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CHROMATIC CORRECTIONS FOR LARGE STORAGE RINGS*

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ABSTRACT

The second-order achromat principle is used to correct the chromatic aberrations in a representative 75 GeV/c storage ring using four families of sextupoles. The ring chosen to illustrate the essential principles of the design procedure has the following general characteristics:

Beam Energy	=	75 GeV
Beta*(x)	=	1.6 m
Beta*(y)	=	0.1 m
Circumference	=	25 km

INTRODUCTION

Beam transport systems containing only linear elements (dipoles and quadrupoles) have chromatic aberrations. These aberrations have two undesirable effects in storage rings. (a) They can lead to a substantial degradation in the quality of the beam spot at the interaction regions. And (b) the tune shift as a function of momentum in a linear lattice limits the useful momentum pass band of the accelerator.

In principle these chromatic effects may be reduced to acceptable values by introducing families of sextupoles in regions where momentum dispersion exists. Furthermore if the sextupole strengths and positions are correctly chosen, all of the second-order geometric and chromatic aberrations can be made to vanish. We have named such systems 'second-order achromats'.[1,2] The sextupoles, however, will introduce third and higher-order geometric and chromatic aberrations. These third and higher-order aberrations must then be minimized to achieve the optimum lattice design. This is accomplished by placing the sextupoles in regions of high beta and by choosing the momentum dispersion at the correcting elements such that the residual geometric and chromatic aberrations are approximately equal. This equality occurs when the chromatic beam size is approximately equal to the monoenergetic beam size at the correcting sextupoles, i.e., when

$$\eta \frac{\Delta p}{p} \approx \sigma_y$$

Two general types of second-order achromats have been devised. Those which have unity magnification and those which magnify or demagnify the beta function. Combinations of these two types of achromats can be used to design composite systems free of all second order aberrations. This basic principle has been adopted in this report to explore the phase space limits of stability of storage rings.

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BASIC DESIGN OF THE LATTICE

A modular section of a storage ring lattice based on the above principles is the following

X--------A--------B---------C----M

X is an interaction region (I.R.) in the lattice and M is a symmetry reflection point midway between two interaction regions. X--A is a magnifying achromat. A---B is a matching section needed to match the magnifying achromat to the main lattice. A--B is required because the magnifying achromat has the same magnification in both transverse planes and the ratio of the beta functions at the I.R. is not necessarily equal to their ratio in the main lattice. B---C represents the main lattice. It consists of a repetition of identical unit cells structured as a series of unity magnifying achromats. C--M is a phase shift network to make fine tune adjustments to the lattice. It may or may not be needed in any given design.

Each achromatic segment has a total phase shift of 360 degrees in both transverse planes because all of the second-order geometric and chromatic aberrations vanish simultaneously only at the 360 degree phase shift points. Regions A---B and C---M must consist only of quadrupole components if the second-order integrity of the system is to be strictly preserved.

MAIN LATTICE STRUCTURE AND CHARACTERISTICS

In the example studied, the main lattice B---C contains 30 unit cells each of which has the following optical configuration.

QF--SF-----BB----SD--QD--SD----BB----SF--QF

Table I gives the characteristic parameters of each main lattice unit cell. The phase shift/cell for the main lattice is not a critical parameter in this design. 60 deg/cell was chosen for the test case but a 90 deg/cell system has also been studied and found to function equally well.

All SF sextupoles in the main lattice are tied together as one family and all SD sextupoles are tied together as a second family. With the proper adjustment of these two families all second-order chromatic aberrations in the main lattice will vanish.

Table I

Main Lattice Cell Parameters

Phase advance/cell	x plane	60 deg
	y plane	60 deg
Total phase advance in B--C		5*360 deg
Beta max		138 m
Beta min		46 m
Total bend angle/cell		1 deg
Radius of curvature		3 km
Total length of a cell		80.36 m

THE MAGNIFYING ACHROMAT

Section X---A is a magnifying achromat. It is similar in characteristics to the main lattice achromat except that each successive cell is a 'magnified' copy of the preceding cell according to the scaling laws shown below in Table II. In the example studied the magnifying achromat has the following optical cell structure

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|---first cell----|-------second cell--------|
.B---QD-SD---QF-SF.B------QD--SD-------QF--SF.     etc.
|-------------half wavelength---------------|
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where all components in the second cell are M times longer than in the first cell. The third cell is M times longer than the second and the fourth cell is M times longer than the third. For the system studied in this report, M = 3 was chosen. Thus each half wavelength has an optical magnification of 3. This gives a total magnification of M*M = 9 for the four cells comprising the magnifying achromat with a corresponding magnification of 81 for the beta functions. Section X---A has a total phase shift of 360 deg.

