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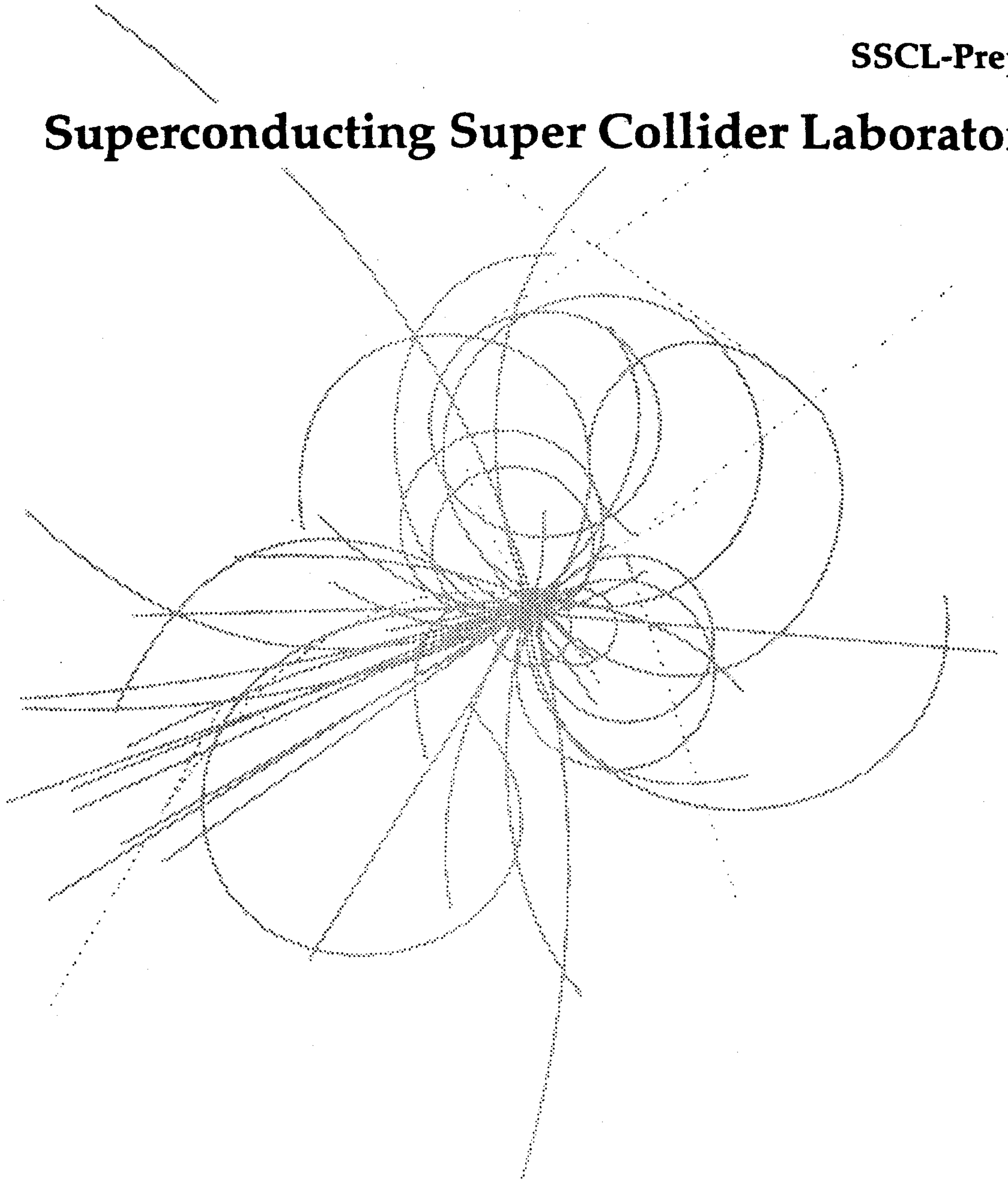
Superconducting Super Collider Laboratory



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I. INTRODUCTION

This paper will summarize a recent study of the effects and correction of linear coupling in the Superconducting Super Collider (SSC) lattice. There are several aspects of the SSC lattice that make direct extrapolation of techniques used on existing machines unreliable. The most obvious aspect of the SSC which departs from previous experience is the small dynamic aperture which lies well within the beampipe. A second aspect is the existence of long arcs with low superperiodicity which allow various sources of skew quadrupole to accumulate to large, and, perhaps, nonlinear values. A third aspect is the relatively large value of systematic skew quadrupole error in the main dipoles. This results from asymmetric placement of the cold mass in the cryostat.

