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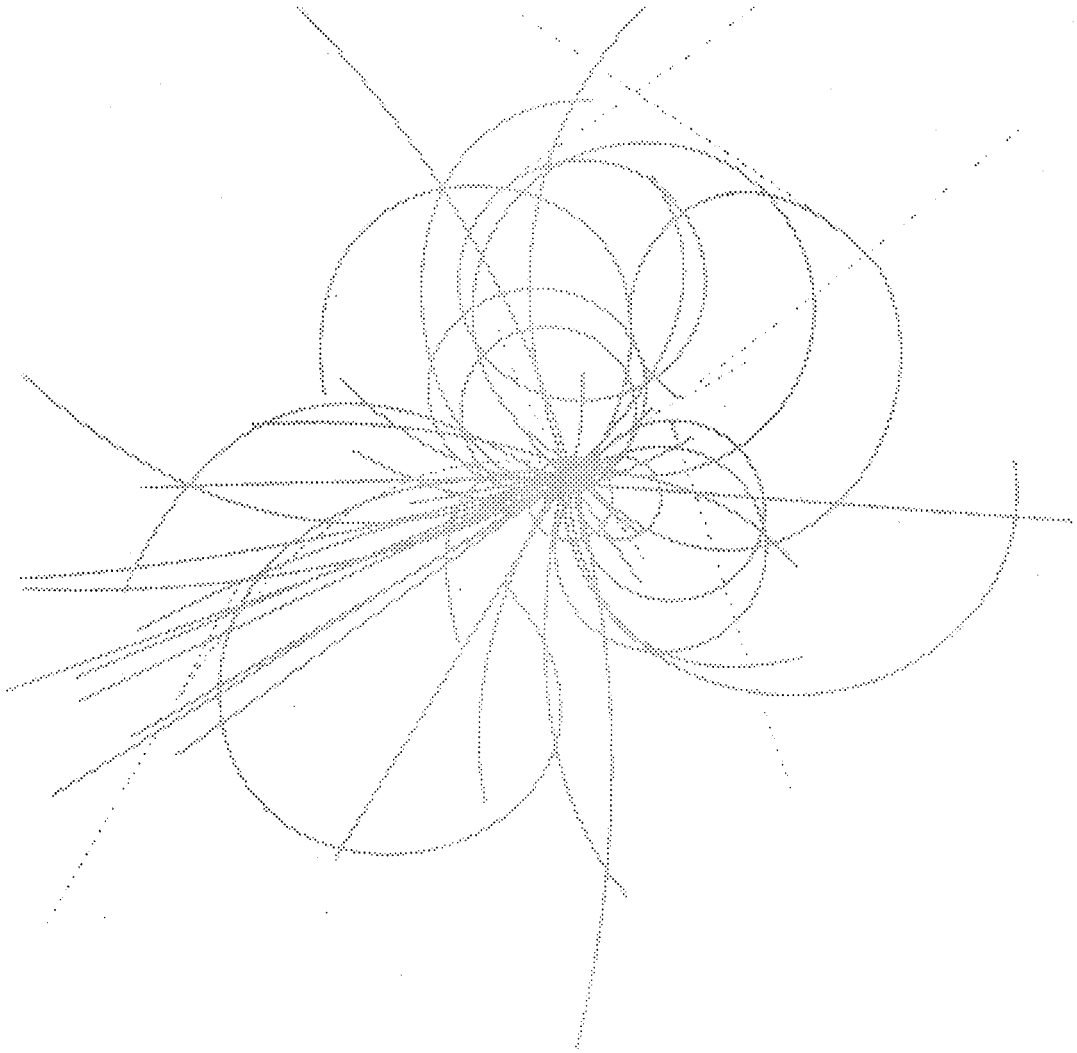

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Compensation of Coupling in the SSC Complex

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Abstract

This paper will describe a study of the coupling effects and their compensation by means of local decoupling techniques for some of the accelerators in the SSC Complex. Results concerning corrections and decoupling for the Low Energy and Medium Energy Boosters will be compared to results obtained for the Collider Ring. Some preliminary experimental data about measurement of coupling quantities will also be presented.

