CLOSED ORBIT ANALYSIS FOR RHIC*

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Abstract

We examine the effects of four types of errors in the RHIC[1] dipoles and quadrupoles on the on-momentum closed orbit in the machine. We use PATRIS[2] both to handle statistically the effects of kick-modeled errors and to check the performance of the Fermilab correcting scheme[3] in a framework of a more realistic modeling. On the basis of the accepted rms values of the lattice errors, we conclude that in about 40% of all studied cases the lattice must be to some extent pre-corrected in the framework of the so-called "first turn around strategy," in order to get a closed orbit within the aperture limitations at all and, furthermore, for approximately 2/3 of the remaining cases we find that a single pass algorithm of the Fermilab scheme is not sufficient to bring closed orbit distortions down to acceptable levels. We have modified the scheme and have allowed repeated applications of the otherwise unchanged three bump method and in doing so we have been able to correct the orbit in a satisfactory manner.

Introduction

We have selected four major types of lattice errors. They are the error in the integrated dipole field strength $\Delta D(B\ell)/B\ell$, the axial tilt of the dipole $\Delta\theta$, and the lateral displacements of the quadrupole along the two transverse directions.

The rms values we have used are the following ones:

$$\Delta(B\ell)/B\ell = 0.5 \times 10^{-3} \quad , \quad \Delta\theta = 10^{-3} \text{ radians,}$$

Lateral quad displacements $\Delta_Q X = \Delta_Q Y = 0.25 \times 10^{-3}$ m.

A 2.5 σ cut was imposed on all distributions of random errors. Sextupoles were modeled as thin lenses, but in all other aspects they were assumed perfect. Higher order multipole errors have not been included. Orbit correctors were assumed to be thin lenses. Both beam position monitors and correctors were assumed ideal, i. e. perfectly aligned with the axis going through an ideally placed quadrupole and monitors were assumed to have a perfect sensitivity.

The tracking/analysis code PATRIS was used to handle the simulation and analysis of closed orbit distortions and furthermore to correct them. The RHIC lattice we used was tuned with $\beta^* = 3$m.

The Results of Statistical Treatment of Closed Orbit Errors in the Kick Approximation

For the purpose of quick statistical treatment of the effects of magnet imperfections on the closed orbit, PATRIS employs an algorithm whose basic ingredients are given in the Courant-Snyder paper.[4] PATRIS runs over 21 independent distributions of random lattice errors and evaluates the appropriate orbit distortion rms values at the end of each magnet. The effects of errors are evaluated in the kick approximation, with nonlinearities, including those coming from chromaticity correcting sextupoles, being disregarded. The only place where nonlinearities are taken into account is evaluation of tune shifts and beta variations as a result of crossing of the sextupoles by a distorted closed orbit. No correctors are engaged at this stage.

The resulting closed orbit distortions are displayed in Figure 1 for the horizontal plane. We have similar results on the vertical plane. One immediately observes how the rms values of closed orbit distortions follow the local values of the relevant beta functions. In the insertions these rms values can become quite large.

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The results of the effects of the sextupole crossing by a distorted closed orbit are given in Table 1. One will notice that 10 out of 21 distributions of random lattice errors produce unstable lattices when the sextupoles are taken into account, at the specified input rms values of magnet imperfections (the value −1.0 in the output is meant to signal an instability). The remaining 11 distributions have produced significant beta variations and tune shifts. The bottom line displays the rms values of the tabulated quantities.

The Results of Realistic Closed Orbit Modeling. The Performance of the Fermilab Correcting Scheme on RHIC

For a realistic closed orbit modeling, it is desirable to have a better scheme than that of a simple representation of lattice error effects by kicks. Furthermore, one would like to see what happens with closed orbit distortions once a certain well-defined sort of correction is implemented. Both goals have been attained in PATRIS, which on the one hand has the capabilities of simulating the lattice errors by incorporating them realistically into its 7 × 7 transfer matrix, and which on the other hand can correct the orbit by engaging the Fermilab correcting scheme, based on the so-called three bump method. The correctors are assumed to be BPM's at the same time and they have been placed beside focusing quadrupoles where the relevant beta function is large. Also in the arcs the orbit correctors at the same time appear to be adjacent to the chromaticity correcting sextupoles.

