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Correction of the First Order Beam Transport of the SLC Arcs*

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ABSTRACT

Correction of the first order transport of the SLC Arcs has been made possible by a technique which allows the full 4x4 transport matrix across any section of Arc to be experimentally determined. By the introduction of small closed bumps into each achromat it is possible to substantially correct first order optical errors, and notably the cross plane coupling at the exit of the Arcs.

1. INTRODUCTION.

The existence of cross plane coupling induced by the rolled achromats which comprise the SLC Arcs has been well documented[1][2]. After the initial commissioning in 1986[1], it was soon realized that gross lattice errors, which were later attributed to magnet misalignments, resulted in large anomalous cross plane coupling, and various attempts to correct the first order optics of the Arcs have since been attempted[3][4][5]. In 1989, a technique developed by Barklow[6] to measure the fully coupled 4x4 R matrix of the Arc was first used to try and correct the coupling[5]. Although the attempt was relatively successful in the north Arc, the technique failed to make any improvement in the south Arc. Since that time, a rigorous analysis of the errors involved in the measurements have been made, and a new technique of adjusting the lattice by use of closed orbit bumps has been adopted. The error analysis, measurement techniques and subsequent correction of the Arc first order optics is the subject of this report.

The coupling is most commonly characterized by the determinant of the C sub-matrix, where

$$R_{4x4}=\begin{pmatrix} A_{2x2} & B_{2x2} \\ C_{2x2} & D_{2x2} \end{pmatrix}=\begin{pmatrix} R_{11} & R_{12} & R_{13} & R_{14} \\ R_{21} & R_{22} & R_{23} & R_{24} \\ R_{31} & R_{32} & R_{33} & R_{34} \\ R_{41} & R_{42} & R_{43} & R_{44} \end{pmatrix} \qquad (1)$$

Since $\det C = R_{31}R_{42} - R_{41}R_{32}$, it is possible to have $\det C = 0$, and yet have non-zero coupling elements. Thus we make use of another parameter χ^2_c, which is described in section 3.

2. MEASUREMENT OF THE FIRST ORDER TRANSPORT MATRIX.

The first order transport matrix (R matrix) for the Arcs was experimentally determined using a technique developed by Barklow[6]. In essence, the technique comprises of generating betatron oscillations of different amplitudes and phases through the Arcs using upstream dipole correctors spaced at different betatron phases in both horizontal (X) and vertical (Y) planes. The resulting oscillation amplitudes are recorded as a function of corrector kick angle at all the beam position monitors (BPMs) in a given Arc. From these data, the R_{12}, R_{32}, R_{14}, R_{34}, elements of the R matrix (henceforth referred to as *R_{12} type elements*) from a given corrector to each BPM are determined. In order to calculate the remaining twelve elements, it is only necessary to assume some (design) R matrix between groups of adjacent BPMs in the Arc, and between the dipole correctors used to generate the oscillations. In addition, the resulting R matrix must be *symplectic:* The six symplectic constraints[7] reduce the number of independent variables of the R matrix from sixteen to ten. In practise, four adjacent Arc BPMs were used (two X and two Y) to reconstruct the R matrix at the first or last BPM in the group. A total of eight sets of oscillation data were recorded, using four X correctors and four Y correctors at the end of the LINAC, giving a total of thirty-two measurements from which the ten independent R matrix elements were derived; hence a non-linear χ^2 reduction with twenty-two degrees of freedom was required. To minimize the error on the resulting R matrix, great care was taken in acquiring the data: Dedicated software was written to average ten BPM readings per corrector setting, and to monitor the energy fluctuations of the beam. Since at best the energy is stable to 0.1-0.2%, a correction for any dispersive addition to the beam displacement had to be made.

In addition to the measurement errors of the R_{12} type elements, it is assumed that there are other unknown systematic errors, for which a numerical adjustment is made to force the mean value of the χ^2 distribution to be twenty-two (the number of degrees of freedom). Experimentally, this systematic error is generally of the same order as the raw measurement errors. Simulations of the effects of misaligned Arc magnets using DIMAD[8] have shown that the measurement techniques used have a resolution equivalent to approximately 100 μm of random magnet misalignments. The precise details of the reconstruction of the R matrix and the subsequent error analysis is given in [6].

3. CORRECTION OF R MATRIX ELEMENTS USING CLOSED ORBIT BUMPS. .

The first step in tuning the transfer matrix for the entire Arc (the global R matrix) is to adjust the transfer matrix across individual achromats (local R matrix); since the gross coupling

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errors generally accrue from optical errors between matched roll boundaries, correction of the optics on an achromat by achromat basis should in principle already greatly reduce the anomalous coupling. As a first stage to the achromat correction, the phase advance in both planes was adjusted to be equal to 6π radians: The gross phase adjustment was performed by a procedure known as PHASEFIX[4]. The present adopted PHASEFIX procedure differs from that in [4] only by the measurement of the phase advance itself, which is now determined directly from the reconstructed R matrix. The principle of the adjustment, however, remains the same.

