Workshop on LHC Interaction Region Correction Systems, BNL, Upton, New York, 1999

LOCAL DECOUPLING IN THE LHC INTERACTION REGIONS

BNL-66797

F. Pilat
Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Local decoupling is a technique to correct coupling locally and operationally, that is, without a priori knowledge of the underlying skew quadrupole errors. The method is explained and applied to the correction of coupling in the interaction regions of the LHC at collision.

1 INTRODUCTION

The local decoupling method is reviewed in Section 1 with a brief history of its application to different machines and experimental work performed so far. In Section 2 we present preliminary results for the correction of coupling generated by triplet errors in the LHC interaction regions, in the collision configuration.

2 LOCAL DECOUPLING TECHNIQUE

The local decoupling algorithm has been proposed by R. Talman [1] as a technique to correct coupling locally and operationally, since the correction scheme does not require a-priori knowledge of the errors. Conceptually the local correction of coupling is similar to a closed orbit correction where the orbit offsets as measured at the beam position monitors (BPM's) are used in a χ–square minimization that sets the strengths of the dipole correctors. In fact local decoupling was originally proposed by Talman in the framework of a general technique for operational corrections, which includes also closed orbit correction, minimization of vertical dispersion, etc. The idea is to determine corrector strengths by minimizing a *badness function* that i) quantifies the effect to be corrected and ii) is built up by measurable quantities. The next few paragraphs will describe how that can be achieved. A more detailed description can be found in [2].

2.1 Method and formalism

Let's define the one turn 4x4 transfer matrix (in the cartesian space) as:

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

It is possible to find a coordinate transformation $x = G^T X$ to an *eigenbasis* where the 1-turn transfer matrix in the new coordinates is *diagonal*:

$$\underline{M} = G^{T^{-1}} M G^T = \begin{bmatrix} \underline{A} & 0 \\ 0 & \underline{D} \end{bmatrix}$$

$$\text{with} \quad G^T = g\begin{bmatrix} I & R_D \\ R_A & I \end{bmatrix} \quad \text{and}$$

$$R_A = \frac{C + \overline{B}}{\Lambda_A - \mathrm{tr}D} \qquad R_D = \frac{B + \overline{C}}{\Lambda_D - \mathrm{tr}D}$$

$$g = \sqrt{\frac{|\Lambda_D - \mathrm{tr}A|}{|\Lambda_D - \Lambda_A|}}$$

where Λ_A and Λ_D are the eigenvalues of the matrix $M+\overline{M}$.

The A *eigenmotion* describes an *ellipse* in the (x,y) space. The major axis is tilted w.r. to the x axis by an angle θ_A given by:

$$\tan 2\theta_A = \frac{2R_{A11} - \left(\frac{\alpha_A}{\beta_A}\right)R_{A12}}{1 - \left[R_{A11} - \left(\frac{\alpha_A}{\beta_A}\right)R_{A12}\right]^2 - \left(\frac{R_{A12}}{\beta_A}\right)^2}$$

An analogous relation exists between the D eigenmotion and the y axis. The **eigenangles** θ_A and θ_D, not orthogonal in general, are a *measure of coupling* since for the ideal uncoupled case $\theta_A = \theta_D = 0$. Another measure of coupling is the **area of the eigenellipse**, given by $(\pi g^2 |R_{A12}|)/\beta_A$ for the A eigenplane. If the coupling is weak, the areas of the 2 eigenellipses differ only by a multiplicative factor independent of coupling.

2.2 Measurable quantities

By driving the beam in such a way that only 1 mode is excited, the motion at one location in the lattice can be described in pseudo-harmonic form:

$$x = g\cos\psi_A \qquad\qquad y = g e_A \cos(\psi_A + \varepsilon_A)$$

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

$$\varepsilon_A = -\arctan\frac{R_{A12}/\beta_A}{R_{A11} - \left(\frac{\alpha_A}{\beta_A}\right)R_{A12}}$$

That is possible if the horizontal and vertical planes are not fully coupled. In practice that means that the uncorrected coupling should be weak, or the machine already has some degree of coupling compensation in place.

The x and y signals are *coherent* (same frequency) and their relationship at a specific position in the lattice is characterized by the *ratio of amplitudes* (e_A) and a *phase difference* (ε_A).