We started our analysis by assuming somewhat too stringent demands on acceptable lattice errors. All four types of errors were assumed to be at 10^{-4} levels in the appropriate units. We noticed that PATRIS always found a periodic solution for the perturbed lattice, but could not correct the distorted closed orbit down to acceptable levels (~1 mm) for a significant fraction of the 12 random error distributions we used. We attempted to cure this problem by introducing more correctors at additional locations, but improvements were almost negligible. We also attempted to correct the orbit with an overall scaling of evaluated corrector strengths, to see if we can undo a possible overcorrection/undercorrection, but no improvement resulted. Finally, we decided to abandon one basic assumption of the Fermilab correcting scheme: it is a single pass around, linear correcting algorithm. We made the necessary modifications and enabled PATRIS to repeat the correction several times if necessary. This action solved the problem; the second pass brought the orbit distortions down to acceptable levels. From that point we moved on to a more realistic set of lattice errors as given in the Introduction for which case we had run 12 different random error distributions.

In five out of these twelve cases badly distorted closed orbits were found, but attempts to correct them resulted in unstable lattices. These instabilities showed up in various ways; in one case the code printed out det $|M - I| \sim 10^{-3}$, which indicated the proximity of an integer tune, and then stopped, in some other cases the code stopped and displayed the message "Tr M > 2" in one plane, and finally there were cases when the code crashed even before being able to evaluate the one-turn map and its linearization M and to conclude that the lattice was unstable.

In the remaining seven cases the modified Fermilab scheme clearly worked well. Their results are displayed in Table 2. The first three cases in the table are called "good" since the second correction sufficed. They are followed by two cases we call "fair" because the results of the second correction are not too far from the levels which might be acceptable (~ 1 mm). The last two cases we call "poor" because after the second correction the maximum excursion of the closed orbit is still huge (i.e. beyond 10 mm!). Furthermore, the improvement between the first and the second correction is only about a factor two. In addition to this, the quality of the first

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correction is very low in both cases; indeed, very sharp readjustments of kick strengths between the first and the second correction are the most significant indicators of this questionable initial efficiency. However, the second correction brings even these two poor cases in line with the others and the third correction is then sufficient.

We would also like to mention that the worst of all working examples (the last example in Table 2), behaved as a sort of average example in the twelve pilot runs with the rms lattice error levels 10^{-4}, when all twelve sets of random errors generated a lattice whose stability was preserved in the process of orbit correction. For this reason, we have retained this example as a kind of "average" case out of twelve cases and have decided to use it to represent a succession of three corrections in Figure 2. Only one superperiod is shown. We showed only the case of horizontal plane. There is a similar behavior in the vertical planes.

Since the kick strength $\delta\theta = \delta(B\ell)/B\rho$ it follows that each milliradian of $\delta\theta$ translates into the integrated strength $\delta(B\ell) = (10^{-3}\ B\rho)$ T·m = 8.5 kG·m at the top magnetic rigidity $B\rho = 850$ T·m. The maximum kick angle we picked up in the seven successful runs was 0.196 milliradians, which will then translate into a 1.7 kG·m demand on the correctors' maximum integrated strength.

