EXPERIENCE WITH METAL AND EPOXY VACUUM CHAMBERS AND THE DEVELOPMENT OF ALUMINA CERAMIC VACUUM CHAMBERS AT THE CEA

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Introduction

The performance of stainless steel epoxy-fiberglas coated vacuum chambers at the Cambridge Electron Accelerator is reviewed with especial attention to radiation resistance and ultimate vacuum capability.

In order to increase chamber life for more reliable synchrotron operation an aluminum oxide ceramic and metal design has been developed.

Location of Vacuum Chambers in Accelerator

The Cambridge Electron Accelerator is an alternating gradient 6 Gev electron synchrotron, composed of 48 magnets, each 3. m. The vacuum chamber is fitted into the magnet gap from the outside and extends the full length of the magnet. (Fig. 1) Because of the alternating gradient structure two types of vacuum chambers are required.

The beam aperture in the open or vertically focussing magnet is the limiting vertical aperture of the synchrotron. This vacuum chamber must therefore provide the maximum vertical dimension possible in the magnet gap. The vertical beam size in the closed magnet (vertically defocussing) is considerably smaller, and is less than the narrowest part of the magnet gap considering the limitation of beam aperture in an open magnet. This allows a closed vacuum chamber to be inserted from the side of the magnet.[1]

Epoxy - Stainless Steel Vacuum Chamber

The present CEA vacuum chamber is made from stainless steel ovals successively welded together at alternate ends to form a tube. The dimensions of the oval cross section corresponds to the requirement of an open or closed magnet. The plan of the tube forms an open vee following the lamination stack for each half magnet. (Fig. 2A) This assembly is coated with epoxy and fiberglas to make a vacuum tight covering. Stainless steel end flanges are then attached to complete the chamber.

The result of this design is an assembly that reduces the eddy current heating from the 60 cycle magnets and retains electrical continuity from end to end permitting the steel frame to be heated for vacuum outgassing by an electric current. The wall is relatively thin (2 mm) and flexes (½ mm) when the tube is evacuated. Bakeout to $100^{\circ}C$ in the laboratory can result in a chamber average base pressure in the low 10^{-7} torr range.

A bellows assembly is used to connect an installed chamber to the drift section located between magnets. These drift sections house R.F. accelerating stations, inflectors, beam monitors, pumps, etc.

The synchrotron can produce external photon and electron beams, and special branching chambers are required to allow these to leave the synchrotron. (Fig. 2B)

The design just described was probably the only feasible one ten years ago when it was selected. Several synchrotrons built since have used essentially the same design. It has adequate structural strength and good vacuum properties.

The major weakness of the construction is the epoxy-fiberglas coating which is not sufficiently resistant to radiation damage. Prolonged radiation exposure gradually hardens the epoxy until it becomes too inflexible (brittle) and fractures spontaneously or from the strain imposed by atmospheric pressure upon the chamber.[2]

The usual kind of failure is a blister that forms the coating, which then cracks, resulting in a leak. Repair or replacement of the epoxy coating of the chamber is then necessary. The formation of leaks in irradiated chambers is hastened by the flexing of the wall caused by air release and re-evacuation. Thus when a section of the synchrotron is let up to atmospheric pressure for routine maintenance on chambers, pumps, targets, inflectors etc., a new leak is often formed in another epoxy chamber which had no leaks prior to the re-evacuation.

The radiation damage problem is worst at certain locations associated with large beam loss at ejection or injection. For example: high energy electrons circulating in the synchrotron are made to strike thin ribbon targets (¼ mm tungsten) to provide gamma ray beams. The electrons emerging from these targets are degraded in energy and bent strongly by the magnetic guide field (as in Fig. 2B) so that they strike the inside of the next vacuum chamber, resulting in large radiation doses at that location.

Radiation patterns downstream of targets and beam controlling devices have been measured at several points as shown in Figure 2B. Cobalt glass dosimeters were used to record the radiation dose which were read on a Bausch and Lomb spectrometer. The highest doses observed per ma-hour of circulating beam were about 5×10^6 rads. Combining this with shortest observed vacuum chamber lifetimes of about 150 ma-hours leads to a figure of about 7.5×10^8 rads exposure to failure of the epoxy.

