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MAGNET SECTOR DESIGN FOR A 15-GeV SUPERCONDUCTING CYCLOTRON

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Summary

Pole shape designs are presented which maintain focused and isochronous orbits in the two stages of a superconducting ring cyclotron kaon factory (CANUCK). The first stage of 15 sectors takes a 100 μA proton beam extracted from TRIUMF to 3.5 GeV. The second stage of 42 sectors continues the acceleration to 15 GeV. The orbit properties have been determined using a median plane magnetic field computed from the current distribution in the coils and in current sheets simulating the saturated steel. The design process and the effects of various factors, including softness of the edges, cross-section of the coils and negative field gullies, will be described.

Introduction

There has been growing interest in proton accelerators combining high intensity (100 μA or more) and high energy (10 GeV–20 GeV).[1] These accelerators can be used for the production of intense beams of kaons, antiprotons, neutrinos and other particles. For the TRIUMF facility such a kaon factory would be a logical extension of its scientific activities.

One accelerator option (CANUCK - standing for Canadian University Cyclotrons for Kaons) consists of two high energy superconducting isochronous ring cyclotrons. This paper describes the design process of the magnet sectors of these machines. A list of some characteristic parameters of a two-stage cyclotron combination on which the design study has been concentrated, is given in Table I.

Table I
Cyclotron specifications

Stage	I	II
Injection energy	430 MeV	3.5 GeV
Extraction energy	3.5 GeV	15 GeV
# sectors	15	42
Radius (max)	10.1 m	41.4 m
Radius (min)	7.5 m	40.6 m
# cavities (1 MV)	9	54
RF frequency	46 MHz	115 MHz
Harmonics	10	100
Excitation currents	2.1×10^6 At	2.5×10^6 At
Coil dimensions	8×60 cm^2	8×60 cm^2
Sector field	4 T	5 T
Gap width	7 cm	7 cm

Each magnet is excited by one pair of main superconducting coils generating a field of about 4 T (Fig. 1). Because only protons are to be accelerated, the isochronism can be maintained by increasing the azimuthal sector width with radius (flare) enabling the power requirement for trim coils to be kept very low. Reversed valley fields up to -1 T increase the flutter, thus reducing the spiral angle requirement. The radial betatron frequency ν_r varies roughly as γ, and crosses several resonances;[2] ν_z can in principle be kept constant by shaping the sectors.

In this paper we will restrict ourselves mainly to the 15 sector magnet design, many aspects of the 42 sector cyclotron being similar.

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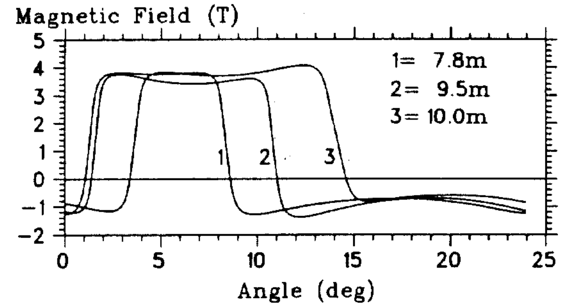

Fig. 1. Magnetic field vs. azimuth for the 15 sector cyclotron.

Computation Sequence

In order to determine the orbit properties in the proposed cyclotrons a series of computer codes is employed for which a flow diagram is given in Fig. 2. The main steps in this sequence are:
– a matrix code using elementary cyclotron relations to determine the basic sector shape (code RING).
– a code to define the coordinates of the physical coil to be put around the basic sector shape.
– a magnetic field computation code (COILS).
– an orbit code using calculated field data in the median plane (CYCLOPS).

It was found that Fourier analysis of the fields gave strong variations in the radial derivatives of the Fourier components, such that analytical expressions for the betatron frequencies from general orbit theories[3,4] did not give adequate results.

