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APPLICATIONS OF THE SECOND-ORDER ACHROMAT CONCEPT [1,2,3] TO THE DESIGN OF PARTICLE ACCELERATORS*

K.L. Brown
SLAC, Stanford, U.S.A. / CERN, Geneva, Switzerland
and
R.V. Servranckx
Saskatoon, Saskatchevan, Canada/SLAC, Stanford, U.S.A.

Abstract

A property of the second-order achromat, whereby dipole and sextupole families may be inserted into a lattice for chromatic corrections without introducing second-order geometrical (on momentum) optical distortions, has been incorporated in several new particle accelerator designs. These include the SLC at SLAC, LEP at CERN, the EROS pulse stretcher ring at Saskatoon, the CEBAF ring at SURA, and the MIT ring.

1. Introduction

Theorem A : One of the important principles of the second-order achromat is the following: "If one combines four or more identical cells consisting of dipole, quadrupole, and sextupole components, with the parameters chosen so that the overall first order transfer matrix is equal to unity (+I) in both transverse planes, then it follows that such a system will have vanishing second order geometric (on momentum) aberrations".

Theorem B : Furthermore, "If the sextupole components are adjusted so as to make one second-order chromatic aberration vanish in each transverse plane of the +I sections, then ALL second order aberrations (geometric, chromatic, and path length) will vanish except for the momentum dependence of the path length".

A typical lattice which is capable of satisifying both theorems is illustrated in Figure 1 below. It is called a "Second-order Achromat" when both theorems, A and B, are satisfied.

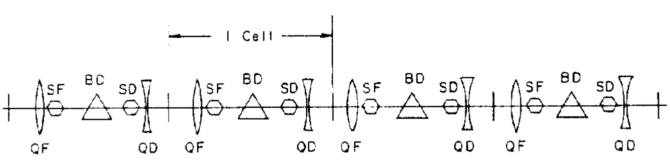

Fig.1 - Example of a four cell second-order achromat.

Theorem A is useful for making chromatic corrections in particle accelerators such as storage rings and linear colliders where low beta sections are used for the interaction regions.

The entire achromat, using both theorems A and B, is useful for the design of secondary beams or for the transport of primary beams, such as in the arcs of the Stanford Linear Collider, where optical distortions must be kept to a minimum.

2. Applications to machine design

The SLC [4] : The Slac Linear Collider (SLC) uses the second-order achromat concept for the design of both the ARCS and of the Final Focus System (FFS).

The collider arcs are composed of a series of second-order achromats so as to maximize the momentum pass band of the system and to minimize the detrimental effects caused by errors in the positioning of the arc magnets. For the SLC arcs each achromat is composed of 10 FD cells (20 combined function magnets). Each cell has 108 degree phase in each transverse plane making a total of 1080 degrees total phase shift for each achromat. Because combined function magnets are used, the system retains its achromatic properties when misaligned magnets are present even though the matrix is no longer +I. This property of the system permits the centroid displacements caused by errors in the positioning of magnets to be compensated by moving other magnets to realign the centroid of the beam.

In the design of the collider FFS system, the chromatic depth of focus is minimized by a chromatic correction section which is patterned after theorem A. Two sextupole families are used to correct for the chromatic depth of focus so as to achieve a small spot independent of the momentum pass band used for the collider. The optical configuration is shown below in Fig.2.

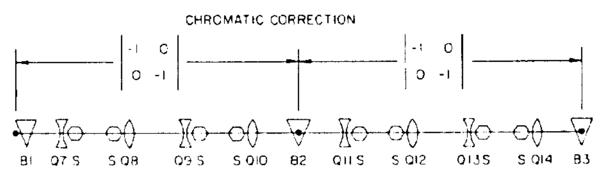

Fig.2 -The SLC final focus chromatic correction system.

LEP [5] : LEP, the large electron-positron collider being constructed at CERN, uses theorem A in the design of the central part of the lattice where the sextupole families are located to correct for the variation in tune caused by the momentum dependence of the quadrupoles (chromaticity). In LEP the central lattice is tuned to a fixed 60 degrees phase shift per cell in both transverse planes, thus satisfying the +I requirement for theorem A. Three families of sextupoles are installed in each transverse plane, all of which may be independently adjusted without introducing any second-order geometric distortions. This permits the sextupole families to be adjusted to compensate for chromaticity as a function of momentum such that the net result is a relatively 'clean' lattice over the full emittance and momentum passband required for the machine. This also allows the sextupole families to be used to best advantage to correct for higher order effects in the resonance properties of the machine.