This has been confirmed by measurements made in an external electron beam where higher dose rates (about 1.3×10^7 rads per ma-hour of circulating beam) were available. A small section of vacuum chamber, fitted with a water cooling jacket to control direct thermal effects was exposed to this beam. Doses to failure of 3×10^8 rads to 1×10^9 rads were measured.

With steady 7-day 24-hour operation there are one to two vacuum chamber failures per week. Chambers that fail from radiation damage are repairable. Areas of local damage can be fixed by stripping the epoxy-fiberglas around the leak and applying a new coating. In many cases the damage is so extensive that the entire chamber must be stripped and recoated. Repair work on these chambers is complicated by the residual radioactivity in the stainless steel frames. Chambers freshly removed from the synchrotron may exhibit radiation levels of 1 R/hr. or more. This requires storage in remote locations for many months so that the radiation level may decay to tolerable levels. Studies of the lifetimes and energy spectra of this radiation indicate that the most troublesome components are due to radioactive products from the irradiated iron and nickel in the stainless steel. The reactions are:

$$Fe^{56}\ (\gamma,\ np)\ Mn^{54};\ T_{1/2}\ (Mn^{54}) = 310 \text{ days}$$

$$Ni^{58}\ (\gamma,\ p)\ Co^{57};\ T_{1/2}\ (Co^{57}) = 270 \text{ days}$$

The long half life of these products requires a cooling down period of about one year to achieve significant reduction in radioactivity levels.

The resin formula used at the CEA to coat the vacuum chamber frames is Hysol 4143 monomer and 3416 accelerator 100/5 parts by weight. This is cured for 2 hours at 60°C, material is easily handled, does not sag on vertical surfaces and has excellent vacuum properties. In an effort to improve the radiation resistance of the vacuum chambers, another epoxy was tested, (Ciba 6010, 906 and Benzyl Dimethylamine 100/80/3 PBW).[3] Variations in the construction details were tried. In Fig. 3 is shown the addition of stainless steel foil laminated into the epoxy, which increases the flexural stiffness of the ring. A chamber design using a solid sidewall and segmented top and bottom strips has been built, and extensively tested. The result of these trials was only marginal improvement, and few were adopted.

Ceramic Chamber

In seeking a new approach to more reliable vacuum chambers the CEA began in 1965 the development of a ceramic and metal vacuum chamber containing only inorganic radiation resistant materials.

Several specific design problems had to be solved before a satisfactory ceramic chamber could be constructed. The following discussion will cover the most important of these.

Alumina is the first choice for the ceramic. It has the highest compressive strength, good radiation resistant properties,[4] and superior metallizing properties. There is a considerable body of experience with ceramic compositions (fired) of 93% Al_2O_3 or higher, the balance consisting of combinations of silicon, and magnesium oxides. Alumina-silicates and similar porcelain materials have been used as well.

Ceramic materials are noted for their brittleness, and it was necessary to achieve a cross section with sufficient wall thickness to give a margin of safety against breaking within the limitations of magnet gap and beam aperture.[5]

The elliptical shape of this envelope was a new development in the application of ceramics. Omitting the details of strain analysis, the high strength of alumina ceramic has allowed the development of all the required apertures with a minimum safety factor of 5.

To cope with the inherent variability of linear dimensions of fired alumina ceramic, the pieces that make up a complete chamber are placed in a position along the chamber that matches the beam aperture to the chamber aperture. It has been necessary to grind the external height in order to fit the available aperture in the magnets. Figure 4 illustrates the position of the chamber in open and closed magnets.

The final wall thickness of the chamber sections varies from 3 to 4 mm in thickness compared to the epoxy construction of 2 mm, but since the alumina does not deflect significantly under atmospheric pressure, the final aperture is virtually the same. The indicated variation of the aperture is 1 to 2 mm over the entire length.

The chamber must have an inner surface which does not accumulate charge. Static charge buildup will result in the formation of electrostatic fields which can cause beam loss. The conductive coating which is applied to prevent this must have sufficient resistivity, however, so that eddy currents induced by the 60-cycle magnetic field, remain low. There are a number of possible solutions here, but for this design a continuous, fired on coating is used. A surface resistivity of 300 ohms/square has been chosen to satisfy these requirements.[6] In addition it is planned to use this coating as a power resistor to provide the necessary heat for vacuum bakeout.