Basic Sector Shape

A matrix method is used to obtain the basic sector shape. For a separated sector cyclotron with field free valleys exact expressions have been given by Schatz.[5] Craddock et al.[6] have given the method to

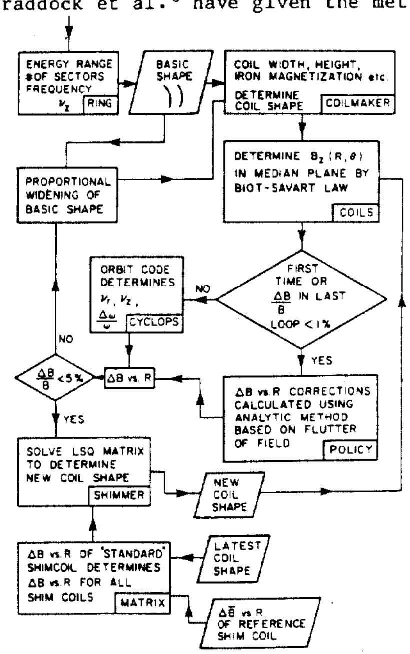

Fig. 2. Flow diagram of computation sequence.

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extract the spiral angle as a function of the vertical betatron frequency from hard edge expressions. This allows us to choose a constant ν_z, avoiding any resonance crossings. The code now includes the effect of the considerable return flux between the superconducting magnet sectors, and the softness of the edges (taken into account via the TRANSPORT K_1 and K_2 constants[7]). The program is capable of handling negative fields in the valleys, including gullies of different widths alongside the hill boundaries.[8] The effect of radial field gradients has also been incorporated.

In the case that the ion trajectories have equal path lengths in the gullies at both sides of a sector, an expression for ν_z results which contains only quadratic and fourth power terms in the spiral angle. This demonstrates in this case invariance of orbit properties under reversal of the spiral direction of the sectors. In general this property is not true, and there is a favoured location for a gully. This result can easily be checked with analytic formulas for ν_z and ν_r using Fourier coefficients of the field.[3]

With a minor change of some definitions the revised code describes the sectors of the MURA-type radial sector ring accelerator.[9]

For the 15 sector machine the matrix code predicts a maximum spiral angle of 72° when soft edges are used instead of 68° for hard edges.

Magnetic Field Computation

The contribution to the magnetic field from the saturated pole pieces may be calculated from an equivalent uniform charge distribution on the pole surface,[10] or equivalently from an infinitely thin current sheet surrounding the pole.[11,12] The median plane axial field produced by the excitation coils and the equivalent current sheets has thus been computed via the Biot-Savart law using the linear segment approximation in our modified version of the AECL COILS code.

The yoke contribution to the magnetic field cannot be calculated with the uniform magnetization assumption. This part has to be obtained from a 3 dimensional magnet code, like GFUN,[13] requiring extensive computation times. Two-dimensional models such as POISSON are not applicable to our geometry although they were very successful in the design of compact superconducting cyclotrons. Iterations towards isochronism involve changes of the pole shape and of the main coils. These changes have negligible influence on the yoke contribution to the field. It is therefore possible to separate the yoke contribution, which requires a one-shot calculation with GFUN, and the contribution due to the main or equivalent coils, which are done by the much faster code COILS.

The finite width of the coils is taken into account by defining N equally spaced coils each with a current I_{total}/N. In practice we take N=1. The relative deviation $\delta B/B$, where B is the mean field, between the N=1 and N=∞ calculation amounts to less than 2×10^{-4}.

When the contribution of adjacent sectors is taken into account the average field for the 15 sector cyclotron is reduced up to 25%. This is due to the large reversed fields. For the 42 sector machine with higher spiral and smaller relative radial range the reversed fields are largely located outside the orbit region such that this reduction is only 5%.

Ring Cyclotrons with Return Field Gullies

The return flux between the sectors ranges from −0.5 T to −0.9 T in the 15 sector design. This has the favourable effect of increasing the flutter and reducing the spiral angle requirements. To provide a localized path for the return flux, giving better defined field free regions between the sectors, "gullies" (reverse field regions provided by steel outside the coils) have been introduced. Gullies provide the advantage of additional edge focusing, increased flutter and reduced spiral.