Coupling must be considered harmful if it leads to irreversible emittance blow-up, a decrease in the dynamic aperture, or inoperability of the machine. These negative effects are generally related to coupling terms that accumulate to large and, hence, nonlinear values prior to correction. The harmful effects can also be caused by the linearly coupled orbits interacting with high-order multipole fields that exist in the other magnets.

The errors that lead to linear coupling are well known. They are systematic and random skew quadrupole error fields in the other magnetic elements, angular alignment errors in the quadrupoles and feeddown from the sextupole fields associated with chromaticity correction, and persistent current fields in the dipoles. A study of the relative importance of the various coupling terms for a simplified SSC lattice is contained in Reference 1 (SSC-N-93 by Richard Talman).

The traditional way of correcting linear coupling is to use two families of skew quads and adjust them so that the separation between the two betatron tunes is minimized. This is a global scheme which is sensitive to only the betatron tunes which clearly are global quantities. Another traditional method is to focus on the sum and difference resonances and use two families to skew quads to correct them. Sometimes both methods are used, which requires four families of skew quads.

The method being proposed for the SSC is intrinsically different and amounts to decoupling one local section at a time. The mathematics required to do this are described in the next section. The primary motivation for local decoupling is that the errors are not allowed to accumulate and reach the level at which irreversible nonlinear mixing occurs. Local decoupling requires a measure of the local effect of the errors rather than the global effect of the errors. The quantity that goes directly into the decoupling calculations is simply the ratio of the out-of-plane tune amplitude to the in-plane tune amplitude. This quantity is directly measurable and has in fact been measured on the HERA proton ring and the Fermilab main ring.

Section 3 contains simulation results of the SSC collider with all known errors included and a full simulation of the correction process. It was found that 46 pairs of independently controlled skew quads are adequate to obtain a reasonably decoupled machine with a reasonable dynamic aperture. It was likewise determined that 16 pairs of skew quads are not sufficient to decouple the machine at injection optics. The minimum acceptable number and optimum placement of skew quads is a matter of continuing study.

A. Decoupling Formulation

The analytic formulation of the local decoupling algorithm is contained in Reference 2, Talman's discussion of single particle motion. A few of the key results will be repeated here for the sake of completeness.

The propagation of the four-dimensional phase-space vector X from point s_0 to s_1 is written in terms of the four-dimensional transfer matrix M shown below:

$$X_1 = M_{10}\, X_0 \ . \tag{1}$$

The localized transfer matrix M_{10} may be written in terms of the once-around transfer matrixes M_1 and M_0 at locations s_1 and s_0, respectively. The relationship is given as

$$M_1 = M_{10}\, M_0\, \overline{M_{10}} \ , \tag{2}$$

where the bar indicates the symplectic inverse of the localized transfer matrix. The approach is to block diagonalize the once-around transfer matrixes at a sequence of points $s_0, s_1, \ldots, s_n$. The procedure necessary to block diagonalize each individual transfer matrix starts by breaking up the 4×4 matrix into four 2×2 matrices denoted by A, B, C, and D. One then forms linear combinations of the B and C submatrices responsible for coupling:

$$M = \begin{bmatrix} A & B \\ C & D \end{bmatrix} . \tag{3}$$

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These are called R_A and R_D and are given by these expressions:

$$R_A = \frac{C + \overline{B}}{\Lambda_A - tr\,D}\,, \qquad R_D = \frac{B + \overline{C}}{\Lambda_D - tr\,A}\,. \tag{4}$$

It can be shown that the matrixes R_A and R_D are not independent of each other and that only four of the eight terms in the two matrixes are in fact independent. It is possible to form two parameters, e_A and e_D, which are physically observable and can be minimized to minimize the coupling. The expression for e_A is given below with a completely analogous expression for e_D:

$$e_A^2 = \left[R_{A11} + \left(\frac{\alpha_A}{\beta_A} R_{A12}\right)\right]^2 + \left(\frac{R_{A12}}{\beta_A}\right)^2. \tag{5}$$

The value of eA **2 is equal to the ratio of the out-of-plane tune amplitude to the in-plane tune amplitude and is a physically measurable quantity. Section 4 describes measurements of this quantity made in the HERA proton ring. The decoupling process consists of forming a weighted sum of the e_A terms at the position of every instrumented BPM, calculating the set of skew quad corrector strengths necessary to minimize the sum, and applying these strengths at the skew quad locations. It should be noted that this method has sufficient information to set each skew quad independently, and it is not necessary to connect the skews in two or four families.