For the design of the longitudinal plan, maximum use of available horizontal aperture could be gained by having the chamber follow the orbit instead of the magnet gap, as originally done. (Fig. 5) This is important because the ultimate strength of the ceramic wall is inversely related to the 4th power of the span for a given thickness. Also in this configuration each piece in the chamber is exactly alike; of great advantage when economy of reproduction is required. The selection of the number of pieces in each chamber is dependent on the minimum cost for different piece lengths, including joints. Studies and modelling have indicated that this cost is substantially constant for lengths between 0.2 and 0.5 meter.[7] An 8-section (45 cm long pieces) has been adopted. Stainless steel end flanges similar to that used for the epoxy chambers complete the assembly.

A branching or ejection chamber is made by combining normal and wide aperture pieces (Fig. 5) so that an ejection tube could be accommodated. It is possible to fit all varieties of external beam requirements with just three different chamber sections. The largest cross section designed is 4 cm high and 20 cm wide.

Attaching fired ceramic pieces together or to metal rings first requires that the ceramic be metallized. There are a number of different materials and processes used for metallizing, but the one chosen has excellent properties for this application.[8,9,10,11] This process consists of coating the surface with a mixture of molybdenum and manganese powders and firing the whole in a reducing atmosphere to 1425°C. In the process the metallic coating diffuses into and bonds to the base material. The attachment of the thin metal ring is done by furnace brazing to this coating.

Several types of joint designs are possible, but a simple face seal of a metal U shaped flange copper brazed to the alumina has been adopted. Adjoining flanges are then inert arc welded together. 45% Cupro nickel has proved to be a very satisfactory alloy for these flanges. It is non-magnetic and has the high resistivity necessary for minimizing eddy currents, which can cause heating and field distortion. This approach gives a flexibility to the assembly which allows adjustment to fit at installation. To counteract the linear load of about 100 Kg on the evacuated chamber imposed by the differential area of end bellows and chamber area, springs were inserted over the flange seal clamping bolts. (Fig. 6) The final result is a chamber that has no imposed loads except the collapsing force of atmospheric pressure.

A necessary accessory for handling such a flexible assembly as the chamber described, is a transport platform. The assembly of the chamber, vacuum processing and carrying to the magnet for installation are done on this platform. In turn there has to be a platform inside the tapered magnet gap. (Fig. 4) The solution here has been to use wedges fastened to a frame which fits the pole profile to provide a flat surface.

The vacuum properties of the finished chamber have proved excellent. The process of fabricating the ceramic pieces involves high temperatures in a reducing hydrogen atmosphere which leaves a very clean surface. Average pressure less than 1×10^{-7} torr can be achieved in a few hours after many days of atmospheric exposure. After 40 hrs. of baking, using the internal resistive coating to raise the temperature to 200°C, average pressures less than 7×10^{-9} torr can be reached.

The CEA is now in the process of equipping the entire synchrotron with ceramic chambers. One chamber has had six months of service, and eight more have been recently installed. This change comes at a fortuitous time as a new injection linac will become operational soon, enabling the acceleration of higher intensity beams. These high intensities would result in increased radiation dose rates to vacuum chambers and even more frequent failure of the present epoxy-fiberglas chambers.

Also under study is a program for using the synchrotron as a storage ring for high intensity beams of counter-rotating electrons and positrons adding a colliding beam capability to the CEA.[12,13,14] The lifetime and size of a stored beam is determined by the rate of interaction with the residual gas. Hence, it is desirable to store beams at the lowest possible pressure. The inherent cleanliness of the ceramic chambers will greatly facilitate the attainment of pressure below the maximum tolerable pressure of about 1×10^{-7} torr.

Provision has been made to incorporate a continuous metal strip to receive the synchrotron radiation which is emitted tangentially from curved parts of the orbit. These strips will be necessary to absorb the large amount of power in the synchrotron radiation at high energy and intensity.