Gullies either on one or on both sides of the pole have been investigated with the matrix code RING. A single gully on the edge with least spiral seems to be most effective, at least for the 3 GeV, 15 sector design. The sector shape obtained for this machine with an initial gully path length of 0.4 times the hill path length has been investigated with the codes COILS and CYCLOPS. For this particular case RING predicts ν_z= 4.5 and $\tan\varepsilon_{max}$=2.52 (see Fig. 3).

The present gully designs do not provide sufficient iron for the return flux, so that field intensities of up to −0.5 T still exist between the sectors.

Coil Shape Determination

Improvements to the average field and the betatron frequencies are realized by an iterative procedure in the shape of both the magnet poles and the main excitation coils.

In our initial work we found the differential effects of an azimuthal widening of the whole magnet sector. From this the necessary change in coil shape was calculated in order to correct the isochronization error. This essentially local method took many iterations (~20) to reach isochronism ($\delta B/B \leq 5 \times 10^{-4}$); there was insufficient control over the parts of the coil outside the orbit area, such that awkward shapes resulted due to discontinuities with the other parts.

A new, global, method was developed. The method involves the calculation of the overall effect of the addition of elemental ("baby") shim coils at various places around the main coil, carrying the same current density as the main coil and whose area can be varied. The sizes of the added shim coils are determined by a least-squares method to reduce deviations of the field. The old coil plus the collection of newly added baby coils defines the new coil shape.

An arbitrary coil with current I generates a field in the median plane $B_z(r,\theta)$. The quantity $\tilde{B}(r) = (N/2\pi)\int_0^{2\pi/N} B_z(r,\theta)d\theta$, where N is the number of sectors, can be evaluated, and with this the deviation field $\delta\bar{B} = \tilde{B}-\bar{B}$, where $\bar{B}(r)$ is the azimuthally averaged field at radius r, as determined by the code RING. $\bar{B}(r)$ increases roughly as the relativistic γ-factor. Isochronization requires $\delta\bar{B}$=0.

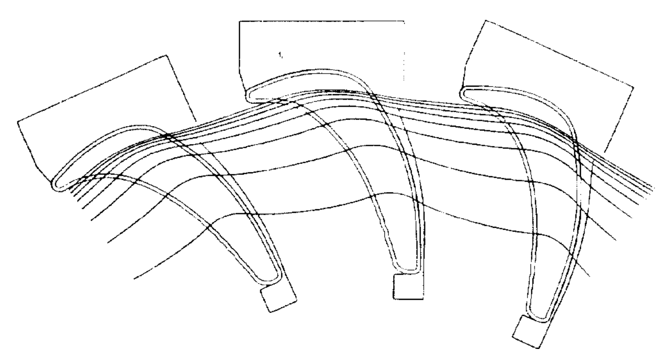

Fig. 3. Sector design and orbits (at 0.5 GeV intervals) for the 3.5 GeV cyclotron using single gullies.

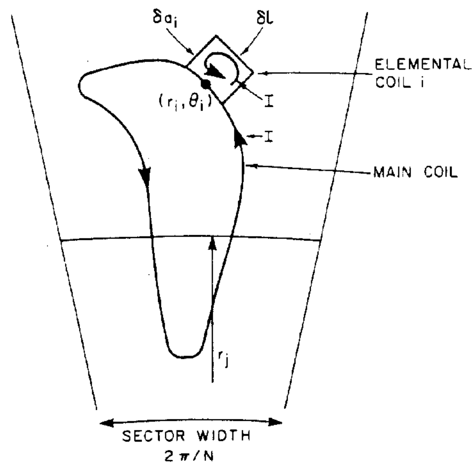

Fig. 4. Shim coil technique.