1.0 Introduction

The analysis of lattices for the SSC circular accelerators is carried out following a general procedure for the corrections and the optics performance evaluation. The perfect lattice is perturbed by a realistic set of errors and the corrections are applied so that the series of operations on the lattice closely reproduce a realistic operational scenario. In fact, the code used to this purpose,[1] together with its graphic postprocessors, can play as a model for development of high level application software. A detailed discussion about the general philosophy underlying this approach to linear correction of the machine can be found elsewhere[2] in these Proceedings and will be not repeated here. It is however worth recalling that the correction of coupling is treated in the context of a series of operations, as for instance closed orbit corrections, retuning, compensation of chromaticity, that are repeated until the perturbed lattice achieves a satisfactory performance.

Coupling of the horizontal and vertical motion in accelerators is usually corrected with two families of skew quadrupoles set up to minimize the separation between the horizontal and vertical betatron tunes; two more families of skew quadrupoles may be used to compensate the effect of the main coupling resonance Q_x-Q_y=0. These are examples of global corrections. The method we use is different in that the coupling is compensated sector by sector, hence it is intrinsically a local correction. By minimizing a badness function, that contains information about the local ratios of out-of-plane tune amplitude versus the in-plane tune amplitude, one can derive the strength of the skew quadrupoles required to decouple the machine. The mathematical formulation underlying this method can also be found in these Proceedings[3] and will not be discussed here.

What will be discussed in detail is the application of this correction method to several lattices in the SSC accelerator complex. Though the sources of coupling in the machines are qualitatively the same, as well as the technique used for its compensation, different schemes have to be developed for the different lattices given their intrinsically different optics design, different error specifications and different required performance.

Finally, we will discuss some experimental results obtained at HERA and at the FNAL Main Ring, whose goal was to demonstrate the capability of measuring coupling quantities, in particular the already mentioned ratio of out-of-plane versus in-plane tune amplitudes, which is the main information to be extracted from the beam position monitors in order to locally compensate the coupling.

2.0 Compensation of coupling for the MEB

A systematic study about the effect of coupling and its correction has been performed for the MEB lattice, and will be discussed here after a brief discussion of the MEB lattice.

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2.1 The MEB lattice

The MEB is a 3960 meters long synchrotron that accelerates the 12 GeV/c beam extracted from the LEB to 200 GeV/c, the injection energy of the HEB. This machine has to provide clockwise and anticlockwise injection into the HEB, when operated as an injector, as well as provide an extracted test beam. The lattice is built of 8 arc modules and 8 straight sections, 6 of which are long and 2 short, so that the superperiodicity of the machine is 2. The transverse stability results we will present concern 2 versions of the lattice, meb16 and the present one, meb20. Since they differ only slightly in some drift lengths, they are essentially equivalent from a beam dynamics point of view. The operating point of the machine is around 25.4 in both planes, close enough to the half integer to make the 1/2 integer resonant extraction possible.

2.2 The errors

The unperturbed MEB lattice has a dynamic aperture of about 1000 π mm*mrad normalized when the chromaticity sextupoles are configured so that the driving terms of the third order resonance are minimized[4]. Simulations are used to evaluate the performance of the lattice in presence of a reasonable set of errors and imperfections. In our model, it is possible to define random alignment errors for all the elements in the lattice as well as random and systematic field errors in the dipoles and quadrupoles. A detailed listing of these errors can be found in Table 1 and 2. The values in parenthesis in Table 2 are the ones used as a starting point for the coupling studies while the other values are the present error specifications for the MEB lattice. Work on the detailed effect of the individual multipoles on the dynamics are still in progress and a matter of continuing study.