In conclusion it can be said that the objective of developing a vacuum chamber made from radiation resistant material has been achieved. A significant bonus has also been gained in obtaining a lower vacuum pressure than previously available.

Acknowledgment

We wish to acknowledge assistance of Dr. G. A. Voss for suggestions on the original concept of ceramic chambers. Assistance in the detail design of ceramic chambers has been given by G. Thebado and R. Giammanco, and contributions to the electrical work were made by R. Fucalaro. The CEA Vacuum Group under J. Hagopian performed all the evaluation, vacuum testing, and installation of ceramic chambers. Credit for successful manufacturing is due to Mr. Glen Lewis and Mr. Robert Bracken of Litton Industries. Especial credit is due the U. S. Atomic Energy Commission for recognizing the need for ceramic chamber development and supporting the present program at CEA.

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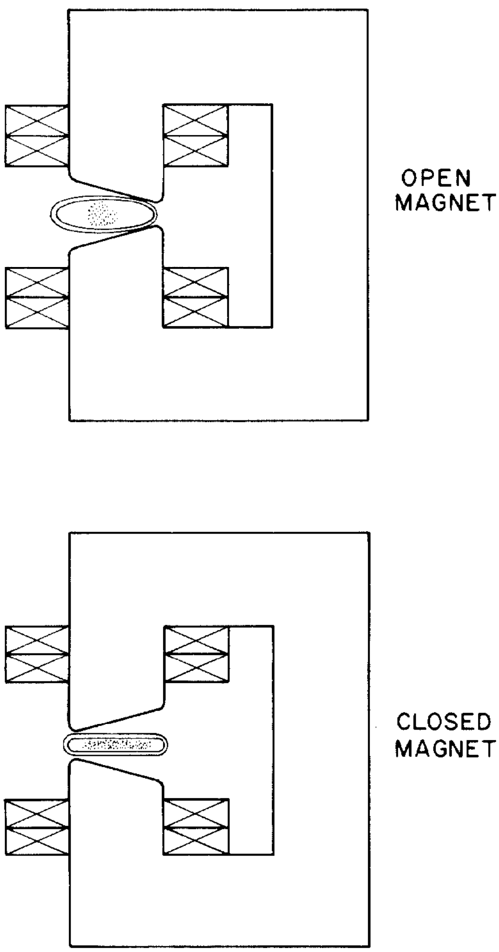


Fig. 1. Pole Tip Profiles.

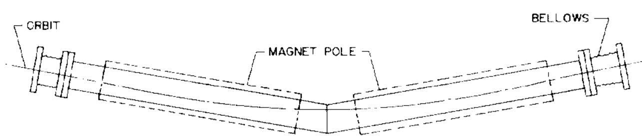


Fig. 2a. Plan of epoxy-stainless chamber.

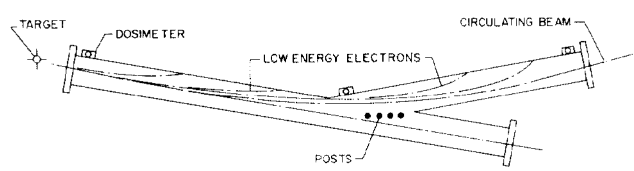
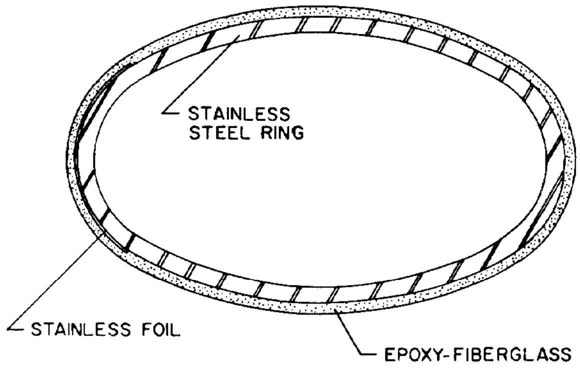


Fig. 2b. Plan of Ejection Chamber.