To address the issue of the hardware ability to make sufficiently precise readjustments between the two subsequent actions of the correcting algorithm, we call the reader's attention to Table 3. In this table we have displayed the kick strengths of the first 25 dipole correctors in each corrective pass. The reader will notice the interesting fact that between the monitors number 7 and 16 the algorithm does not readjust the values of the kick strengths found in the first pass. Indeed this region is an insertion without sextupoles and one can show that the kick strengths evaluated by the Fermilab correcting scheme, for a given set of orbit distortions, in a region free from nonlinearities depend only on the elements of the linear transfer matrix in this region and not on anything outside the region. The presence of external nonlinearities will only degrade the quality of the correction inside the nonlinearity-free region, i.e. the corrected closed orbit will not shrink to zero, but the corrector strengths inside the region remain unaffected. However, the presence of nonlinearities does affect correction strengths in the regions with nonlinearities. Therefore, if one takes two cases, one with sextupoles on and another with sextupoles off, then a one-pass Fermilab correction will shrink the corrected closed orbit distortions to zero at every monitor/corrector if all of the sextupoles are off, and nowhere exactly to zero if some of the sextupoles are on. Furthermore, the two cases will have different kick strengths in the regions with sextupoles, but the same strengths in the nonlinearity-free regions.

From the foregoing it should also be obvious that the second and further passes must leave the correctors' strengths unchanged in nonlinearity-free regions while at the same time keeping readjusting other correctors to get better and better orbit in each subsequent pass. In a real RHIC, of course, the insertions will contain nonlinearities from sources other than the chromaticity correcting sextupoles and the modified Fermilab algorithm will therefore readjust the insertion correctors in each pass too.

We notice that with the hardware ability to readjust the dipole correctors to an accuracy of 10^{-3} of the required maximum integrated corrector strength we can change the kick strength by approximately $0.2 \times 10^{-3} = 2 \times 10^{-4}$ milliradians. From Table 3 it is now obvious that the hardware will be capable of readjusting the kick strengths to move effectively from the second pass to the third one, which was enough in all our cases of successful orbit correction (i.e. seven out of twelve cases when the lattice was not made unstable by the very first correction). The 10^{-3} readjusting accuracy might be insufficient for a proper execution of the fourth correction, but an improvement of the hardware ability from a 10^{-3} to a 5×10^{-4} level will guarantee a feasibility of the fourth correction, if needed.

Conclusion

In our analysis of the closed orbit problem in RHIC, we have inevitably had to face the fact that this is by no means an easy machine to correct. Even at the very stringent 10^{-4} lattice error rms values, the Fermilab scheme could not correct the orbit to acceptable levels, in a single pass. A multipass generalization of the correcting scheme, which we implemented in PATRIS, worked well at this level of errors but failed in 5 out of 12 cases when the lattice errors were allowed to assume more realistic rms values. In these five "pathological" cases the lattice was still stable, the closed orbit was found by PATRIS but the first correction failed by producing an unstable lattice. Moreover, the uncorrected orbit was so grossly distorted that it exceeded physical aperture limitations in several places in the lattice. Under such harsh but not unlikely circumstances, the beam would never make its first turn around in a real machine and there would be no orbit at all to correct.

The problem will have to be dealt with in the framework of the first turn around strategy. The orbit would then be already partially corrected (or pre-corrected) once the first turn around has been established, and at that point a multipass Fermilab algorithm will have worked. We are currently working in this direction, having two possible approaches or a combination thereof in mind. One is to invest more efforts in attempting to undo a possible overcorrection in the Fermilab scheme's first pass. The other is to try first to establish a reasonably behaved orbit at reduced strengths of chromaticity correcting sextupoles.

References

1) Conceptual Design of the Relativistic Heavy Ion Collider-(RHIC), BNL 51932, May 1986.
2) PATRIS is a spin-off code from the PATRICIH family. It makes use of 7×7 matrix notation, sympletic conditions and it was initiated by A.G. Ruggiero
3) R. Raja, A. Russel and C. Ankembrandt, Nucl. Instr. and Meth A242, 15 (1985).
4) E. Courant and H. Snyder, Annuals of Physics 3, 1 (1958)