Table 1: Alignment rms errors specifications

elements	Δx (mm)	Δy (mm)	$\Delta\theta$ (mrad)
bends	2.0	1.0	0.5
quadrupoles	0.5	0.5	0.5
sextupoles	0.5	0.5	0.5
beam position monitors	1.0	1.0	0.0

Table 2: Field errors specifications.
The field multipoles are given in units of 10^{-4} at a reference radius R=2.54 cm.

multipole component	error in bends systematic	error in bends random	error in quadrupole systematic	error in quadrupoles random
b1	0.10 (0.10)	0.10 (0.10)	(---)	(---)
b2	1.00 (1.50)	0.50 (0.50)	1.00	1.00
b3	0.30 (0.30)	0.10 (0.10)	2.00	1.00
b4	0.30 (0.50)	0.10 (0.30)	1.00	1.00
b5	0.10 (0.20)	0.05 (0.10)	1.00	1.00
b6	0.05 (0.10)	0.03 (0.10)	0.50	0.50
b7,b8,b9	0.02..(----)	0.02 (----)	0.03	0.03
a1	0.10 (1.00)	0.05 (0.10)	(----)	(----)
a2	0.05 (----)	0.05 (----)	0.10	0.10
a3	0.03 (----)	0.05 (----)	0.10	0.10
a4	0.03 (----)	0.05 (----)	0.10	0.10
a5	0.02 (----)	0.02 (----)	0.05	0.05
a6	0.02 (----)	0.02 (----)	0.05	0.05
a7,a8,a9	0.02 (----)	0.02 (----)	0.05	0.05

The main sources of coupling are the roll alignment error in the quadrupoles and the skew quadrupole field error a1 in the dipoles. What follows is a systematic study of the combined effect of these errors and their compensation, with the goal of determining the required tolerances and a viable compensation scheme.

2.3 Effect of coupling

The set of errors that has been used for this particular study are the alignment errors listed in Table 1 and the field errors in the dipoles listed in parenthesis in Table 2. There are no field errors in the main quadrupoles. Before tracking, the closed orbit is corrected and the chromaticity reset to zero. Particles with initial conditions at increasing amplitude are tracked and the dynamic aperture identified with the normalized emittance of the last particle surviving after 1000 turns. The effect of the normal field errors in the dipoles is to reduce the dynamic aperture from about 1000 to 250 π mm*mrad.

Table 3: Effect of the a1 error term and of the roll alignment error. Q_x=25.420, Q_y=25.435

systematic a1 10-4 at 2.54cm	random a1 10-4 at 2.54cm	roll error (mrad)	local coupling badness (max)	eigenangles (degrees)	dynamic aperture (π mm mrad)
0.0	0.0	2	0.70	30	250
1.0	0.1	0	0.02	23	250
1.0	0.1	2	0.8	45	100
0.5	0.1	2	0.6	45	100
0.1	0.1	2	0.15	45	80

Table 4: Effect of the a1 error term and of the roll alignment error Q_x=25.392, Q_y=25.427

systematic a1 10-4 at 2.54cm	random a1 10-4 at 2.54cm	roll error (mrad)	local coupling badness	eigenangles (degrees)	dynamic aperture (π mm mrad)
0.0	0.0	2	0.06	32	200
0.1	0.1	2	0.038	33	150
1.0	0.1	2	—	—	—

Table 3 describes the effect of coupling caused by the a1 field errors term in the dipoles and by the roll alignment error in the quadrupoles. The amount of coupling in the machine is measured by the eigenangles, that describe the inclination of the horizontal eigenplane of the coupled motion with respect to the uncoupled horizontal plane. If no coupling is present, the angle is zero. As it can be seen, the roll alignment error alone does not have a substantial effect on the dynamic aperture even if creates a large coupling. The systematic a1 error does on the contrary fully couple the horizontal and vertical motion (eigenangles of 45 degrees), causes a substantial reduction of the dynamic aperture and degrades the linear aperture of the machine, as can be seen from Figure 1.

