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DESIGN OF A VACUUM CHAMBER FOR THE MAGNETS OF A SEPARATED SECTOR CYCLOTRON

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Abstract

The K = 200 separated-sector cyclotron (SSC) of the National Accelerator Centre (NAC) will be used to accelerate both light and heavy ions and requires a vacuum of $\sim 10^{-5}$N/m^2 for sufficient beam transmission. A vacuum chamber which fits into the narrow (60 mm) pole gap of the sector magnets of this SSC and excludes the pole pieces and the main excitation and field trimming coils from the vacuum has been designed. Factors to be considered in such a design and some design alternatives are discussed. The mechanical design of the thin-walled chamber and of the support structure preventing its collapse is described. An analysis of magnetic field perturbations showed that they can be kept sufficiently small. Necessary precautions and methods to achieve this are presented together with results of the analysis.

1. Introduction

The layout of the K = 200 SSC of the NAC is described in another paper submitted to this conference.[1] Briefly the SSC consists of four identical sector magnets with a magnet angle of 34°, two delta resonators with vertical transmission lines connected in a half-wave configuration, and a number of electrostatic and magnetic injection and extraction components. A flat-topping resonator may later be added in one of the two valleys not occupied by the main resonators. The specifications of the SSC and the design of the abovementioned components have been described previously.[2]

It is intended that the SSC be used to accelerate both light and heavy ions up to Kr and Xe, and that the extraction energy be variable. After being pre-accelerated the ions will be injected into the SSC at an orbit radius of about 1 m, and extracted at an average orbit radius of about 4,2 m. They will complete between 50 and 200 turns and travel up to 4 km from injection to extraction. On their path the ions may change their charge state and be lost to the beam by virtue of charge exchange collisions with the residual neutral gas particles. Calculations have shown that for the conditions prevailing in this cyclotron the heavy ion beams of Xe and Kr will be attenuated most strongly, in spite of having to complete relatively few turns[3], and that a vacuum of approximately 10^{-4} and 10^{-5}N/m^2 must be maintained in the chamber for sufficient transmission of light and heavy ion beams respectively.

The vacuum vessels of existing cyclotrons with separated magnets have either been constructed as a single chamber or consist of several sections which are sealed at their interfaces when fitted together. In our case we strongly favour partitioning the vacuum vessel into eight chambers, as is schematically shown in figure 1, for the following reasons. The fabrication, testing, transportation and assembly of the smaller chamber units is much simpler than that of a single octagonal chamber having a very complicated structure, an outer diameter of approximately 9 m and a height of up to 1,5 m. Access to the central region of the SSC and to the resonator and magnet components will be easier, both during the erection and testing of the SSC and later during operation, should repairs become necessary. A sealing method similar to that of the SIN ring cyclotron[4] will be used and will simplify and speed up the procedures for connecting and disconnecting the different chamber units. In this SSC, however, the designing of a suitable vacuum chamber unit for the sector magnets was a prerequisite to deciding whether or not the vacuum vessel could be partitioned since the space in the central region, and more particularly between the sector magnets and the main resonators near injection, is very restricted.

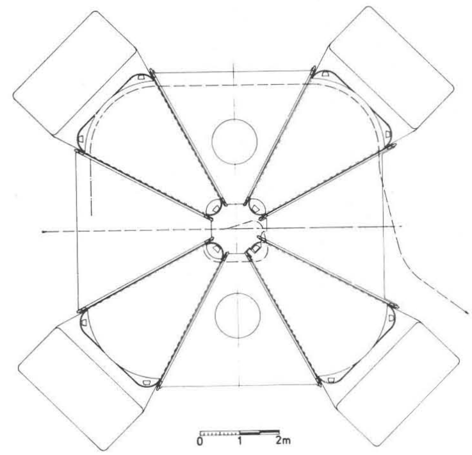

Fig. 1: Octagonal structure of the vacuum vessel for the SSC

2. Considerations for the Design of the Chamber

The factors to be taken into account in designing a vacuum chamber for the sector magnet may be briefly classified in considerations of available space, and vacuum, mechanical and magnetic aspects.