Table 1. Closed Orbit Analysis with Sextupoles Tune Shifts and Beta Variations

	HORIZONTAL		VERTICAL	
Dis.	DBETA/BETA	D-TUNE	DBETA/BETA	D-TUNE
1	-0.61080e+00	0.11678e+00	0.17343e+00	0.36227e-01
2	0.21213e+00	0.11024e+00	-0.10000e+01	-0.10000e+01
3	0.12634e+00	0.53150e-01	0.32545e+00	0.21784e-01
4	0.74651e-01	0.29184e-01	-0.10000e+01	-0.10000e+01
5	-0.10000e+01	-0.10000e+01	-0.10000e+01	-0.10000e+01
6	0.44044e+00	0.59466e-01	0.21207e+00	0.67815e-01
7	-0.75274e-01	0.31351e-02	0.83884e-02	-0.89551e-02
8	0.54885e-01	0.58652e-01	0.31767e+00	-0.60770e-01
9	-0.10000e+01	-0.10000e+01	-0.10000e+01	-0.10000e+01
10	0.32682e+00	0.27776e-01	-0.10000e+01	-0.10000e+01
11	-0.10000e+01	-0.10000e+01	-0.10000e+01	-0.10000e+01
12	0.79245e+00	0.10302e+00	0.10874e+01	0.18147e-01
13	0.26772e+00	0.66674e-01	0.12157e+01	0.31952e-02
14	-0.10000e+01	-0.10000e+01	-0.10000e+01	-0.10000e+01
15	-0.10000e+01	-0.10000e+01	0.98408e+00	0.36816e-01
16	0.15255e+01	0.11120e+00	-0.10000e+01	-0.10000e+01
17	0.34190e+00	0.75801e-02	-0.15200e-01	0.59675e-01
18	0.17660e+00	-0.12165e-01	-0.41959e+00	-0.11303e-01
19	-0.10000e+01	-0.10000e+01	0.20870e+00	-0.36469e-01
20	0.41621e+00	0.52842e-01	0.84593e+00	0.81115e-01
21	0.60671e+00	0.49663e-01	0.98606e+00	0.43429e-01
rms:	0.56475e+00	0.70768e-01	0.69632e+00	0.45952e-01

Table 2. Some Characteristics of Successfully Corrected Orbits

Seed	Iter. #	Corr. Orbit Dist. Max(mm)	rms(mm)	Comment	Kick strength(mrad) Max	rms
-23	1	6.150	2.015	Good	0.12355	0.03075
	2	0.358	0.133		0.11658	0.03089
	3	0.003	0.001		0.11625	0.03092
17	1	-3.246	1.336	Good	-0.17355	0.04743
	2	-0.966	0.339		0.15357	0.04412
	3	-0.006	0.002		0.15351	0.04412
43	1	5.228	1.689	Good	0.12248	0.03580
	2	0.784	0.281		-0.08124	0.03205
	3	-0.004	0.001		-0.08124	0.03208
7	1	8.389	2.863	Fair	0.13484	0.04460
	2	-2.245	0.742		0.13641	0.04224
	3	-0.046	0.015		0.13609	0.04227
25	1	-11.324	3.884	Fair	0.10809	0.03640
	2	2.803	0.948		-0.09056	0.03175
	3	-0.029	0.008		-0.09056	0.03161
-7	1	-25.296	8.099	Poor	0.19611	0.05392
	2	11.974	4.052		0.09209	0.02962
	3	-0.315	0.111		0.09209	0.02932
-54	1	-28.990	10.612	Poor	0.15719	0.04916
	2	15.876	5.866		-0.09022	0.03136
	3	-0.652	0.227		-0.09022	0.03040

The reader will notice that we have displayed both the orbit distortions and the kick strengths to an excessive number of significant digits. This has been done merely to show what the algorithm does and it in no way implies that we expect the orbit distortions to be observable to such high accuracy.