A shim coil at position (r_i, θ_i) of the main coil contributes to the average field at radius r_j (see Fig. 4). This contribution δB_{ij} is linear in the area of the shim coil, or $\delta B_{ij} = V_{ij}\,\delta a_i$ where δa_i is the width of the shim coil (and fixed length $\delta\ell$ along the main coil). The contribution to the mean field at radius r_j of all shim coils is

$$\delta B_j = \sum_i V_{ij}\,\delta a_i \ . \qquad (1)$$

In matrix notation:

$$\underline{\delta B} = \underline{\underline{V}}\ \underline{\delta a}\ , \qquad (2)$$

where $\underline{\delta B}$ is the vector of field deviations due to the applied shim width vector $\underline{\delta a}$. The matrix elements V_{ij} can easily be calculated. Putting $\underline{\delta B} = \underline{B} - \underline{\bar{B}}$ the change $\underline{\delta a}$ yielding isochronism is computed using a least-squares criterion.

An important simplification can be made. To a good degree of accuracy the contributions δB_{ij} are only dependent on the distance $r_{ij} = |r_i - r_j|$, not on the actual coil shape. It suffices to calculate the field of one shim accurately with COILS and obtain the effect of all the other shims from this; a $1/r_i$-dependence due to the azimuthal averaging has to be taken into account for the strength of the elements.

The predicted $\bar{B}$ after a coil change, and the calculated $\bar{B}$ (using COILS) were found to be in excellent agreement (corrections being predicted to ~90% accuracy). When the field is sufficiently isochronous ($\delta\bar{B}/\bar{B} < 10^{-2}$), the $\delta\bar{B}$-error is taken from the isochronization error in the orbit code CYCLOPS.

In Fig. 5 the deviation $\delta\bar{B}$ is shown before and after such an iteration step. A matrix of 200 shim coils and 400 radii was used. The resultant coil change as a function of the shim number are generally of the order of a few mm. The ν_r and ν_z-behaviour is shown in Fig. 6. It takes ~3 more iterations to bring $\delta\bar{B}/\bar{B}$ down to 2.10^{-4}.

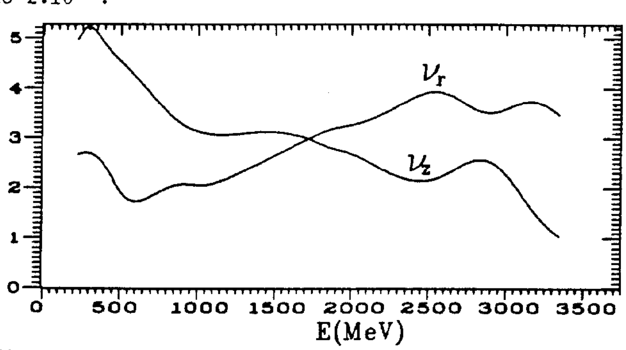

Fig. 6. Resultant ν_r and ν_z vs. energy.

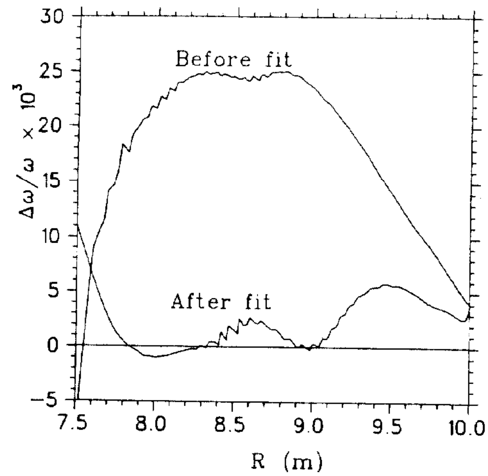

Fig. 5. Isochronization error before and after a single iteration step.

In the new method the effect of shim coils over the whole radial range of the main coil is considered, and generally very smooth coil changes result. There is a freedom to force the required coil changes to either side of the sector by adjusting the weighting factors for the shim coils in the least-squares procedure. This is used to alter the betatron frequencies.

For a 2 GeV orbit in the 15 sector machine the effect of one shim of length 1 cm and width 1 mm is a phase slip of 0.5° and a change in ν_z of 0.003.

Conclusion

A rapid method has been described for obtaining the magnet sector shapes used as a basis for a complete design of the superconducting magnets of CANUCK.

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