CHROMATICITY CORRECTION OF SMALL PROTON SYNCHROTRON FOR CANCER THERAPY

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Abstract

For the 230 MeV proton synchrotron for cancer therapy designed for PMRC, the chromaticity correction is investigated for the reduction of the injection loss. It can be performed by using twelve sextupole printed coil magnets installed into the focussing and defocussing quadrupole magnets of the ring. Also it is shown that the chromaticity can be corrected by sextupole magnets inserted into four quadrupoles in the LLUMC synchrotron.

Introduction

A dedicated proton accelerator for cancer therapy is designed[1]. It is a slow cycling and separated-function synchrotron with six superperiods. To reduce the injection loss of a synchrotron, it is necessary to decrease the tune spread. There are two sources of tune spread; one is space charge effect, and the other is related to chromaticity. The former determines eventually the upper limit of the beam intensity. The tune shift allocated in the design is 0.15. The chromaticity is defined as $\Delta\nu = \xi\delta = \xi\Delta p/p$, where $\Delta\nu$ is tune spread, ξ is chromaticity, and $\delta = \Delta p/p$ is momentum spread. It is necessary to prepare chromaticity correction in advance for the synchrotron of medical use to get the design intensity from the beginning of operation, because the patients should not be forced to be motionless for a long irradiation time. Fermi National Accelerator Laboratory designed and built a dedicated 250 MeV proton synchrotron for Loma Linda University Medical Center(LLUMC)[2]. The beam tuning process showed chromaticity correction is crucial[3]. A small synchrotron, MIMAS, was built as an injector of SATURNE[4]. Since momentum spread of the injection beam is large, the chromaticity is carefully corrected by superposing sextupole field on focussing and defocussing quadrupole field. This correction method is conceptually applied to the PMRC design.

Chromaticity Correction

Chromaticity is related to the sextupole error component in the dipole magnets. Chromaticity correction is the cancellation of this error component by the excitation of additional sextupole magnets. Horizontal and vertical chromaticities are given by[5],

$$\xi_x = (4\pi)^{-1}\int_c (2\lambda\eta - K)\beta_x ds, \text{ and}$$
$$\xi_y = (4\pi)^{-1}\int_c (K - 2\lambda\eta)\beta_y ds,$$

where, ξ_x and ξ_y are horizontal and vertical chromaticities,
$\lambda = (2B\rho)^{-1}(\partial^2 B_y/\partial x^2)$,
η is dispersion function,
$K = (B\rho)^{-1}(\partial B_y/\partial x)$,
β_x and β_y are β-functions, and
the integral is around the ring.

From these equations, correction sextupole magnets(λ) should be set at the places where dispersion(η) is not zero and β-functions are large. β_x is large and β_y is small at focussing quadrupole magnets and vice verse as shown in Fig. 1 for PMRC ring. The ring has six focussing quadrupole magnets and six defocussing ones. They are 200 mm long each. So by setting sextupole magnets on the same places of the quadrupole magnets around the ring, connecting them in series to two groups according to their location of focussing and defocussing sections, and exciting them with two power supplies, ξ_x and ξ_y can be controlled to get the optimum values. Since there are six focussing and six defocussing magnets in the ring, twelve sextupole magnets are located at the position of quadrupole magnets.

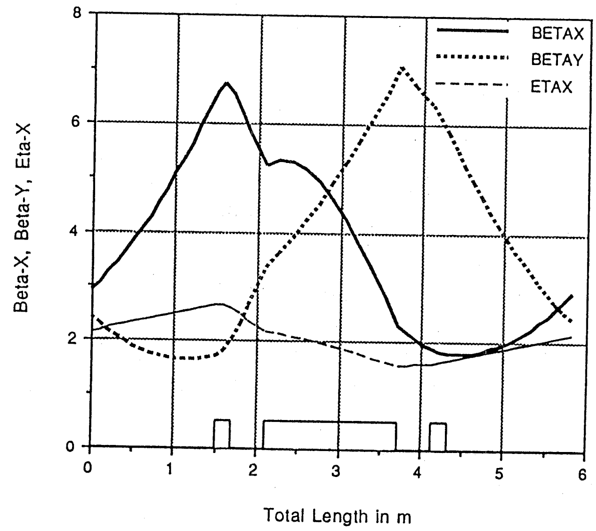

Fig.1 β- and η-functions of 230 MeV PMRC proton synchrotron.

