Paper presented at 12th International Conference on High Energy Accelerators, Fermilab, August 11-16

TRI-PP-83-62
Aug 1983

CA8407176

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MAGNET FIELD DESIGN CONSIDERATIONS FOR A HIGH ENERGY SUPERCONDUCTING CYCLOTRON

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Summary

This paper reports the pole shape designs for a two stage superconducting isochronous cyclotron combination (CANUCK) to accelerate 100 µA proton beams to 15 GeV. The pole shape of the 15 sectors of the first stage 3.5 GeV proton cyclotron provides isochronism over the full energy range and a constant axial tune over all but the lowest energies. Progress on the pole design of the 42 sector 15 GeV second stage is also reported. The magnetic fields are computed from the current distribution of the superconducting coils and the infinitely thin current sheets simulating the fully saturated poles. A least squares method is used to minimize deviations from isochronism by adjusting the size of various elemental shim coils placed around the main coil. The method to obtain the desired axial tune is described.

Introduction

The possibility of employing isochronous cyclotrons to accelerate protons to energies in the multi GeV region has been discussed by a number of authors.[1] Because of their cw beam the beam current in these machines can be of the order of 100 µA or more, one or two orders of magnitude higher than the present day synchrotrons. This makes high energy cyclotrons ideal accelerators for a kaon factory (15-30 GeV, intensity 50-100 µA), where high intensities of kaons and other secondary particles are required. The physics need for kaon factories has been extensively emphasized in a number of conferences and workshops.[2]

The TRIUMF facility[3] consists of a six-sector isochronous H^- cyclotron with a variable energy up to 520 MeV and a maximum beam current of 130 µA. Several options for a kaon factory accelerator are being investigated: one is based on synchrotrons (either a 15 GeV 30 Hz rapid cycling synchrotron or a 30 GeV synchrotron with transition energy higher than the final energy), the other to employ a cascade of two superconducting ring cyclotrons. In this last option the time structure of the beam is nearly identical with the injector cyclotron, and the full current of TRIUMF can be used for further acceleration.

A list of parameters of the cyclotron combination CANUCK (Canadian University Cyclotrons for Kaons) is given in Table 1 and a proposed site layout is illustrated in Fig. 1. The 3.5 GeV cyclotron would have a radius roughly equal to that of TRIUMF while the second stage 15 GeV cyclotron would be 4 times larger and require a tunnel several meters wide.

As pointed out by several authors[4,5] the unavoidable passage of integer and half integer resonances during acceleration can be accomplished successfully. The vertical tune ν_z can in principle be kept constant by shaping the sectors. In recent papers the sector design for the 3.5 GeV cyclotron[6] and resonances and extraction[5] were discussed; in this paper we present new results regarding the axial focusing scheme for the 3.5 GeV cyclotron, and present the sector shape for the 42 sector 15 GeV cyclotron.

General Principles

Some basic parameters of the accelerators were fixed by the following requirements:
- The energy range of accelerated particles requires a cascade of two superconducting cyclotrons with a field of 4 to 5 T, one cyclotron bringing the energy from 450 MeV to 3.5 GeV, the other from 3.5 GeV to 15 GeV.[1]
- The number of sectors N for each cyclotron is chosen such that the horizontal tune ν_r does not reach the π-stopband, which occurs for $\nu_r \approx \gamma = N/2$ where γ is the relativistic factor. Thus there are 15 sectors for the lower and 42 sectors for the higher energy cyclotron.
- The cyclotrons are proton machines only, hence the shimming of the magnetic field for isochronization and axial focusing can be done by designing the appropriate shape of the sectors, i.e. of the magnet poles and of the superconducting coils around them. Therefore the power requirement for the trim coils can be kept very low.
- Because each magnet has one pair of excitation coils, giving about a constant field in the sector, the isochronization of the machine has to be achieved by flaring (increasing azimuthal width) of the sectors and the axial focusing by spiralling of the sectors.

The initial shape of the sectors and hence of the coils around them is found by a hard edge matrix method.[7] The restrictions imposed to the geometry of the orbits in a ring cyclotron with N sectors are: a) isochronism, i.e. for the path length L in one period: $L = 2\pi\bar{R}/N$, where $\bar{R} = \beta R_c$ with $R_c = c/\omega$ the cyclotron radius, and b) closure, i.e. the bending angle in one period is $2\pi/N$. These conditions immediately give the orbit length in the hill and in the valley for each energy considered, and allow determination of the spiral angle necessary for a fixed value of the axial tune.[1] This in turn gives the edge focusing angle at the entrance and exit of the sector magnets, so that a direct multiplication of the transfer matrices can be performed, providing the beta function and phase advance per period for horizontal and vertical motion, and the horizontal dispersion function.