Table 3. Table of Kick Strengths (milliradians). Horizontal Plane

MON. #	Mag. #	ITER. # 1	2	3	4	5
1	6	0.042472	0.076945	0.046834	0.042339	0.042335
2	34	0.112830	-0.004767	-0.005301	-0.005304	-0.005308
3	62	0.037541	0.059505	0.049341	0.045199	0.045197
4	90	0.138669	0.012961	0.010967	0.011046	0.011043
5	118	-0.023418	0.005356	-0.026847	-0.031044	-0.031050
6	146	0.076070	-0.028085	-0.029744	-0.030097	-0.030098
7	173	0.036559	0.023843	0.022304	0.022606	0.022607
8	185	0.027164	0.027164	0.027164	0.027164	0.027164
9	205	0.022299	0.022299	0.022299	0.022299	0.022299
10	217	0.003942	0.003942	0.003942	0.003942	0.003942
11	229	-0.026121	-0.026121	-0.026121	-0.026121	-0.026121
12	271	-0.008038	-0.008038	-0.008038	-0.008038	-0.008038
13	283	0.013105	0.013105	0.013105	0.013105	0.013105
14	299	-0.020396	-0.020396	-0.020396	-0.020396	-0.020396
15	315	-0.018751	-0.018751	-0.018751	-0.018751	-0.018751
16	333	0.009413	-0.025828	-0.032798	-0.035617	-0.035617
17	361	0.077437	-0.008263	-0.010680	-0.011295	-0.011300
18	389	0.069349	0.077276	0.058949	0.055566	0.055564
19	417	0.127981	0.022859	0.021157	0.020951	0.020949
20	445	-0.003765	-0.009032	-0.017066	-0.020455	-0.020456
21	473	0.125491	0.006630	0.005244	0.005070	0.005063
22	501	-0.046165	-0.025401	-0.045892	-0.049341	-0.049342
23	529	0.046987	-0.060338	-0.061279	-0.061321	-0.061325
24	557	-0.017000	-0.004707	-0.013266	-0.016718	-0.016720
25	585	0.157191	0.036337	0.035051	0.035147	0.035142

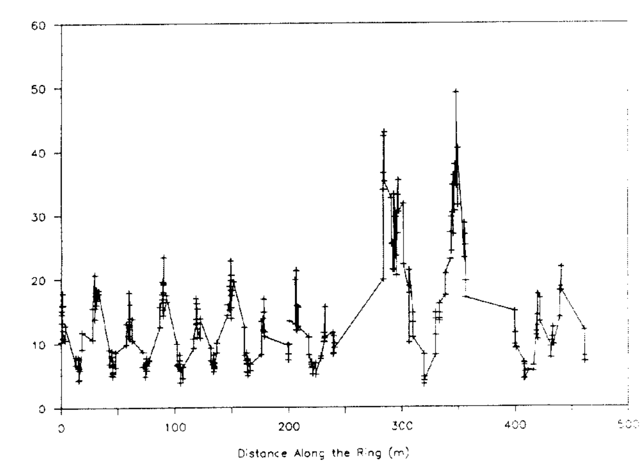

Fig. 1. Expectation value in mm of horizontal closed orbit uncorrected distortions in RHIC from 21 different simulations.

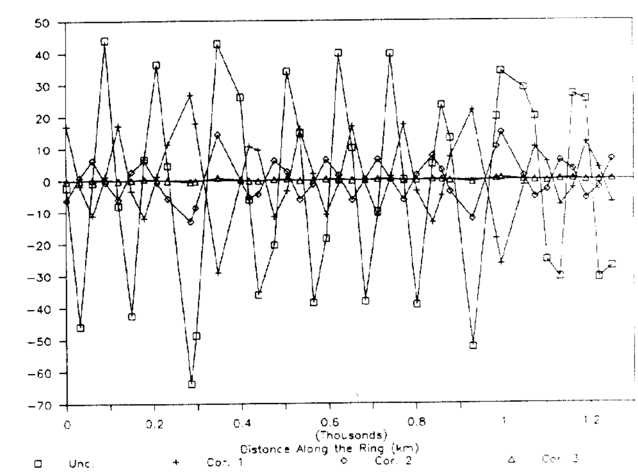

Fig. 2. A realistic RHIC closed orbit in the horizontal plane uncorrected (□), after 1st (+), 2nd (◇) and 3rd (Δ) correction step.