B. Decoupling Studies at the SSC

The specific problem of decoupling the SSC lattice has been studied using the accelerator simulation code described in Reference 3 (Schachinger and Talman). The specific issue has been to investigate the possible planments, patterns, quantity, and strengths of skew quads necessary to decouple the collider.

The quantities used to parameterize the decoupling process are the decoupling badness function defined above and the peak and average values of the vertical dispersion. A brief summary of results is contained in Table 1.

The study concluded that the collider can be satisfactorily decoupled in the presence of all known coupling terms if the tunes are separated by an integer difference of at least 1. It is necessary to use approximately 100 independently powered skew quads located in cell centers which have a strength of (GL) of 35 Tesla. Alternatively, 56 skew quads at the location of the missing dipoles will decouple the lattice, but a peak strength of 67 Tesla appears to be required.

The optimum location, number, and placement of skew quad correctors are matters of continuing study. The ultimate choice of corrector scheme will involve a consideration of the dynamic aperture in addition to the local badness and vertical dispersion criteria. However, these last two parameters provide a quick means of making preliminary comparisons of different corrector layouts.

C. Experimental Measurements at HERA Proton Ring

The local decoupling technique described in the previous sections requires as input the local decoupling badness function, which is defined to be the ratio of betatron tune amplitudes measured at many places around the accelerator. The ability to measure the decoupling badness in a real operational environment is critical for the local decoupling method to work. An experimental measurement of this quantity was therefore carried out on the HERA proton ring. The experiment consisted of capturing turn-by-turn BPM data from each of the 137 monitors in each plane (274 monitors total) at injection. The data were analyzed using Fourier transform techniques, and the horizontal and vertical betatron tunes were determined. The amplitude of the vertical betatron tune line in the horizontal BPM data was extracted, as was the amplitude of the horizontal tune line (which was, of course, dominant). The transformed BPM data for the horizontal and vertical planes are shown in Figures 1 and 2, respectively. The ratio of the small-to-large tune amplitudes at each BPM is given in Figures 3 and 4.

Table 1

Number	Badness	Vertical Dispersion	Comments
			small al (0.04 units) GREV5 lattice
32	4.69	0.4 m rms	$\mu_x = 123.285$ $\mu_y = 124.265$
32	0.059	1.1 m rms	$\mu_x = 123.285$ $\mu_y = 125.265$
			injection energy 1.8 TEV
32	NA	NA	no solution unstable optics
			al = 0.3, 10F lattice 20 TEV
92	0.0029	0.8 m rms 2.2 m peak	one pair of skew quads every 8 cells
100	0.0031	0.4 m rms 1.6 m peak	minimum eta placement
200	0.001	0.2 m rms 0.8 m peak	one pair of skew quads every 4 cells
47	0.03	0.3 m rms 0.8 m peak	one quad in missing dipole 500 detectors

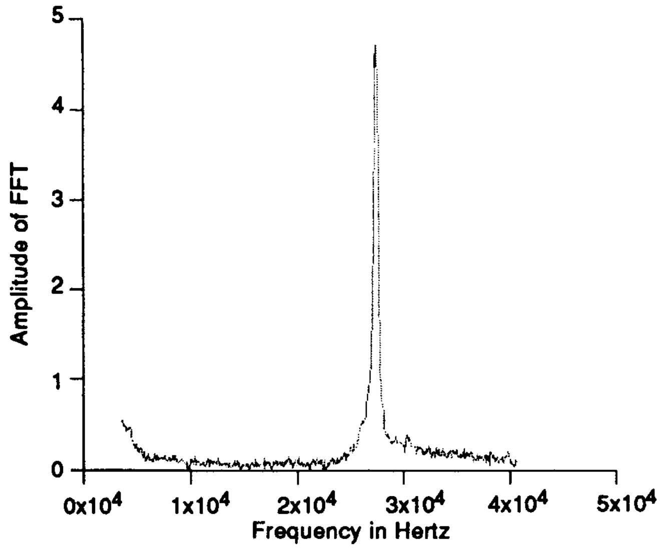

Figure 1. Horizontal Data.