A computer code based on these considerations[1] has been extended[8] and can include fringe field effects (which tend to weaken the axial focusing), constant reversed fields in the valleys (which simulate the effect of the reversed fields between the sectors due to the superconducting coils) and the use of gullies alongside the hills.[9] The gullies, a part of the iron return yoke across the orbit region, with a gap in the median plane

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

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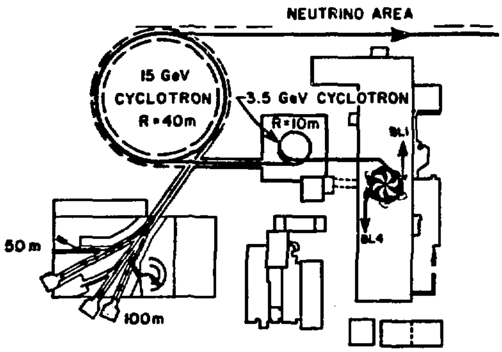

Fig. 1. Layout for CANUCK cyclotrons at TRIUMF.

for passage of the accelerated particles, increase the flutter and provide extra edge focusing. They can give rise to field free straight sections between the sectors in which superconducting RF cavities can be placed and which can be used for injection and extraction.

The magnetic field from the fully saturated pole pieces is calculated from the equivalent infinitely thin current sheets surrounding the poles.[10,11] The code COILX obtains the median plane field of the poles and the main coils by partial integration of the Biot-Savart law employing the linear segment approximation (Fig. 2 gives the field in a sector of the 3.5 GeV cyclotron).

Runs with POISSON on the 3.5 GeV cyclotron simulating the ring structure have demonstrated the importance of the contribution of the magnet yokes to the average magnetic field. For better precision the three dimensional code GFUN[12] has also been used. However, here only a one-shot calculation is required since changes in the coil and pole shape, necessary for fine trimming of the field, have negligible influence on the yoke contribution to the field.

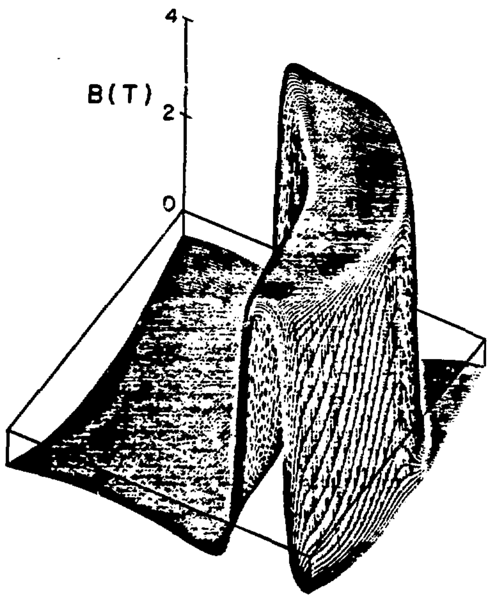

Fig. 2. 15-sector cyclotron field.

A least squares method is applied to minimize deviations from isochronism. It consists of the adjustment of the size of elemental shim coils placed at various locations around the main coil. A shim coil generates roughly a dipole field and affects the field at all other places. However to a good approximation the contribution of a shim coil at radius r_i to the azimuthally averaged field at radius r_j is only dependent on the distance (r_i-r_j), not on the actual coil shape, so that a field calculation for one shim (with code COILS) is needed, and the effect of all other shims is obtained from this. Due to the azimuthal averaging a $1/r_i$-dependence has to be taken into account for these shims. We mention that a similar method (with iron shims) has been applied for shimming the TRIUMF cyclotron.[13]

For isochronism the coil change may be applied to either side of the sector but by adjusting the proportion using weighting factors for the shim coils the axial tune may also be changed by small amounts. In order to achieve a constant axial tune, thereby avoiding any resonance crossings, larger tune shifts had to be realized. We therefore applied a linear shift with radius of the sector (zero shift at the lowest energy radius, maximum shift at the maximum energy radius), leaving the azimuthal sector width constant (see Fig. 5). The resultant change in axial focusing is used to determine the change to be applied for constant axial tune. In this process the isochronization is hardly affected ($\Delta B/B < 2 \times 10^{-3}$), and can be adjusted independently with the shim coil technique.