3. EROS [6], SURA [7], and MIT [8]

EROS : The lattice for EROS is given below as an example of a pulse stretcher ring design. The elements starting with F are drift sections. The elements starting with H are horizontal bends. Those starting with Q are quadrupoles and the elements starting with D are quadrupole-sextupole elements. The SE elements are the extraction sextupoles. The curved sections are tuned to +I.

The total system is composed of the following segments :

- The first straight section containing the extraction point :

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LEP ARCS = 6 [cell(SD3,SF1) cell(SD2,SF2) cell(SD1,SF3)] 6 [cell(SD1,SF1) cell(SD2,SF2) cell(SD3,SF3)]

where cell(SD,SF) = QF L23 SF L21 BBB L22 QD L23 SD L21 BBB L22

and S = sextupoles families,
Q = quadrupoles families,
B = dipoles,
L = drifts.

Fig.3 - The lattice arrangement for sextupoles in LEP

DSH FS1 QS1D FS2 QS2F FS3 QS2D FS3 QS3F
FS3 QS3D FSE1 SE2 FSE2 QS3F FS3 QS3D
FS3 QS3F FS3 QS3D FS3
QS3F FS3 QS2D FS3 QS2F FS2 QS1D FS1 DSH

- Start of the first curved section :

DSH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DSH

- The injection straight section with c.o. kickers :

DSH FS1 QS1D FK11 K1 FK12 QS2F FS3 QS2D FIE2 FIE1 QS3F
FS3 QS3D FSE1 SE2 FSE2 QS3F FK21 K2 FK22 QS3D
FS3 QS3F FS3 QS3D FS3
QS3F FS3 QS2D FS3 QS2F FS2 QS1D FS1 DSH

- The second curved section :

DSH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DFCH
DFCH FC3 DDCH FC2 HC FC1 DSH

In EROS the cells containing Q3F and Q3D constitute the regular straight section cells which define the properties of the machine: that is, the tune, the injection, and the extraction properties.

The cells with the D*** elements and HC constitute the curved sections cells, four at each end tuned to a matrix of +I in each curved section. The sextupole components of the D elements are tuned to set the total chromaticities to 0 vertically and to -15 horizontally. The sections with Q*1 and Q*2 are magnifiers to match the beta values of the regular straight sections with those of the curved sections. The betas are 15 meters max and 5 meters min in the straight sections and 3 meters and 1 meter in the curved sections. There is an obvious mismatch in the alpha's when one recognizes that the symmetries do not match. But the mismatch is minimal as regards the actual beta functions in the curved sections. The basic setup guarantees that tuning the D sextupoles does not affect the extraction procedure (on momentum) although it does affect its energy dependence. The achromatic behaviour of the straight sections guarantees that the extraction sextupoles SE do not affect the chromatic properties of the lattice. The comparison between the original EROS design, the Sura design, and the first Amsterdam design shows that the beta-mismatch between curved sections and straight sections introduces higher order terms whose importance is directly linked to the size of the mismatch. In EROS the chromatic excursions were not very important so no eta matching sections were needed. The curved sections are composed of four identical 90 degrees phase shift cells, the combination of which satisfies theorem A above.

CEBAF(SURA) : This machine is similar to EROS but is not constrained to fit in a building so the curved sections are more or less matched to the straight sections. Among many possible designs the following structure for the ring was retained : two straight sections and two curved sections like the EROS design.

CEBAF uses 1/2 integer extraction while EROS uses a 1/3 integer extraction system. CEBAF needed eta matching so each curved section was made of 12 cells. The 8 central ones contain full scale dipoles tuned in groups of four to a +I matrix. The four outer ones, in groups of two, have dipole values chosen to produce the matched eta of the four central ones and tuned individually so as to make another +I matrix by combining the four of them.

MIT : The MIT machine is very much like EROS but with less of a beta-mismatch. For the MIT design, J. Flanz looked more carefully into the possibilities to use some specific symmetries to improve the higher order behaviour. The MIT machine has two long straight sections and two short ones. Each 90 degree bend section consists of four cells forming a +I matrix without eta matching.

4. Summary

The importance of the second-order achromat concept for the design of particle accelerators and beam transport lines is now well established. We have included here five such examples to illustrate the techniques used in the designs for the benefit of others who may wish to use these methods.