All lengths scale like M. The strength K(n) of a multipole is defined here as

$$K(n) = \frac{B(o)L}{BR\ a^n}$$

where n = 0 is a dipole, n = 1 is a quadrupole, and n = 2 is a sextupole. B(o) is the field at the pole of the multipole. a is the radius of the aperture. L is the length of the multipole, and BR is the magnetic rigidity of the particles.

Table II

Scaling Laws for a Magnifying Achromat

MULTIPOLE	STRENGTH	LENGTH
Dipole	$M^{-1/2}$	M
Quadrupole	M^{-1}	M
Sextupole	$M^{-3/2}$	M

MATCHING SECTIONS

Both matching sections A---B and C---M contain a succession of quadrupoles and drift spaces. These sections introduce some chromatic distortions but they are small if the sections are designed to have small excursions in the betatron oscillation amplitudes. These residual chromatic aberrations are easily corrected by a slight perturbation to the main lattice sextupoles in the achromat (six cells) immediately adjacent to the matching section being corrected.

IMPLEMENTATION FOR A 75 GeV STORAGE RING

The above principles have been applied to design a test lattice for a storage ring at 75 GeV/c. Since the objective was to explore the limits of validity of the chromatic correction, other pragmatic problems such as the effects of synchrotron radiation upon the beam emittance have been ignored. The magnifying achromat used for the test case contains bending magnets in every cell including the interaction region so as to explore the maximum available phase space limits for stability in storage rings. Magnifying achromats having the first bending magnets located two or four unit cells away from the I.R., as is required for e^+e^- storage rings, have been explored but further work is required to achieve a satisfacotry solution in this configuration.

Figures 1, 2 and 3 show the resulting tune-shift diagrams, the beta function variations at the I.R., and the stability diagrams as a function of momentum. These results were obtained by tracking test particles for 240 superperiods using the program DIMATS.[3]

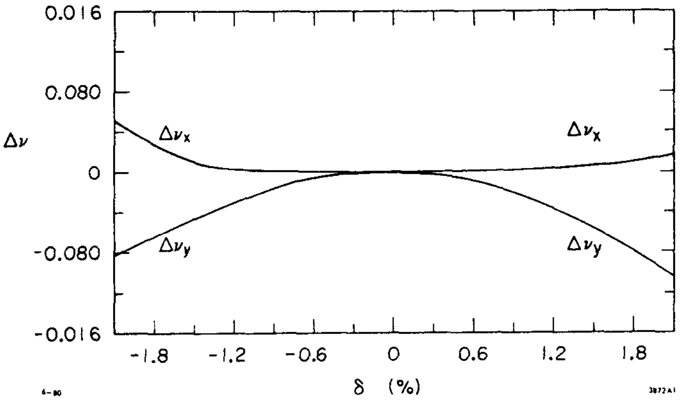

Fig. 1. Tune shift vs momentum

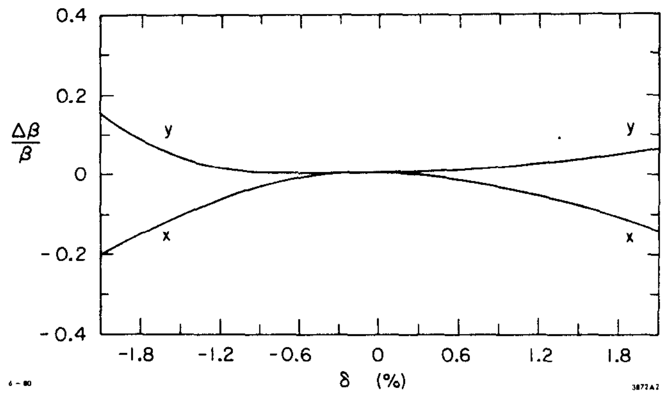

Fig. 2. Beta function variations at an interaction region.