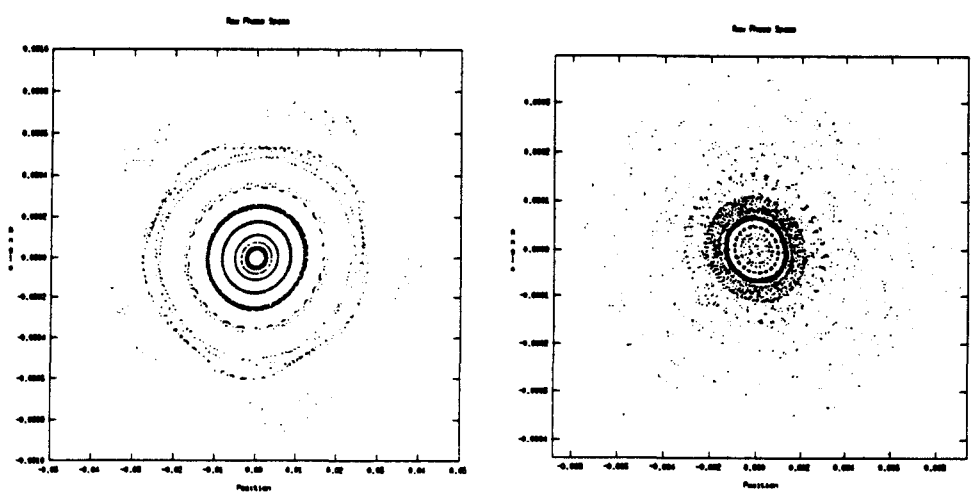

Figure 1: Horizontal and vertical phase space for the MEB lattice with no coupling compensation.

This effect has been observed for several fractional tunes, and one example is described in Table 4. In presence of 1 unit of systematic a1, it is not possible to find a closed orbit at this particular tune.

2.4 Decoupling

The reduction in dynamic aperture caused by the a1 error term makes a decoupling scheme necessary and the purpose of this study is to compare possible options for the distribution of skew quadrupoles around the ring in order to optimize the correction. To minimize their strengths, the skew quadrupoles should be placed in pairs at locations where the difference between the vertical and horizontal phase advances $(\phi_x^2-\phi_x^1)-(\phi_y^2-\phi_y^1)$ is as close to $\pi/2$ as possible.
As it can be seen from Table 5, it is not possible to satisfactory decouple the machine when the systematic a1 is larger than 0.1 units, even when every cell in the arc is equipped with a skew quadrupole pair, for a total of 64. Moving the position of the skew quadrupoles within the cell does not improve the correction, as can be seen in Table 6. When the systematic a1 is of the order of 0.1 units, a satisfactory solution can be found with a much smaller number of pairs. 2 pairs per arc for a total of 16 will compensate for 0.1 units of a1 and 2 mrad of roll error. For a roll error of 0.5 mrad, 1 pair per arc (or alternatively 1 pair per straight section) for a total of 8 is enough to keep the eigenvalues everywhere below 5 degrees. The solution of placing the skew quadrupoles in the dispersion free straight sections is to be preferred in that it avoids generation of vertical dispersion.

Table 5: Decoupling. The skew quadrupoles are located close to the main quadrupoles

systematic a1	random a1	roll error (mrad)	number of skew pairs	local coupling badness	eigenangles (degrees)	global coupling badness
1.0	0.1	2	62	1.0	45	105
0.5	0.1	2	62	0.3	45	92
0.1	0.1	2	62	0.003	5.5	13
0.1	0.1	2	16	0.007	7.0	3.6
0.1	0.1	2	17	0.003	5.5	3.7
0.1	0.1	0.5	17	0.0012	4.0	4.1
0.1	0.1	0.5	8	0.007	6.0	1.8
0.1	0.05	0.5	8	0.002	3.0	0.005

Table 6: Decoupling : The skew quadrupoles are located close to the main dipoles.

systematic a1	random a1	roll error (mrad)	number of skew pairs	local coupling badness	eigenangles (degrees)	global coupling badness
1	0.1	2	16	1.2	45	105
1	0.1	0.5	16	1.3	45	92
0.5	0.1	0.5	16	0.3	5.5	13
0.1	0.1	0.5	16	0.001	5.2	4.6

The last entry in Table 5 corresponds to the present specifications for the MEB field and alignment errors: the reduction of the random a1 to 0.5 units allows the configuration of 8 pairs of skew quadrupoles to keep the eigenvalues below 3 degrees everywhere around the ring, which is considered to be quite satisfactory. The behavior of the local coupling badness and of the eigenangles after correction is described in Figure 2.