OVAL RING CHAMBER

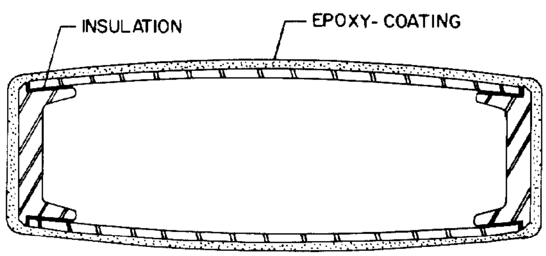


Fig. 3. Solid Side Wall.

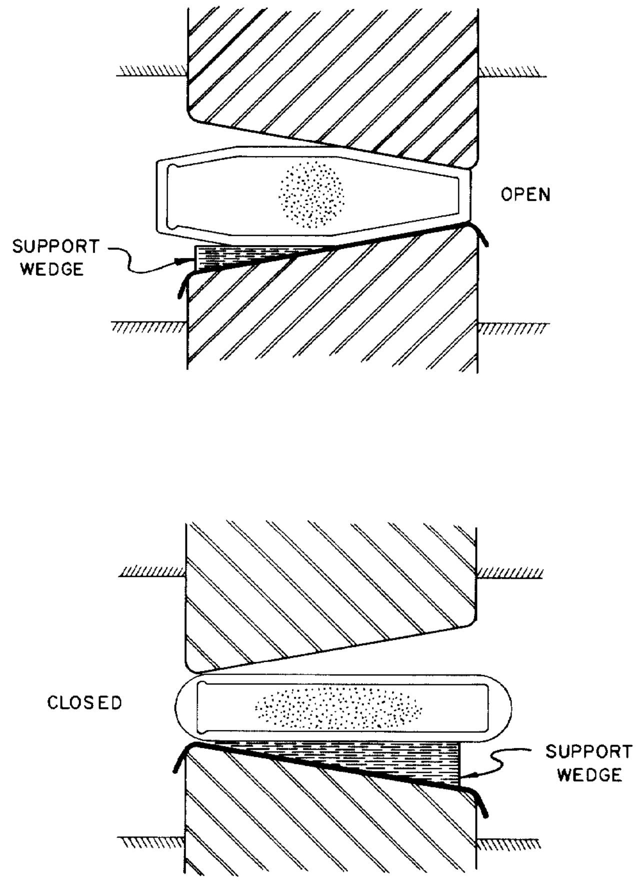


Fig. 4. Ceramic Chamber Sections.

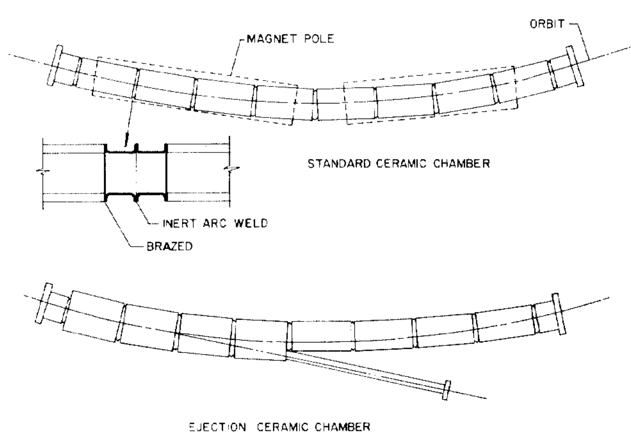


Fig. 5. Ejection Ceramic Chamber.

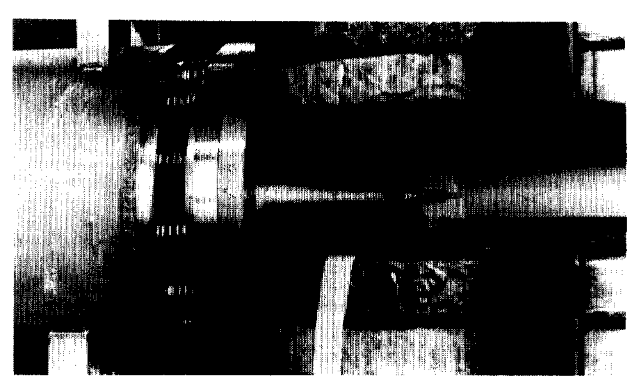


Fig. 6. Terminal Flange, Ceramic Chamber.