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NONPLANAR MACHINES*

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1. INTRODUCTION

With the advent of very large accelerators, problems associated with varying geological strata have led to investigating the possibilities for construction of terrain-following machines. Such machines would, by their very nature, lose planar symmetries and need three-dimensional specification of their equilibrium orbits. The removal of planar symmetry introduces cross-coupling, correction and monitoring problems. The bend arcs of the SLC are terrain-following and highlight the problems inherent in nonplanar configurations. "Overpasses" added to the Fermilab main ring carry it over the CDF and D0 detectors. These overpasses employ a vertical kick followed by a later opposite reverse kick, moving the machine to a higher level over the detectors. After passage over the detectors, the process is reversed and the orbit is restored to its original level. Had the SSC been located at FNAL, it might have been desirable to "fold" the halves of the accelerator relative to each other in order to locate the accelerator at a deeper

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level beneath the Fox river. This possibility is now moot with the choice of the Texan SSC site, although a mild folding could perhaps be used to position the two clusters of interaction regions in the SSC closer to the surface.

This talk examines methods available to minimize, but never entirely eliminate, degradation of machine performance caused by terrain following. Breaking of planar machine symmetry for engineering convenience and/or monetary savings must be balanced against small performance degradation, and can only be decided on a case-by-case basis.

2. EFFECTS OF SYMMETRY BREAKING

For a planar machine, the first order transfer matrix is of the form

$$R = \begin{pmatrix} X & X & 0 & 0 & 0 & X \\ X & X & 0 & 0 & 0 & X \\ 0 & 0 & X & X & 0 & 0 \\ 0 & 0 & X & X & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & X \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

where the Xs are nonzero elements. The 6 x 6 matrix acts on the vector $V = (x, x', y, y', z, \delta)$ whose elements are the horizontal, vertical, longitudinal and momentum displacements from the equilibrium orbit and the vector V_{out} after a rotation is related to the input vector V_{in} by

$$V_{out} = R \times V_{in}$$

Of the 11 nonzero elements, two are constrained by conservation of phase space, and the R_{56} element is usually not required to be set to a predetermined value. Therefore, to correct for random errors will require eight correctors. In terms of Twiss parameters for a circular machine, the eight quantities requiring correction are $\theta_x, \alpha_x, \mu_x, \theta_y, \alpha_y, \mu_y, \eta_x$ and η'_x .

In a machine with cross-coupling errors, the transfer matrix is

$$R \approx \begin{pmatrix} X & X & X & X & 0 & X \\ X & X & X & X & 0 & X \\ X & X & X & X & 0 & X \\ X & X & X & X & 0 & X \\ 0 & 0 & 0 & 0 & 1 & X \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

There are now 10 additional nonzero elements. The symplectic conditions effectively result in four further constraints,¹ and thus six additional corrections suffice to set the transfer matrix back to nominal value. This is a very considerable increase in correction complexity. The ability to fully correct cross-coupling is almost certainly required, as increased orbit complexity can increase long-term beam losses through an enhancement of chaotic or stochastic behavior. Further problems are caused by the need for 2D monitoring of the orbits. Therefore, we examine the methods below to obtain nonplanar machines where the 2D behavior is confined to small localized regions of the machine, or the transitions are adiabatic and the cross-coupling is kept small.

3. THE SLC SOLUTIONS

The SLC arcs are an example of a terrain-following transport system. The problems of constructing such a system are very real, but the overall performance demands were substantially less serious than would be encountered in a circulating storage ring employing a similar design strategy. We discuss first the original strategy for correction which proved to be inadequate, and then the later modifications required for operation.