2.1 Geometrical Aspects and Available Space

The vacuum chamber is to be located in the region between or around the two triangular-shaped pole pieces, separated in our case by a constant gap of 60 mm. The geometry of these poles is shown in figure 1. Having an area of more than 6 m^2, they will be nearly 4 m long radially, just over 2,5 m wide near extraction and 0,6 m high. Three spacers will be inserted in the gap at the three corners of the pole pieces to prevent excessive changes of the gap width under the various forces acting on the magnet.

Excitation of the required magnetic fields will be accomplished by two types of coils. The main coils will be fitted around the pole pieces as a single vertical layer of 25 turns, and will have horizontal and vertical dimensions of approximately 25 mm and 0,45 m respectively after insulation and mechanical tolerances have been taken into account. The field trimming coils (approximately 27 pairs per magnet) will consist of curved copper strips spanning the pole gap azimuthally. They will be symmetrically located on the upper and lower pole faces, and together will occupy about 12 mm of the gap width. Their connecting leads will run alongside the rims of the pole pieces. The space available in the pole gap for walls of a possible vacuum chamber is further restricted by the 30 mm required as a beam aperture.

The distance between diagonally opposite magnets in the central region will be about 1,2 m and that between adjoining magnets (including the coils) approximately 0,79 m at the first ion orbit. In order that the energy gain per turn will be sufficiently high during 12th harmonic acceleration, the total mechanical width of the delta resonator, measured between the outer

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electrodes at the first orbit, will be 0,75 m. At injection, therefore, less than 20 mm is available between the main resonator and the magnets for the vacuum chamber structure. At larger radii the available space increases rapidly.

2.2 Vacuum Aspects

In order to pump down the vacuum vessel to a pressure of $1 \times 10^{-5} N/m^2$ (high to ultra-high vacuum) and maintain it with a reasonable pumping capacity, leaks and outgassing from the surfaces of materials in the chamber must be reduced as far as possible. This is particularly important for the magnet sections of the SSC because the narrow pole gap forms a low-conductance passage for any gas emanating from this region. Owing to the high outgassing rates of mild steel and insulation materials[5] the gas loads resulting from epoxy insulated coils and the pole surfaces can increase the required total pumping capacity for the SSC by as much as an order of magnitude. Moreover, the many lead-throughs and joints required for the electrical and cooling-water connections of the coils (typically 1000 for this SSC) can cause the cyclotron to be operationally unreliable. It is desirable, therefore, that the pole pieces and coils be kept outside the high vacuum, preferably in air. Leak testing of the chambers should be possible without first having to assemble them with the pole pieces of the magnets.

2.3 Mechanical Aspects

The chamber should have a simple structure so that as little machining as possible is required and too complicated welding operations are avoided. The chamber must be secure against atmospheric forces when evacuated. Given the space restrictions and pole area described in 2.1, the design of a chamber fitting into the pole gap is therefore a particularly difficult problem. The ease with which the chamber can be assembled with the magnet must also be taken into account. Components such as the coils and the magnetic inflector channel should be as accessible as possible.

2.4 Magnetic Aspects

The strong magnetic fields for guiding and focussing the ion beams are highly critical. Excessive field perturbations caused by the magnetic properties of the chamber walls and/or the provisions for structural support and sealing must therefore be avoided. This is particularly difficult because of the narrow pole gap. Unavoidable field perturbations must be corrected to a tolerable level. The materials and methods used for fabricating the chamber must be carefully chosen with regard to magnetic properties, particularly when they are used inside the pole gap. Should it become necessary to insert the chamber between the pole pieces and the yokes, the walls must be made of a ferromagnetic material or be kept sufficiently thin, so that the MMF required will not be increased considerably.

3. Discussion of Some Design Options

The various alternatives, when considering a chamber design, can be characterized by the location of the chamber walls in relation to the pole pieces. Several sealing methods could be used in conjunction with most of the options presented and they are therefore not discussed explicitly.

3.1 Poles in Vacuum

In this category of chamber designs the poles are completely or partially in high vacuum or in rough vacuum. The characteristics of these design options are shown schematically in figures 2, 3 and 4. In such designs the gas load with which the high vacuum pumps have to cope increases in proportion to the areas of the pole piece and coils exposed to the high vacuum. This load can be reduced by special means such as coating the pole surfaces with nickel, enclosing the coils in vacuum tight stainless steel boxes, etc. The problems caused by having many joints in vacuum can be solved by bringing the connections out of the chamber by means of ducts flanged onto its walls.