The dynamic aperture of the decoupled machine is 250 π mm*mrad, comparable with the aperture of the machine with only normal multipoles in the bend and no active coupling source. The improvement on the linear aperture of the lattice can also be observed in Figure 3.

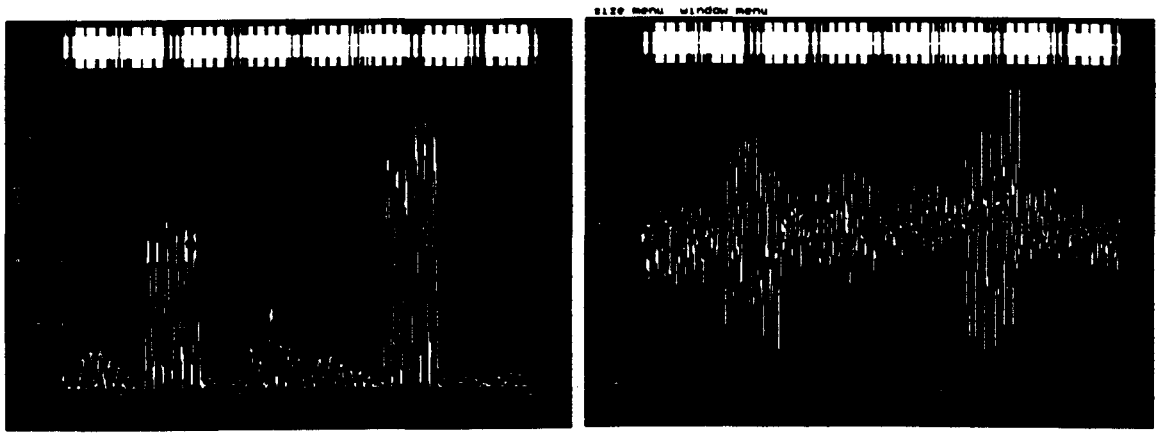

Figure 2: Local coupling badness and eigenangles in the MEB after correction.

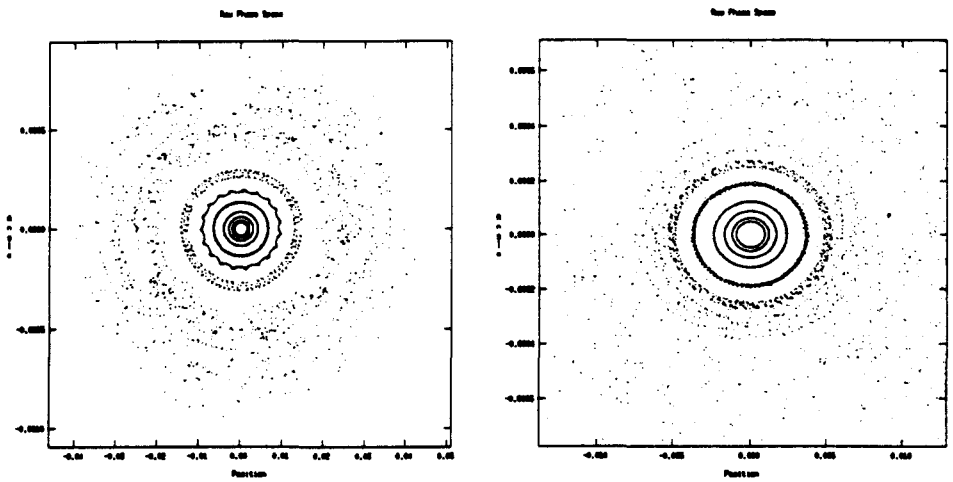

Figure 3: Horizontal and vertical phase space for the MEB lattice after correction of coupling.