By collecting *turn by turn* x and y positions at a *double plane BPM*, it is possible to measure the quantities e_A and ε_A with a network analyzer. From these one can derive the matrix elements R_{A11} and R_{A12}. The coupling can be locally measured at every double plane BPM in the machine.

2.3 Correction of coupling

A badness function to be used for minimization must quantify coupling and go to zero in the absence of coupling. It must also be build with measurable quantities to be "operational". Measurable quantities are: e_A , the ratio of out of plane vs. in plane oscillations, and the phase difference ε_A.

A natural choice for the ***coupling badness*** B^C function is the following:

$$B^C = \sum_{d=1}^{N^d} e_A^2 \frac{\beta_x(d)}{\beta_y(d)} \qquad N^d \textit{ number of detectors (BPMs)}$$

By weighting e^2_A with the ratio of betas one insures that all detector have comparable weight in the minimization process. e_A is a function of the off diagonal matrix elements R_{A11} and R_{A12}. One can calculate the ***influence functions***:

$$R_{A11}(d) = R^o_{A11}(d) + \sum_{a=1}^{N^a} q_a^{skew} T_a^C(d)$$

$$R_{A12}(d) = R^o_{A12}(d) + \sum_{a=1}^{N^a} q_a^{skew} U_a^C(d)$$

where the R^o functions represent the effect of the unknown errors at the position of detector d, T^C and U^C can be calculated from the unperturbed lattice functions for every skew corrector and B^C is a function of the N_a skew quadrupole corrector strengths q_a^{skew}. When $N^d > N^a$ one can determine the **skew quadrupole corrector strengths** by a *fitting procedure* so that the following conditions are met:

$$\frac{\partial}{\partial q_a^{skew}} B^C\left(q_1^{skew} \ldots\ldots q_{N_a}^{skew}\right) = 0$$

The procedure to set the skew quadrupoles for coupling corrections relies only on measurements at double plane BPMs in the ring.

2.4 Brief history of studies and experimental work

Local decoupling is implemented in the code Teapot and the latter has been used to study coupling correction schemes for several accelerators. In particular, local decoupling schemes have been studied for the SSC Collider ring, for the LEP lattice and, more recently, for RHIC. In all cases the schemes worked well is simulation, with residual eigenangles after correction below a fraction of a degree everywhere in the ring. Local decoupling is an integral part of the RHIC decoupling scheme [3]. Two families of skew quadrupoles are used for global decoupling via the minimum tune separation technique. In collision, the additional coupling effect due to the IR triplets is locally corrected by 12 skew quadrupoles, 2 per interaction region. The IR skew quadrupoles can be set either by "dead-reckoning" the measured a_2 errors in the triplet, or by local decoupling. The latter has the advantage of correcting also for the unknown residual alignment errors.

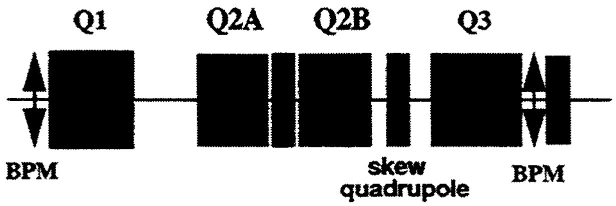
Experimental work on local decoupling has been started at HERA in 1991 and LEP in 1992. Local coupling has been successfully measured in both machines [4]. Setting the skew quadrupoles on the basis of the measurements and verifying the correction of coupling however must still be demonstrated. Local decoupling is part of the correction strategy in RHIC and experiments are planned in the 2000-2001 runs.

3 APPLICATION TO THE LHC INTERACTION REGIONS

A feasibility study of local decoupling for the LHC IR has been started. Even if the a_2 field error in the triplet will be known (and compensated for), the coupling effect due to residual roll errors of the quadrupoles can be quite substantial in the collision configuration. A way to set the skew quadrupoles in the IR correction packages to correct for that can be very useful.

3.1 The correction scheme

The following configuration and correctors has been assumed for the study;



Coupling is measured at the dual plane BPMs in the IRs and the skew quadrupole corrector layer in the IR corrector package is used, with a total of 16 BPMs and 8 skew quadrupoles in the LHC ring. Skew quadrupole correctors are present in IP1, IP2, IP5 and IP8.