Once the phase per achromat has been corrected, fine tuning of the R matrix elements was achieved by implementing small amplitude closed orbit bumps[9]. The orbit deviation makes use of the sextupole component of the magnetic field to adjust the optics: Horizontal bumps adjust the in-plane optics (by adjusting the effective quadrupole field), while vertical bumps adjust the coupling elements (by subsequent introduction of a skew-quadrupole field). The closed bumps were generated using two magnet movers spaced five cells (ten magnets) apart; hence the movers are separated by 3π radians phase advance, and are thus referred to as 3π bumps.

For any given achromat, there are ten possible 3π bumps (five in both the X and Y planes). Since it was impossible to individually correct each of the ten independent R matrix elements, the weighted sum of the squares of the differences of the elements with respect to their design values was minimized. Two χ^2 were defined: $\chi^2_{\alpha\beta}$, which sums over the in-plane optical parameters[1], and χ^2_c, which sums over the four coupling, or C sub-matrix elements. χ^2_c is defined as:

$$\chi_c^2 = \sum_{i=1}^{4} \sum_{j=1}^{4} \left[r_i - R_i\right] (V_r^{-1})_{ij} \left[r_j - R_j\right] \tag{2}$$

where

r_i are the *reconstructed* elements of the C sub-matrix,
V^{-1}_r is the inverse of the corresponding 4x4 covariance matrix,
R_i are the *design* values of the C sub-matrix.

$\chi^2_{\alpha\beta}$ is similarly defined, only now the sum is formed over the difference between designed and measured in-plane optical parameters.

The 3π bumps are treated as linear perturbations to the R matrix of the achromat: If the amplitude of the p^{th} bump is B_p, then the R matrix elements become

$$R_{ij} \rightarrow R_{ij} + \frac{\partial R_{ij}}{\partial B_p} B_p \tag{3}$$

The derivatives $\partial R_{ij}/\partial B_p$ were calculated using DIMAD. Thus, having experimentally determined the R matrix across the achromat and calculated the corresponding $\chi^2_{\alpha\beta}$ and χ^2_c, a program was used to select the best of the five horizontal or vertical bumps together with the corresponding bump amplitude to minimize the required χ^2. From the knowledge of the existing orbit through the Arcs, a new reference orbit was generated which included the required 3π bumps, to which the Arc was steered using the magnet movers.

4. RESULTS.

Figure 1 shows the det C behavior for the north Arc after the initial PHASEFIX and the final det C behavior after application of one set of vertical and horizontal 3π bumps. The typical size of the bumps were of the order of 150 μm to 500 μm in amplitude. The final value of det C at the exit of the Arc was zero (within the error). Figure 2 shows how χ^2_c for each achromat responded to the application of the vertical 3π bumps. The observed response was in good agreement with the DIMAD predictions. The values

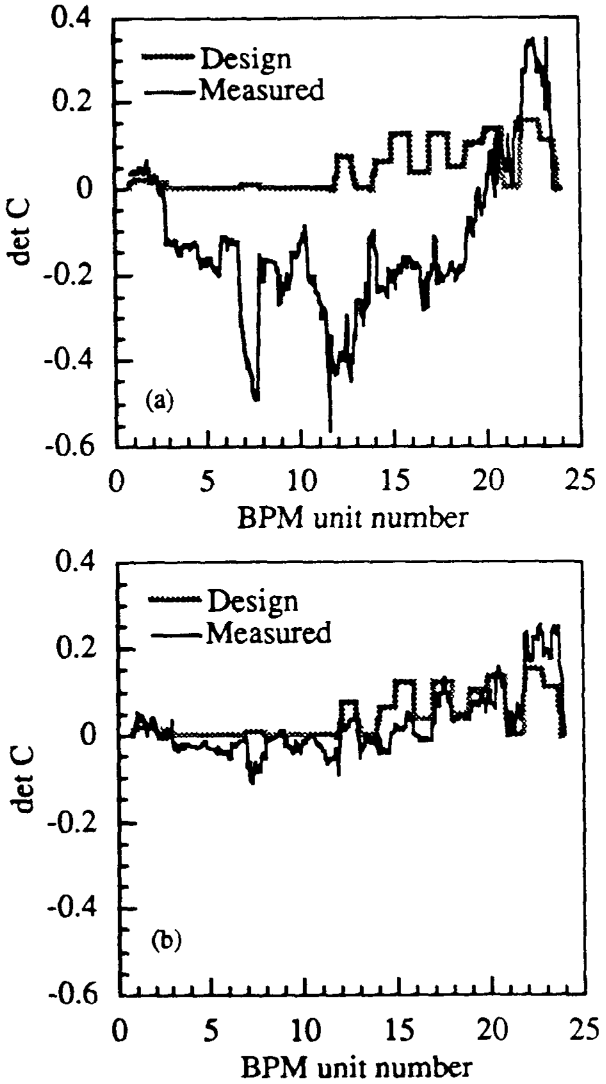

Fig. 3 North Arc det C (a) after PHASEFIX and (b) after application of vertical and horizontal 3π bumps.