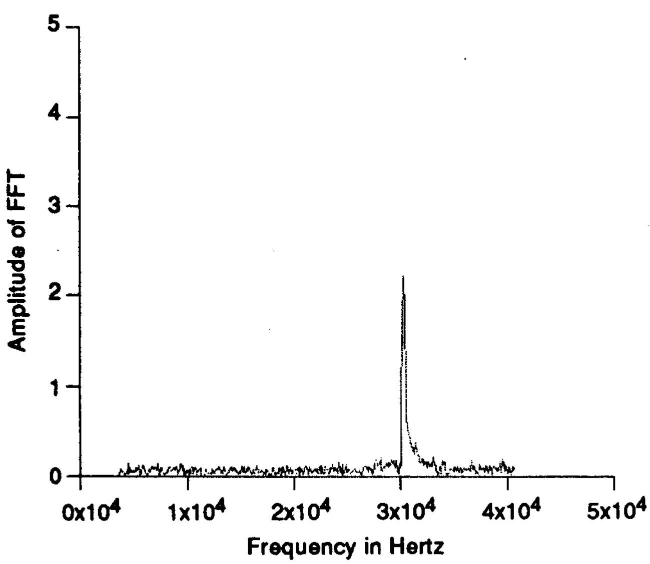

Figure 2. Vertical Data.

The horizontal coupling badness has a maximum value at the location of the skew quad pair in the IR sections. However, the RMS value is less than the corresponding function in the vertical plane, indicating that the global decoupling will put a large local perturbation into the optical functions while reducing the overall coupling. The magnitude of the coupling functions are proportional to the tilt of the local eigenplanes.

The measurement of the local coupling functions on an operating accelerator shows that the quantities necessary for local decoupling can be experimentally measured. It remains to be demonstrated that these values can be used to locally set skew quadrupole strengths.

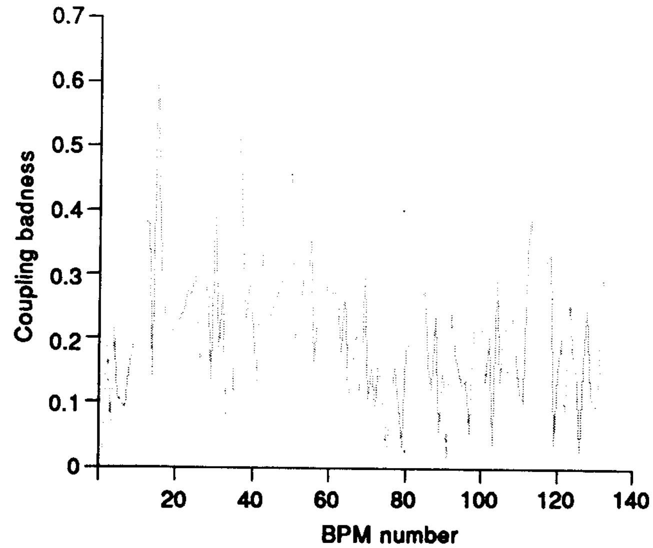

Figure 3. Horizontal Coupling Badness.

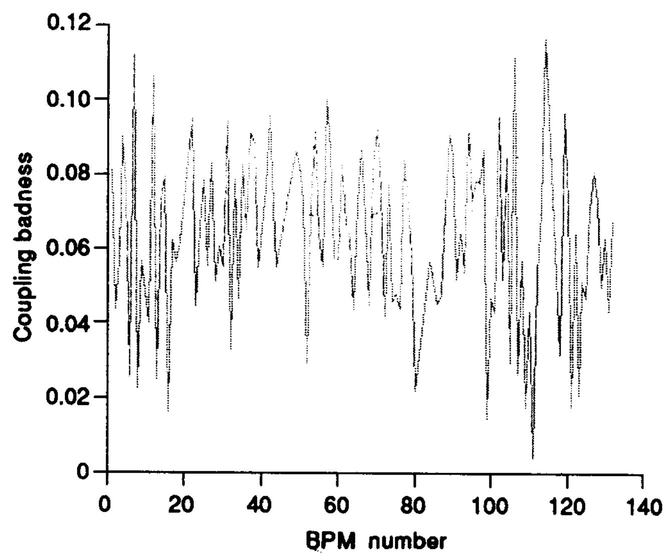

Figure 4. Vertical Coupling Badness.

II. CONCLUSIONS

This paper has shown results indicating that it will be possible to locally decouple the SSC lattice using a local decoupling algorithm. The mathematical basis of the algorithm was described briefly, and references were given for a complete description. Experimental measurement of the local coupling function required by the algorithm has been demonstrated on the HERA proton ring.

III. REFERENCES

[1] Richard Talman, Coupling Effects in the SSC Regular Arcs, SSC-N-93, December 1985.

[2] Richard Talman, "Transverse Motion of Single Particles in Accelerators," *AIP Conference Proceedings*, No. 184, 1987, p. 190.

[3] L. Schachinger and R. Talman, "TEAPOT: A Thin-Element Accelerator Program for Optics and Tracking," *Particle Accelerators*, 1987, Vol. 22, pp 35-56.