3.1 Initial SLC Strategy

The SLC arcs consist of two 180°-bend transport systems to bring the electron and positron beams from the linac into head-on collision. The transport systems are based on combined-function FD lattices with 108° phase shift per cell. The lattice is

second-order chromatically corrected using combined function sextupoles. The cells are combined into "achromats" consisting of 10 cells, with a net phase advance of 6π , corresponding to a unit transfer matrix across an achromat. The strategy adopted for terrain following was to physically rotate or roll each achromat around the axis of the equilibrium orbit. To a first approximation, a particle exiting from a horizontally oriented achromat into one rolled through ϕ degrees will enter a magnetic bend field with a vertical component proportional to $\sin\phi$ and will thus suffer a continuous component of vertical deflection, leading to a vertical bend radius proportional to $\sin\phi^{-1}$. The change corresponds to adiabatically changing the equilibrium orbit but discontinuously moving the center of curvature of the orbit. Subsequent elements are positioned relative to the plane defined by the vector of the entry equilibrium orbit and the new center of curvature. Mathematically, the effect of such a roll is described by the rotation matrix R_ϕ

$$R_\phi = \begin{pmatrix} \cos \phi & 0 & \sin \phi & 0 & 0 & 0 \\ 0 & \cos \phi & 0 & \sin \phi & 0 & 0 \\ -\sin \phi & 0 & \cos \phi & 0 & 0 & 0 \\ 0 & -\sin \phi & 0 & \cos \phi & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

If the orbit is rolled at the start of achromats the overall transfer matrix, R , for a set of rolls $\phi_1 \dots \phi_n$ is

$$R = R_{\phi_1} \times \dots \times R_{\phi_n} \quad .$$

and if

$$\sum \phi_i = 0 \quad .$$

it can be verified that R is a unit transfer matrix. The original SLAC design used a set of rolls whose final net value was zero to provide a terrain-following orbit. Even had the arcs been free of placement and field errors, the orbits would have been strongly cross-coupled as long as the net roll was nonzero.

Such a design is predicated on a net cancellation at large separations of roll-associated terms. In practice, the level of errors was such that the achromats were no longer unit transfer matrices, and unacceptable beta beats and cross coupling resulted at the output of the transport lines. The recipes used to provide acceptable transfer properties (for a single transit) are now outlined.

3.2 Revised SLC Arcs

Subsequent to commissioning of the SLC, procedures were devised to measure and correct the phase advances as carefully as possible in order to maintain cancellations of effects from highly separated rolls. The horizontal dispersion function was, to a high approximation, matched across roll boundaries by splitting the roll into two successive half-rolls. An approximate local betatron match was made by using a graded set of rolls in the first three cells of the achromats. Finally, lattice errors were corrected for by second harmonic quad and rotated quad excitations. These combined steps provided an acceptable single-pass transport system.² However, such a system would be unacceptable for use in a large storage ring.

For the most part, the difficulties encountered with the SLC lattice stemmed from the use of combined function elements locking the rotation of the dipoles, quadrupoles and sextupoles. Had it been possible to roll only the dipoles and leave the orientation of the quadrupoles unchanged, first-order betatron mismatches at the entry to rolled achromats would have been eliminated. Elimination of dispersion mismatch as discussed was simple, and therefore the problems encountered were largely specific to a combined function lattice.

However, even in the presence of a combined function lattice, it is possible to provide a local match at the boundary to rolled achromats as discussed in Sec. 3.3.

3.3 Local Matching at Roll Boundaries

For circular storage rings, strong cross-coupling could only be permitted over small sections of the arcs and therefore local cancellation of the rolls would be required; this is possible³ using a match section. If the lattice is rolled by $\phi/2$, followed by a

transfer section R , rolled again by $\phi/2$ and followed by R , the resultant R_{out} is unit when

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

The resultant matching section will internally produce strong beta beats, cross-coupling and anomalous dispersion. The cancellations are again sensitive to error, and before employing such a scheme it would be necessary to check that introducing these match sections would not "narrow-band" or deteriorate machine performance.

4. THE FNAL OVERPASSES

T. Collins⁴ proposed two methods to locally separate the Fermilab main ring from the Tevatron at the location of the CDF and D0 detectors. Both methods required kicking the beam vertically, letting it coast upwards, kicking it back to a horizontal orbit at a new level as it passed over the experimental detector and then reversing the process to put it back on its original orbit. Simplistically, if the first upward kick is separated by an even multiple of π from the second restoring kick, the dispersion functions will be restored to their original values.

The actual proposed schemes differed in the fine detail of their execution. The first method continued, after a kick, with the identical lattice now positioned on the plane containing the new input equilibrium orbit vector but with the center-of-curvature unchanged. This corresponds to a "fold" in a circular machine. The new equilibrium orbit remains circular and, if left undisturbed, would return to its original level after a rotation through π radians.