3.1 Preliminary results

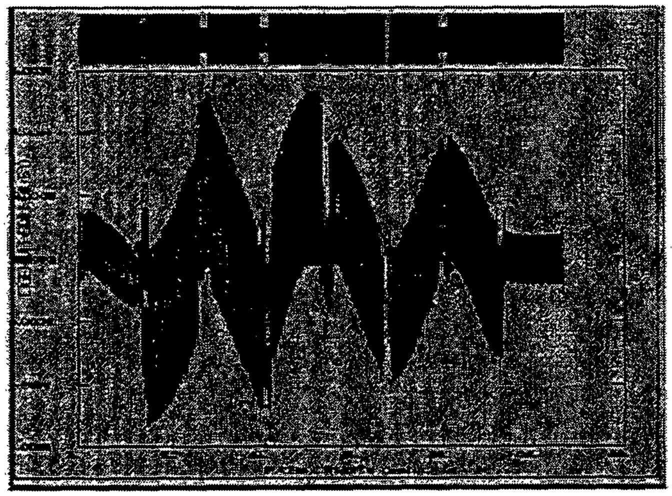
The effectiveness of the correction has been tested against a distribution of random roll errors in the HGQ quadrupoles. Table 1 summarizes the results.

Table 1: Effectiveness of correction as a function of errors.

RMS roll angle [mrad]	coupling badness (before corr.)	coupling badness (after corr.)	max eigenang (before corr.) [deg]	max eigenang (after corr.) [deg.]
0.2	8.41	0.001	45.0	0.08
0.3	10.47	0.45	45.0	0.34
0.4	11.75	3.16	45.0	6.18
0.5	12.64	6.35	45.0	20.0

Local decoupling is doing a good job in correcting for a random distribution of roll errors up to 0.4mrad. The limit seems to be reached at ~0.5 mrad with the present scheme. A reasonable figure of merit for decoupling quality is to keep the eigenangle less than 10 degrees everywhere in the ring. In simulations that has been verified to correspond to a mininum tune separation of less than 0.001.

Figure 1: Residual coupling around the ring after local decoupling (random alignment errors in the triplet of 0.2 mrad).



As an example, the integrated skew quadrupole strengths necessary for correcting a random distribution of 0.4 mrad in the triplets are listed in Table 2.

Table 2: Skew quadrupole integrated strengths.

skew quadrupole	interaction region	integrated strength [m^{-1}]
sql1	IP1	0.573 10^{-4}
sqr1	IP1	0.259 10^{-4}
sql2	IP2	0.139 10^{-4}
sqr2	IP2	-0.138 10^{-3}
sql5	IP5	0.947 10^{-5}
sqr5	IP5	0.240 10^{-4}
sql8	IP8	0.112 10^{-4}
sqr8	IP8	-0.157 10^{-5}

3.3 Future plans.

A detailed study of decoupling corrections will be done for the LHC Interaction regions, in the framework of a planned study on effect of alignment and linear corrections. Concerning linear decoupling, more specifically, one needs to evaluate different schemes as well as testing a statistically significative number of errors distributions.

4 CONCLUSIONS

Preliminary results on the effectiveness of local decoupling for the LHC at collision are promising. Coupling is reduced to a fraction of a degree everywhere in the ring by operationally setting the skew quadrupoles in the interaction regions on the basis of coupling measurements at the IR beam position monitors. A more detailed study for the LHC is planned as well as experimental work on the decoupling technique at RHIC.

5 REFERENCES

[1] R. Talman, *"A Universal Algorithm for Accelerator Correction"*, Proceedings of the "Advanced Beam Dynamics Workshop on effect of errors in accelerators, their diagnosis and correction", Corpus Christi, October 1991.

[2] L. Schachinger, R. Talman, *"Manual for the program TEAPOT"*, November 1994

[3] F. Pilat, S. Peggs, S. Tepikian, D. Trbojevic, J. Wei,*"The effect and correction of coupling generated by the RHIC triplet quadrupoles"*, PAC95, Dallas.

[4] G. Bourianoff, S. Hunt, D. Mathieson, F. Pilat, R. Talman, G. Morpurgo, *"Determination of coupled-lattice properties using turn-by-turn data"*, Proceedings of the "Stability of Particle Motion in Storage Rings" Workshop, BNL, October 1992.