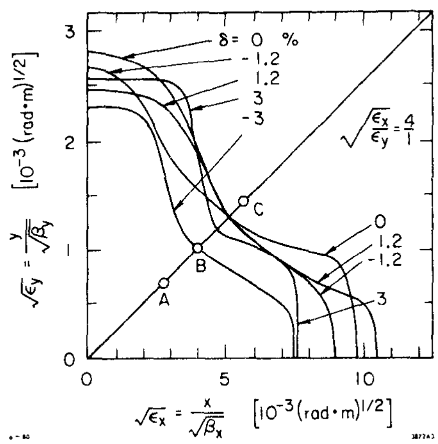

Fig. 3. Stability diagrams.

Further diagnostic tests were made by exploring the optical distortions introduced by the sextupoles. 5000 rays were traced, using the program TURTLE,[4] from the beginning of a magnifying achromat through the I.R. to the end of the next magnifying achromat. The central core of the beam, corresponding to a monoenergetic linear lattice, is displayed by the $ signs. The 'noise' surrounding the central core of the beam is clearly illustrated by the numerals and alphabet. This noise represents the optical distortions introduced by the sextupoles. Results, corresponding to the phase space points A, B, and C in Fig. 3, are shown in Figs. 4(a), 4(b) and 4(c). For point A [Fig. 4(a)] no significant optical distortion is present and the beam is completely stable. For point B [Fig. 4(b)] the emittance and the momentum spread of the beam have been increased by a factor of 1.4. The noise level has increased but the beam is still observed to be stable. In Fig. 4(c) (point C) the emittance and momentum spread have been increased by a factor of 2 from that at point A. The noise has become significant and the resulting system is found to be unstable. By unstable we mean that particles are observed to be lost while tracking them for 240 superperiods using the DIMATS programs.

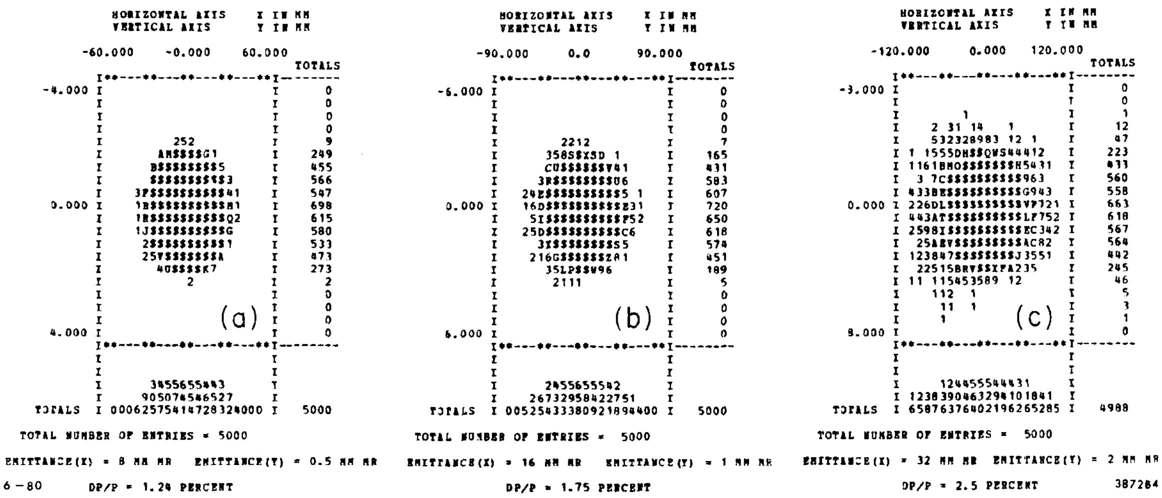

Fig. 4. Results of 5000 rays traced from the main lattice through an interaction region back to the main lattice. The $ signs display the results for a perfectly linear lattice. The numbers and alphabet show the non-linear optical distortions caused by the introduction of sextupoles.

CONCLUSIONS

It is the conviction of the authors that the principles of the unity magnification achromat combined with the magnifying achromat can be used successfully to design lattices for colliding beam machines at high energy. Work should now proceed to investigate more pragmatic solutions and to explore possible applications to smaller machines.

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3) DIMATS is a tracking program developed by R.V.S. using the second-order matrix formalism of TRANSPORT.[5]

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