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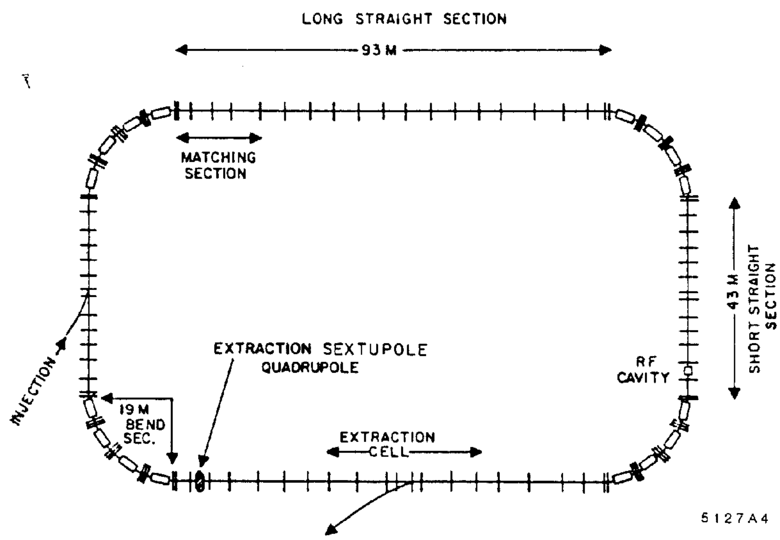

Fig. 4 MIT

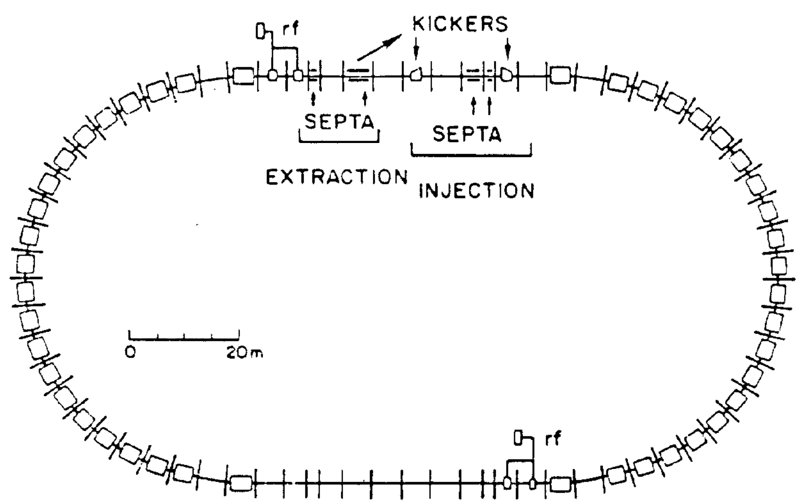

Fig. 5 SURA

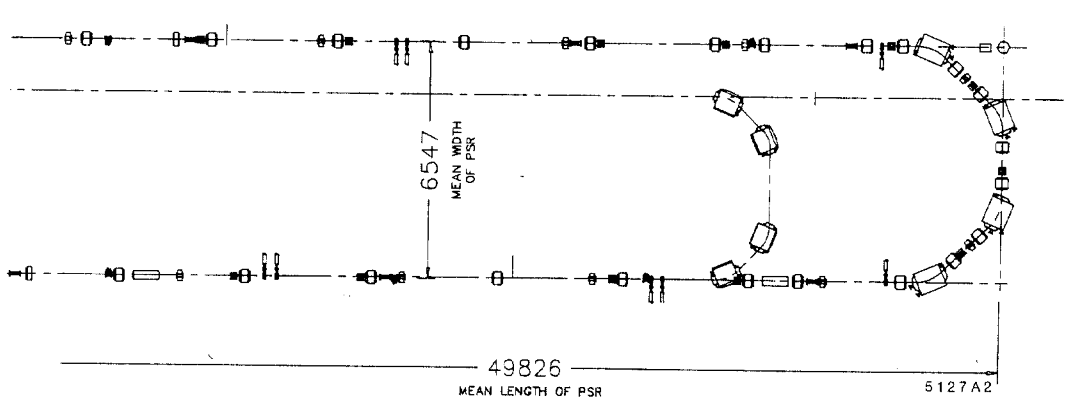

Fig. 6 EROS