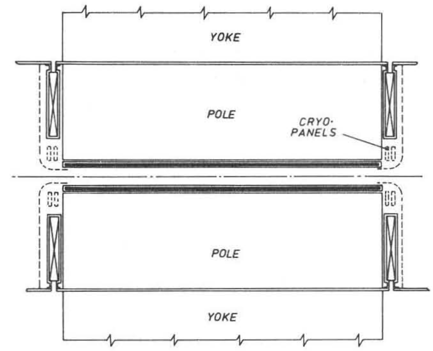

Fig. 2: Chamber design with poles completely in high vacuum.

A variation of this design, indicated by dashed lines in figure 2, and proposed for the heavy-ion SSC of GANIL[6], incorporates a differentially pumped chamber. Excessive amounts of gas are prevented from reaching the beam region by means of low conductance passages between the trimming coils and the additional panels. These slits separate the high vacuum region from a region containing the pole and coils as well as some cryopanels.

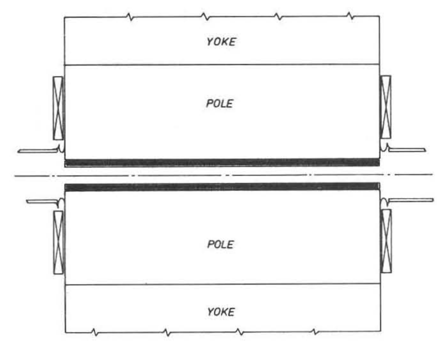

Fig. 3: Chamber design with poles partly in high vacuum.

This design, used in the SIN ring cyclotron[4], leaves the main coils in air and results in a simpler chamber structure, but would still yield relatively high gas loads in our case. However, a variation of this design is used for the single vacuum vessel of the heavy-ion SSC of VICKSI.[7]

The problem of large gas loads can be avoided by completely enclosing each pole and its coils in an additional chamber, as is shown schematically in figure 4.[8] Such a design is used in the K = 220 SSC of the IUCF. The rough vacuum ($\sim 1 N/m^2$) prevents the inner chamber from collapsing. The pressure difference between the two regions may not, therefore, become too large. The field trimming coils can be removed without disassembly of the magnets.

When trying to adapt these possibilities to the design of a separate chamber for our SSC magnets, we have encountered severe design difficulties due to the restricted space between the magnets and resonators at injection. Moreover, much valuable space is taken up in the central region. We have, therefore, rejected these options in favour of the possibility discussed below.

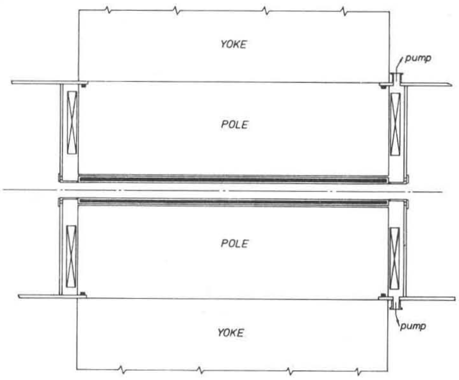

Fig. 4: Chamber design with poles in rough vacuum

3.2 Poles in Air

A vacuum chamber design which leaves the poles and all coils in air is already in use in a large cyclotron with separated magnets, namely at TRIUMF[9], where the ultra-high vacuum requirements are particularly stringent. At TRIUMF the chamber is supported from the foundation and from a separate structure above the cyclotron by long tie rods protruding through holes in the magnets. In our case, however, the required diameters of these rods and holes would be very large in comparison with the width of the pole gap, thus causing excessive perturbations of the magnetic field. A design with narrow holes requires another support technique with short rods or bolts. Such a design is shown schematically in figure 5.