<u>The Sector Designs</u>

For the 3.5 GeV 15 sector cyclotron 200 shim coils are used, their effect being calculated at 400 radii. For the first iteration step the resultant coil change as a function of the shim number is given in Fig. 3. It is seen that this figure is symmetric with respect to location index 300 and 800 (marking bottom and top of the coil, respectively), showing that in the L.S. procedure the required coil changes have been put equally on both sides of the coil (equal weights). The deviation from the isochronous field is less than 2×10^{-4} in 4 iteration steps with the shim coil method and final coil changes are of the order of a few millimeters. The predicted $\overline{B}$ after a coil change and the calculated $\overline{B}$ (with COILX) are in excellent agreement (Fig.4), demonstrating the accuracy of the method.

Figure 5 demonstrates the axial tuning technique. For the initial proton energies the flutter is too high

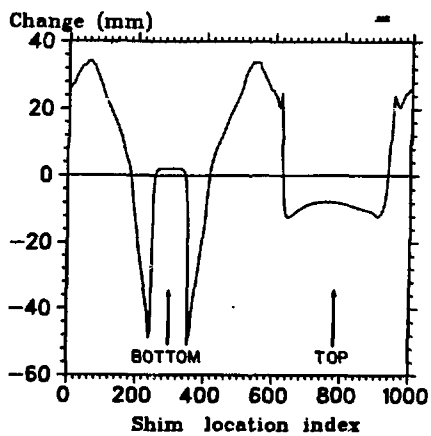

Fig. 3. Coil change vs. shim number.

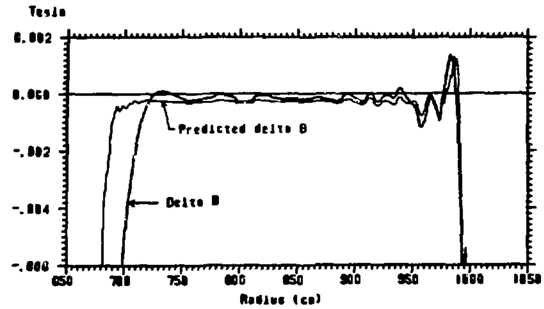

Fig. 4. Predicted $\delta\bar{B}$ and calculated $\delta\bar{B}$.

(zero spiral) to give the low constant axial tune of higher energies. However the resonance crossings occur very fast because of the high energy gain per turn. The maximum spiral angle of this cyclotron is 75°.

Figure 6 shows the sector shape for the 15 GeV machine and the isochronization curve. The axial tune is about constant over most of the radial range except for the outer radii where the design remains to be completed.

Conclusion

The shimming and tuning technique has been applied to both cyclotrons, to give isochronism, and constant axial focusing over most of the radial range.

We would like to thank J. Chuma for computer calculations and graphics.

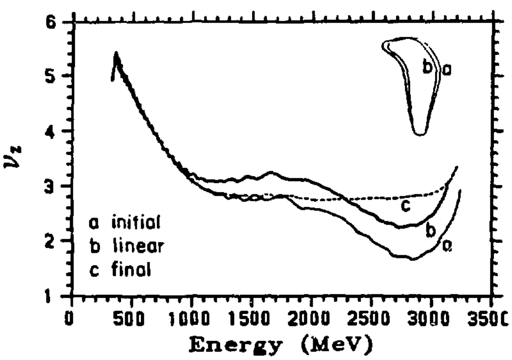

Fig. 5. Axial tuning technique.

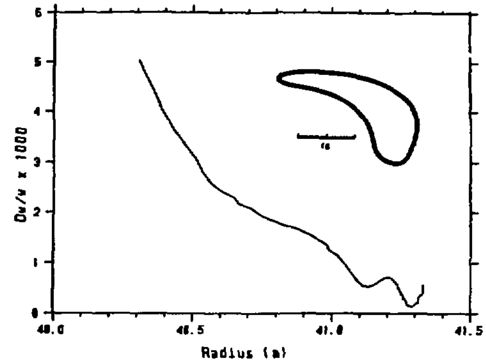

Fig. 6. Isochronism and sector shape 15 GeV cyclotron.

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