Figure 2 shows the chromaticities calculated by DIMAD code for different error field in the bending magnets. The horizontal and vertical natural chromaticities are -0.21 and -2.62 respectively. It is assumed that the correction sextupole field of 200 mm long is superimposed on the quadrupole field. The most left-side and right-side plots in the figure correspond to the error fields $\Delta B/B = -8\times10^{-4}$ and $+8\times10^{-4}$ at ±50 mm from the center.

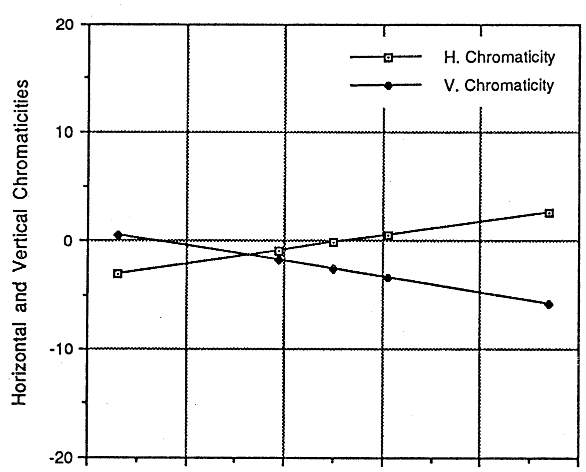

Fig.2 Calculated chromaticities for various error sextupole strengths in dipole magnets.

Figure 3 shows the correction field strength of the sextupole magnets to give $\xi_x = \xi_y = 0.0$ for the error components shown in Fig. 2. The design momentum spread of the injection beam $\delta = \Delta p/p$ is ±0.3 % for this ring.

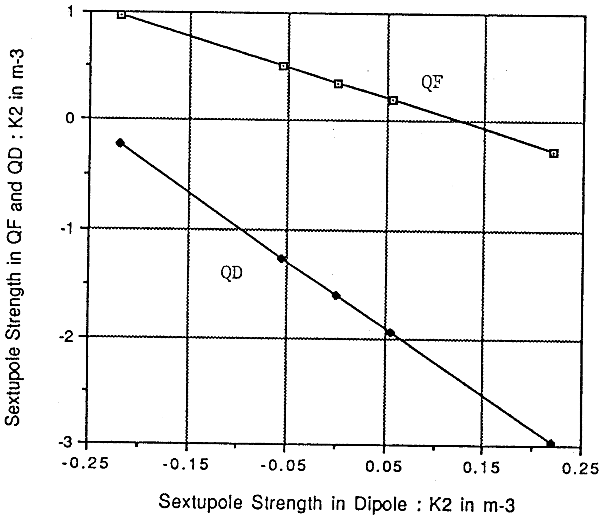

Fig.3 Correction sextupole strengths to make chromaticity zero for various error sextupole strengths in dipole magnets.

Printed coils

A medically dedicated accelerator should be as small as possible. As calculated above the field strength of the correction sextupole magnets is weak for PMRC ring, it is possible to make the magnets as spiral coils on printed circuits. Two copper coils are printed on the both sides of a thin printed circuit board. The current flows from the one outside terminal to the center, through the board to the other side of it, and then from the center to the other outer terminal with the same angular direction to generate the same magnetic field of the first one. The magnet current is estimated as less than 5 A for 20 turn coil for each magnet pole. They can be installed inside the quadrupole magnets without occupying extra spaces in straight sections. This method was developed at SACLAY[6].

Chromaticity correction calculation for LLUMC ring

Before shipping the proton synchrotron to LLUMC, California, thorough tuning and beam tests were carried out at Fermilab. The lattice of the Fermilab design is characterized by edge focussing to make the ring as small as possible. It has four superperiods, and consists of four long straight sections and eight 45° bending magnets. A couple of bending magnets are separated by short straight sections and a 100 mm long quadrupole magnet which changes the tune for slow beam extraction. The design horizontal and vertical tunes are 0.60 and 1.322, and the measured tunes are close to the design values. The horizontal and vertical natural chromaticities are 0.651 and 1.25, but the measured horizontal chromaticity is ranging -12.7 to -22.2 and the vertical chromaticity is 8.6 to 14.6 during excitation of the bending magnets. These chromaticities produce big tune spreads of $\Delta\nu =$ ±0.02515 to ±0.0666 for $\delta = \pm 0.3$ %. Since this was supposed to be a cause of beam loss at injection as shown in Fig. 4, error field correction by shim was considered but not realized.