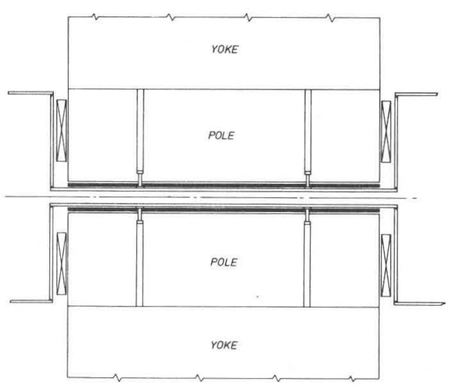

Fig. 5: Chamber design with poles in air and using short bolts for support

The basic structure of the chamber is simple. It consists of a tube with a rectangular cross section and vertically narrow dimensions which extends through the pole gap and has flanges welded onto its sides. Onto the outside of the chamber walls ferrules are welded, into which bolts may be screwed to secure the chamber to the pole faces. A narrow gap is left for the field trimming coils. The supports are distributed in a matrix fashion over the pole area. The short bolts are inserted through holes in the poles. The field trimming coils are mounted on the outside of the chamber and enough space is available for placing their connections alongside the rounded pole edges. The pole gap spacers are left in air and the chamber does not protrude into the central region except for the flanges. Figure 6 shows this design and assembly concept in greater detail. Assembly is relatively simple and provisions can be made for leak testing the chamber without the poles. In the following paragraphs we show that the mechanical design problems of such a chamber can be solved, and that the magnetic field perturbations introduced by such a solution can be limited to tolerable levels.

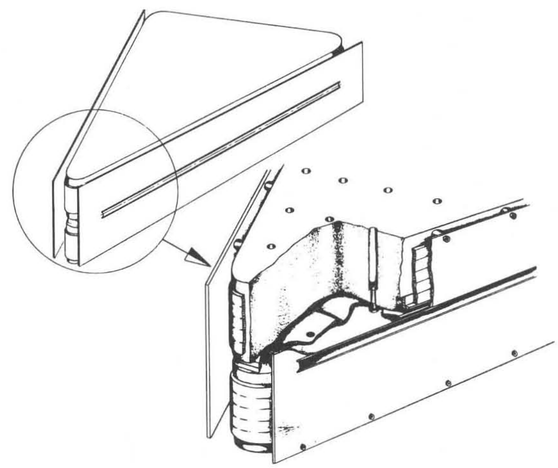

Fig. 6: Assembly of the chamber with the pole pieces

4. Mechanical Design of the Chamber and Support Structure

The first objective in the mechanical design of the chamber was to determine the distribution of the plate-supporting points over the walls and flanges of the chamber which would keep the deflection of any part of the chamber below 1 mm. This limits the wall thickness to 8 mm. As a first approximation to finding the support distribution for the chamber wall, a small area in the centre of the plate was considered, and the equation for the deflection of a plate subjected to a uniform load distribution, and supported by columns arranged in a rectangular grid,[10] was applied. Of the various combinations of column spacings which gave deflections of less than 1 mm, the combination of 410 mm × 250 mm was chosen. These spacings were then applied in a non-rectangular multi-column support configuration better suited to the trapezoidal shape of the chamber. A finite element analysis of this configuration using the system ASKA[11] showed that the deflections did not increase markedly. Moreover, the resultant yield stresses were always below the yield stress of suitable stainless steel grades (e.g. AISA 310).[12] With this configuration 48 supports are required for each chamber wall in the pole gap.

To obtain an estimate of the thickness of the vertical flange, the flange was regarded as a uniformly-loaded simply-supported beam. Stress and deflection values remained acceptable provided that the plate thickness was not less than 15 mm. Thereupon the flange was regarded as being secured along its upper and lower edges to the pole pieces by bolts spaced at intervals of 380 mm and a finite element analysis of the whole chamber structure performed, the results of which confirmed that the stresses and deflections remained acceptable everywhere.[13] Figure 7 shows the deformation obtained by this analysis for the upper quarter of the chamber.

The second objective in designing the chamber was to find a method to suitably secure the chamber to the pole pieces. The maximum load to be borne by any one of the supports does not exceed 8100 N. Various methods for securing the chamber to the pole pieces, such as mutually interlocking T- or L- brackets were investigated. In the end the solution employing bolts and ferrules was chosen. The diameters of the holes and bolts have to

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be kept as small as possible. For the same reason bolts of a non-magnetic material are required. The bolts must have a diameter of 10 mm to safely withstand the applied load without deforming plastically. It is intended that they be torqued to a pre-load of about 8500 N so that there will be no resultant bolt deflection. The diameter of the holes in the pole pieces will be 11 mm for a distance of 50 mm from the pole face, and will then widen to 17 mm to accommodate the bolt heads. The depth of the ferrules must be 13 mm and since the gap between the pole face and chamber wall is 7 mm wide, the ferrules must be sunk into the chamber walls to a depth of 6 mm. The present design of the chamber is shown in figure 8.