3.0 Compensation of coupling for the LEB

A study to evaluate the effect of coupling and its compensation has been performed also for the LEB, the 570 m long booster that accelerates the beam extracted from the Linac at 1.3 GeV/c to 12 Gev/c. The LEB has a superperiodicity of 3 and a high transition γ so that the machine operates below transition. An analogous investigation on the effect of the alignment roll error and of the skew quadrupole error a1 in the dipoles has been carried out. The conclusion of this study is that 6 pairs of skew quadrupoles placed in the straight section achieve a very satisfactory decoupling, when the roll alignment error in the quadrupoles is 1 mrad and the skew quadrupole error in the dipoles is 0.1 units (at a reference radius of 5 cm). The eigenangles are below 1.5 degrees everywhere in the machine.

4.0 Comparison with the Collider Ring.

The Collider Ring, being a much larger machine with two very long arc regions and two interaction regions, requires a more sophisticated decoupling scheme if the system has to be able to compensate for the effect of a systematic a1 error term that might be as big as 0.3 units. A comprehensive study of possible decoupling schemes for the collider ring has been performed[3,5] where different skew quadrupole arrangements have been compared and analyzed. The preferred solution is the one where 56 skew quadrupoles are distributed in the arcs and 24 skew quadrupoles in the interaction region, for a total of 80 skew quadrupoles in the ring. Even for a systematic a1 as large as 0.3, the eigenangles can be kept under 10 degrees everywhere in the ring if the local decoupling scheme is adopted. This solution moreover retains the possibility of decoupling the machine globally, if desired, by wiring in families the 24 skew quadrupoles in the interaction regions.

5.0 Experimental measurement of coupling quantities

The ability to observe local coupling quantities is critical for the operational feasibility of the local decoupling technique. In particular, the local out-of-plane versus in-plane tune amplitude ratio, that enters the badness function is a quantity that can be measured experimentally. The ratio A_{xy}/A_{xx}, where A_{xx} and A_{xy} are respectively the amplitudes of the horizontal and vertical betatron tune as observed by an horizontal bpm, and A_{yx}/A_{yy} (with analogous definitions for A_{yx} and A_{yy} readings at a vertical bpm) can be extracted from beam position monitor data. We will briefly describe two measurements recently performed at the Hera proton ring and at the Fnal Main Ring whose goal is to demonstrate the feasibility of extracting local coupling information from bpm data.

5.1 The HERA measurement

The experiment consisted in reading out 134 beam position monitors per plane in the Hera proton ring at injection energy (40 GeV/c). The turn-by-turn data for 1024 turns have been processed via FFT analysis in order to extract the horizontal and vertical tune signal for each bpm; this ratio is the local coupling badness. The injection errors provided sufficient excitation to measure the tune amplitudes. After the rejection of signals coming from faulty bpms we were able to measure the horizontal and vertical local coupling badness in the machine. More detailed results about this measurement can be found elsewhere in these Proceedings[3].

5.2 The FNAL measurement.

The goal of this experiment is to measure the the badness in the machine, correct for the local coupling and verify experimentally the decoupling by remeasuring the badness after correction. While in Hera the betatron oscillation is excited by injection errors, at the Main Ring the beam receives a non destructive excitation in the form of a low level RF signal. The beam is excited horizontally or vertically with the assumption that the eigenmotion A and D of the coupled system are close to, respectively, the x and y motion (weak coupling assumption). The signals are read at 2 vertical and 2 horizontal bpms and the data processed by FFT analysis in order to determine the badness, as a function of different skew quadrupole strengths.
This non destructive measurement was possible because the signal to noise ratio had been improved by analyzing the autocorreleation of the signal instead of the bare signals from the bpms.
The first part of the program, the non destructive measurement of coupling badness, has been accomplished and the second one, the actual verification of local decoupling, is the subject of an upcoming dedicated measurement at the FNAL Main Ring.

6.0 Conclusions

The local decoupling technique has been applied to compensate for coupling in several lattices of the SSC complex and satisfactory solutions could be found for the LEB, MEB and Collider. Preliminary experimental results that demonstrate the ability of observing local coupling quantities have also be presented.

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