The calculated chromaticities for various error fields in the dipole magnets are shown in Fig. 5. The error field dependence of chromaticity is bigger than

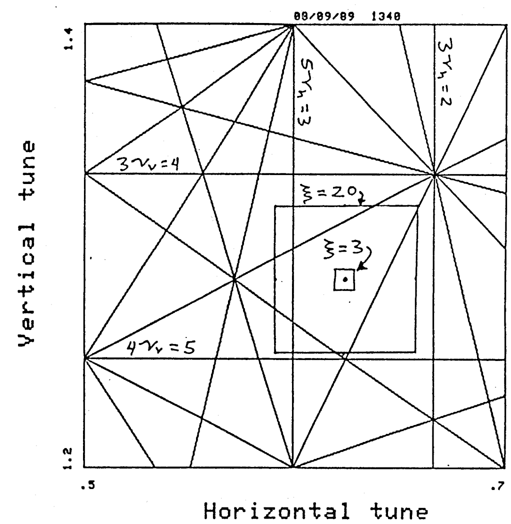

Fig.4 Tune diagram of LLUMC synchrotron lattice. It is seen that when chromaticity $\xi = 3$, the operating point are in the stable region, when $\xi = 20$, resonance crossing occurs[3].

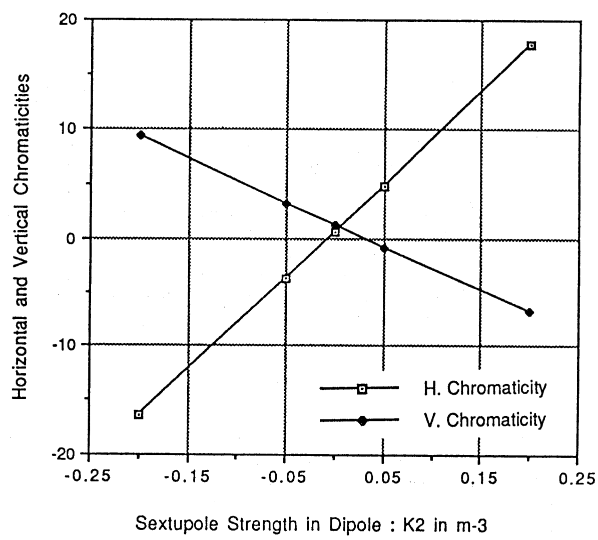

Fig.5 Chromaticities for various error sextupole strengths in dipole magnets of LLUMC synchrotron.

the PMRC design. Dispersion is almost constant and about 9 along the long and short straight sections. If sextupole correction magnets of 100 mm long are installed into the four quadrupole magnets and connected in series, the chromaticity can be corrected as shown in Fig. 6. In this case, an error field of $\Delta B/B = -8\times10^{-4}$ at ±50 mm from the center is assumed. The calculated chromaticities are $\xi_x = -16.5$ and $\xi_y = +9.3$ without correction. Since the variable is one, both the horizontal and vertical chromaticities can not be zero simultaneously. However, both chromaticities can be smaller than the natural chromaticities with correction. Chromaticity correction by sextupole magnets installed in the quadrupole magnets which change the tune during slow beam extraction is simpler and more flexible than the correction by shims installed in the bending magnets. Moreover, it does not need to disassemble the bending magnets.

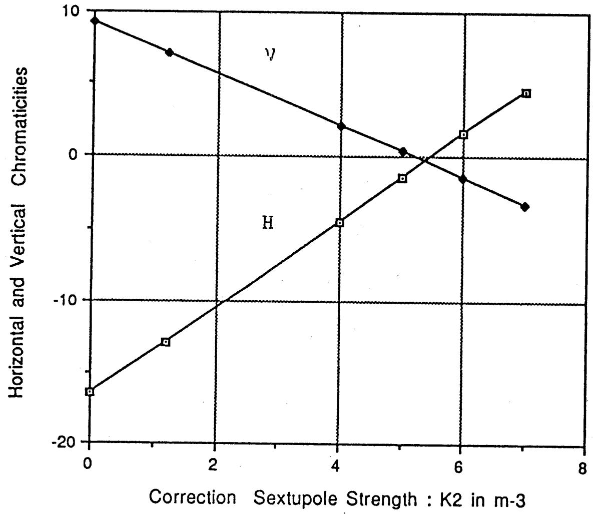

Fig.6 Chromaticities generated by an error sextupole strength are corrected by sextupole magnets installed in quadrupole magnets.

Conclusion

For PMRC ring, the injection loss will be improved with chromaticity correction using twelve sextupole printing coil magnets installed inside of quadrupole magnets. These twelve magnets are excited with two independent power supply to control the horizontal and vertical chromaticities respectively. It is shown that the chromaticity can be corrected by sextupole magnets installed in the quadrupole magnets in the LLUMC synchrotron.

References

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