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[1] In this case, in-plane optical parameters refer to β_x, β_y, α_x and α_y, calculated using the reconstructed R matrix and knowledge of the *design* beam parameters.

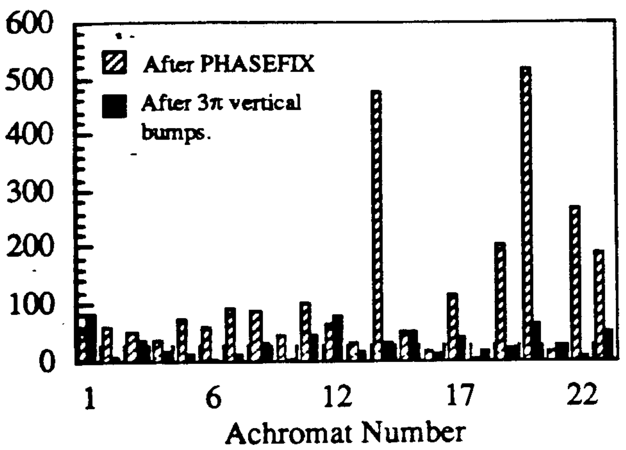

Fig. 3 North Arc χ^2_c before and after application of vertical 3π bumps.

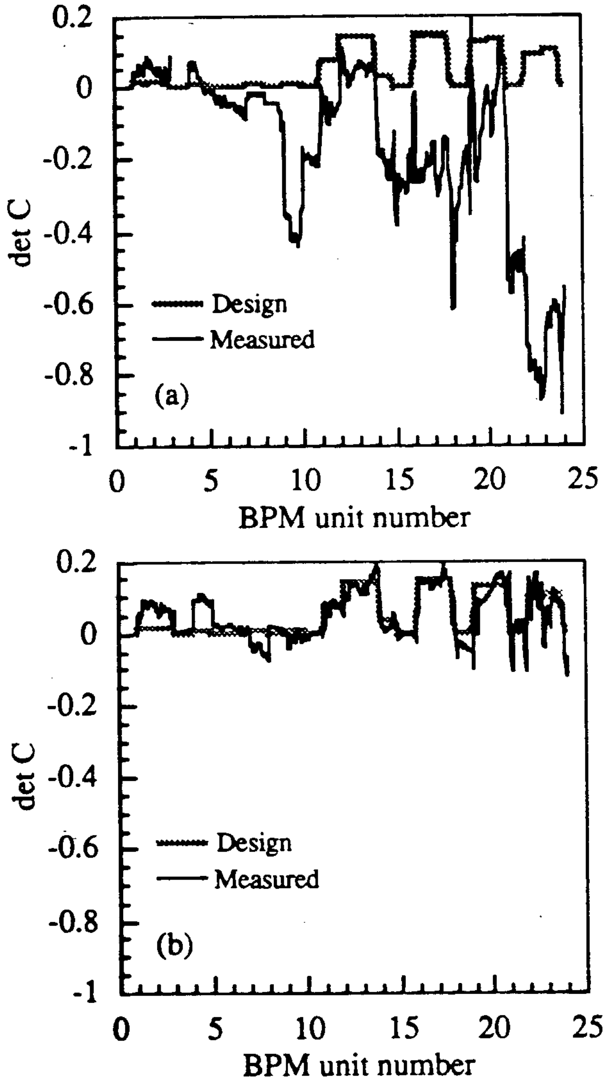

Fig. 3 South det C (a) after PHASEFIX and (b) after complete tuning.

of $\chi^2_{\alpha\beta}$ show a similar reduction after the application of the horizontal bumps.

The det C behavior of the south Arc has historically always been much worse than the that of the north Arc. Figure 3(a) shows det C for the south Arc after the initial PHASEFIX. After two iterations of horizontal and vertical 3π bumps, the agreement of the measured det C behavior with the design values were far better than had ever previously been achieved. However, the coupling present at the exit of the Arc was still unacceptable, and in general, the behavior of the two χ^2 did not correspond to the DIMAD predictions as well as in the north. This may well be due to optical errors not attributed to magnet misalignments (such as gradient errors). The coupling at the exit of the Arc was eventually brought near to zero by the application of SKEWFIX type corrections[4], where whole blocks of vertical movers are adjusted in unison. SKEWFIX corrections were made in achromats 7, 12, 13, 14 and 15 and figure 3(b) shows the resulting det C behavior. At this point, the coupling at the exit of the south Arc was considered acceptable.

5. CONCLUSIONS.

The first order optics of the north and south SLC Arcs can now be successfully corrected by the application of closed 3π bumps. The careful analysis of the errors of the 4x4 R matrix reconstruction allow correction of the Arc R matrix to an accuracy equivalent to 100 μm random magnet misalignments. The south Arc still manifests some unknown behavior characteristic of errors not due to magnet misalignments, and the SKEWFIX type adjustments that were required to correct the coupling may have significantly perturbed the optics of those achromats: Such effects still require further investigation.

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