection 4

This chamber is an example of a time limited vacuum chamber design. The most important considerations were maximum transparency and minimum construction time. With such a brief, materials other than stainless steel were excluded because of the time needed for development and a design based on existing standard components was proposed, see fig. 4.

The central cylindrical corrugated tube of 0.2 mm thick stainless steel joins the two self supporting domes to give a minimum volume chamber of good transparency.

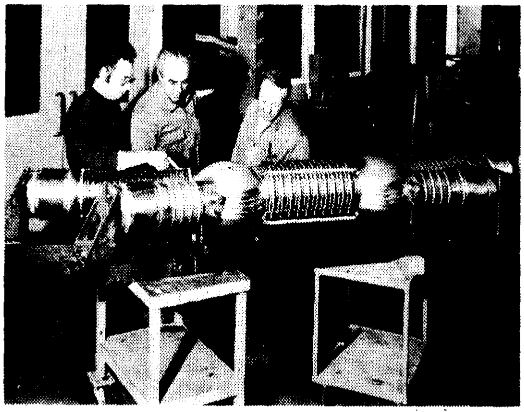


FIG.4

The computer model used in the finite element analysis of this chamber is given in figure 5.

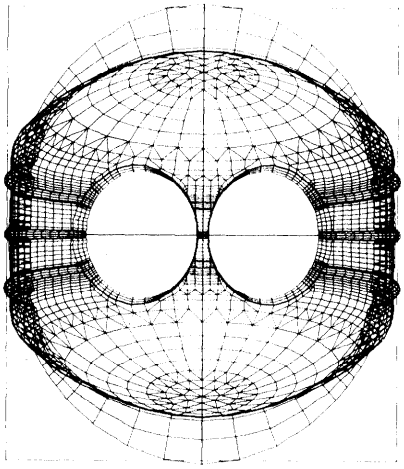


FIG.5

c) The inconel chamber for intersection 8

This is an example of a design in which an external support can be used to hang the chamber. In this case the supporting structure is an analysing magnet. The chamber is shown in figure 6. It consists of 2 intersecting corrugated cylinders, this design gives not only the best overall transparency but also the largest physics window. Inconel was chosen in preference to stainless steel because it has a very high elastic strength when heat treated and can therefore be made that much thinner (0.2 mm).

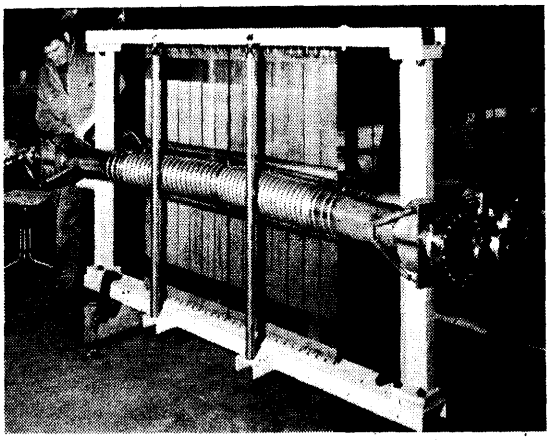


FIG. 6

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