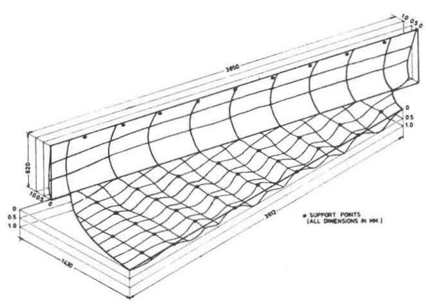

Fig. 7: Deformation of the chamber under atmospheric forces

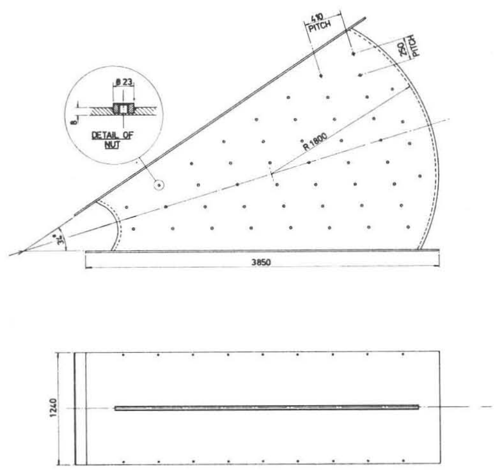

Fig. 8: Present design of the chamber

5. Analysis of Magnetic Field Perturbations

The field perturbations resulting from the installation of this chamber have two different origins, (i) the magnetic properties of the stainless steel used for the plates, ferrules and bolts, and (ii) the holes in the poles.

Special care must be exercised in selecting a suitable austenitic steel grade with a very low magnetic permeability which will not be affected by welding. Measurements on various welded and unwelded plate samples showed that relative permeability values of as low as 1,008 ($\pm$ 0,001) can be obtained for stainless steel (Uddeholm grade UHB Stainless 904), with welds having no apparent effect beyond the tolerance given in brackets. Inserting two 8 mm thick plates of this steel into the 60 mm pole gap will for a given excitation increase the field by 0,21 ($\pm$ 0,03)%. The field perturbations of $\pm$ 0,03% are negligible in practice. For two 15 mm thick plates the equivalent values are 0,40 ($\pm$ 0,05)%. The field increase could therefore be up to 0,2% at the position of the supports because of the increased steel thickness there, but will in practice be much lower since the diameter of the ferrules is small in comparison with the gap width.

The holes in the poles, on the other hand, have the effect of reducing the magnetic field locally. The size and shape of such field bumps were determined for various ratios of D/G (D = hole diameter, G = gap width). It was found that for D/G < 0,5 the field perturbations can be represented by the following parameterization:

$$b(x) = -\, b_o \exp(-x^2/a^2) \qquad (1)$$

where: x = distance from hole axis
$b(x) = 100\Delta B/B$ = percentage field deviation in the median plane, and
$a \simeq 3G/4$.

The value of b_o depends on D/G and increases nearly exponentially with it. For the required holes, i.e. when D = 11 mm, b_o is approximately 0,22%. This can be reduced by an order of magnitude, however, by placing thin washer-shaped shims around each hole on the pole faces. Ferromagnetic washers with an outer diameter of 14 mm would only have to be ½ mm thick in our case to achieve this. Saturation of such shims can be minimized by using thin washers with a large area.

To determine the effect of the local field perturbations on the beam, equation (1) was used to estimate the magnetic flux deficiency and the deviations from the average field index and flutter. For the chosen configuration of supports we calculated that the maximum phase slip of the beam over the radial range of one field trimming coil due to the magnetic flux deficiency will be about 0,6^{o} for unshimmed holes. If 'fine tuning' with neighbouring field trimming coils is employed the maximum phase deviations will be less than 0,3^{o}. Deviations from both radial and vertical betatron frequencies were estimated to be less than 0,015. These values will be reduced by an order of magnitude for shimmed holes, but are also acceptable as such in this SSC.

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