The second method continued the lattice after the kick with a slightly modified lattice. This modified lattice maintains the components in a horizontal plane but with the front-to-back inclinations set parallel to the equilibrium orbit. For this

new lattice, the dipole magnets have no transverse horizontal field component and therefore do not effect the vertical component of motion introduced by the kick. With this configuration, the equilibrium orbit lies follows along a constant pitch screw and has a rotation period virtually identical to that of the regular circular orbit. In both cases the betatron motion is automatically matched across the boundaries, while the dispersion functions remain mismatched. The dispersion function mismatches can be removed by $n\pi$ remote cancellation and/or local matching.

The scheme, as actually implemented, used the screw lattices for the interconnecting links and remote $n\pi$ cancellation to remove the dispersion errors. Kicks were provided by rotating existing dipoles in the original lattice through 180° . This bypass scheme proved to be satisfactory. However, the use of the pre-existing tunnel required the original radius of curvature to be maintained. Rotating dipoles to provide vertical bend decreased the available bend power at the transition boundaries, and this coupled with the constraint of maintaining the original radii of curvature caused a halving of the maximum peak achievable energy.

We now describe a design that would, for a new machine, avoid both this peak energy loss and provide clean first-order matching.

5. ADIABATIC ROLL SOLUTIONS

The preferred method of obtaining matching is via slow adiabatic transitions. The weakness of the FNAL design lies in the use of strong localized vertical kicks to the orbits. This problem can be avoided by providing distributed vertical bend by a fixed small rotation within the FODO cell of a string of successive dipoles (as at the SLC). If only the dipoles are rotated and the other elements remain with horizontal orientations, first-order betatron mismatches do not occur. A small dispersion mismatch occurs after entry into this bend section. Exact dispersion matching can be provided using two dipoles at entry and exit to this section with rolls set to provide vertical dispersion match.

The recipe to lay out such a section is to put in place the dipoles with a fixed rotation relative to the horizontal, to horizontally place all other elements, and for the

front-to-back inclinations to be set parallel to the equilibrium orbit. The equilibrium orbit would then describe a screw or spiral with monotonically increasing pitch. The horizontal projection of this path would be a circle with radius virtually unchanged from that of the regular circular orbit. Such a building block provides vertical kick free from first-order mismatches and makes use of the same lattice components and spacing, as in the regular lattice.

These "increasing spiral" building blocks can be used to directly provide level changes or, in combination, to provide the kicks required to match into folded or uniform screw sections. Combination of increasing spiral sections with screw or folded sections will also be free of first-order mismatches and use identical components and spacing as the main lattice.

6. SUMMARY

The various building blocks proposed or used to accomplish changes of accelerator level are summarized in Table 1.

Table 1. Building Blocks

Building Block	Elements Tilted	Center-of-Curvature	Subsequent Orbit
Rolled	All	Kicked	Circular orbit
Folded	All	Unchanged	Circular orbit
Uniform screw	Dipoles only	Slowly changing	Uniform spiral
Increasing spiral	Dipoles only	Slowly changing	Increasing spiral

The first method of rolling all elements of the lattice, as at the SLC, is highly sensitive to errors and causes cross-coupling over extended regions of the machine. With matching sections at the roll boundaries, it is possible to largely overcome this problem. A. Garren has proposed a scheme for use with the SSC that connects a folded lattice using single rolled achromats,⁵ with cross-coupling confined to the small region of the rolled achromats, thus avoiding most of the problems encountered at the SLC.

The FNAL bypass solution is the basis of the last three building blocks listed in Table 1. In combination, they can provide level change without the introduction of first order errors and use only regular lattice elements and spacing.

However, nothing comes entirely for free and the presence of local vertical dispersion within the building block could have deleterious side effects when higher order effects are taken into consideration. When all the trade-offs are considered, the added complexities in assembly, the introduction of high-order errors, surveying and the lessened shielding of produced muons from vertically inclined beams combine to make the above options less attractive. Therefore, after detailed weighing of the various factors, future storage rings probably will continue to be planar.

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