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FIRST TURN AROUND STRATEGY FOR RHIC*

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Abstract

We present a strategy for achieving the so-called first turn around in RHIC. The strategy is based on the same method proposed to correct a distorted closed orbit in RHIC, i.e. on a generalization of the local three-bump method.[1] We found out that the method is very effective in passing the beam through a non-ideal, insufficiently known, machine. The perturbed lattice was generated by the code PATRIS, which was also adapted to control the newly developed software. In ten distributions of errors the software was capable of passing the beam through in 2-3 injection attempts, at full sextupole strength. It was also determined that once the beam makes the first turn around and all the correctors are energized, it stays in the machine for at least several hundred turns.

I. INTRODUCTION

An accelerator lattice cannot be expected to be perfect and as a consequence the same is true for the closed orbit in the machine. Since assumptions can be made about the order of realistic lattice imperfections, it is also possible to estimate the order of the resulting closed orbit distortions. If there is a well-defined correcting scheme, a distorted closed orbit can also be corrected to a level of distortions which are acceptable. This in turn requires a beam circulating in the machine, so that the orbit readings can be taken. An important consequence is the existence of a very special moment in the history of every accelerator, i.e. the situation when the machine is completed and ready to work, but the beam has yet to be injected for the first time. The problem is the unknown machine which will obviously give rise to a distorted closed orbit, but which cannot be corrected before the readings are taken. Since correctors cannot be adequately set, the beam is first injected without any correction and can easily encounter physical aperture limitations and be lost before making the first turn around. This necessitates implementation of a special strategy called "the first turn around strategy", to complete one turn, after which one hopes to know enough about the effects of lattice imperfections to be able at least to keep the beam in the machine until the orbit can be better corrected. In the case of RHIC, realistic closed orbit analysis[1,3] indicates that there are very good chances that the beam hits the walls of the vacuum chamber before making a full turn. Hence, developing a "first turn around strategy" is a necessity for RHIC.

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II. RHIC LATTICE - ITS IMPERFECTIONS & CONSEQUENCES ON THE CLOSED ORBIT

There are four types of lattice imperfections which are considered to be major sources of orbit distortions. They are the error in the integrated dipole field strength $\Delta B\ell/B\ell$, the axial rotation of the dipole $\Delta\theta$, and the lateral displacements $\Delta_Q X$ and $\Delta_Q Y$ of the quadrupole in the two transverse directions. The RMS values of the lattice errors applicable to RHIC are the following ones:

$$\begin{gathered}\Delta\left(B\ell\right)/B\ell = 0.5\times10^{-3}, \qquad \Delta\theta = 10^{-3}\mathrm{rad} \\ \Delta_Q X = \Delta_Q Y = 0.25\times10^{-3}\mathrm{m}\ .\end{gathered} \tag{1}$$

We have simulated the closed orbit distortions in RHIC, with the above RMS values of random errors in the lattice. We used PATRIS as the code of choice. Throughout the simulation sextupoles were assumed to be thin lenses, but otherwise perfect, higher order non-linearities were absent, and the effects of errors were realistically incorporated into the 7×7 transfer matrix used by PATRIS. Beam position monitors were assumed ideal, i.e. perfectly aligned with the axis going through an ideally placed quadrupole and having a perfect sensitivity. They were placed beside each quadrupole and measured orbit distortions in the plane where beta function was large. Correctors were modeled as thin lenses, but otherwise they were also considered ideal, i.e. ideally placed like BPM's and having a perfect adjustability.

The results of our realistic closed orbit analysis showed the following characteristic features, tested on 10 different Gaussian distributions of lattice errors. With the accepted RMS values, with no correction and with no checks for possible violations of physical aperture restrictions, largest orbit distortions reached $\sim$ 40 - 50 mm at some BPM's in the arcs and $\sim$ 100 mm in the insertions. This means that the beam would have good chances to violate aperture limitations at some point and strike the wall of the vacuum chamber. This was one of the characteristic properties of the uncorrected closed orbit, but the same would happen during injection, resulting therefore in a beam loss and in a failure to make the very first turn around in the absence of any correction.

III. IMPROVED METHODS FOR CLOSED ORBIT CORRECTION

There are many ways of getting the beam around for the first time. Even though it is not necessary, one is tempted to use some of the methods developed for the purpose of closed orbit correction and adapt them to make the first turn around. However some restrictions do

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apply here. Closed orbit correction methods that require circulating beam are obviously inappropriate, while others may be applicable with more or less success. It is worthwhile to mention that the local three–bump method is one of the best methods and is easily adapted to steer the beam through the machine for the first time. Indeed, this was the method of our choice and we initially developed software based on this method. With the RHIC's realistic errors, the software accomplished the first turn around in just 2 or 3 injection attempts and subsequently closed and further corrected the orbit to distortions being less than one millimeter at BPM's.

This simple scheme, however, could not be implemented for RHIC's hardware in a straightforward manner; RHIC BPM's and correctors are not placed beside each other, but at the two opposite sides of each quadrupole. Hence, there is always a quadrupole, and in the arcs also a sextupole, inside each BPM – corrector pair. They both act as a significant orbit perturber and invalidate the simple three–bump method. This necessitated its generalization which we carried out.

Our starting point is the formula (4.7) for closed orbit distortions, appearing in ref [2]. If the errors can be reasonably represented as delta functions or kicks it goes over into[3]

$$Z_i = \frac{\sqrt{\beta_i}}{2\sin\pi\nu}\sum_{j=1}^{n}\theta_j\sqrt{\beta_j}\cos\nu\left(\varphi_i-\varphi_j-\pi\right) \qquad \varphi_i-\varphi_j>0 \tag{2}$$

which describes the effects of kicks at j-th locations (j=1,2... n) on the orbit distortion at i-th location Z_i. In this formula ν is the tune in the plane described by the above expression, θ_j is the effective kick at the j-th location, β is the appropriate beta function and φ the phase advance. Subscript j refers to the perturber, while i refers to the point of observation. In this formula, the effects of the perturbations, expressed through θ_j, are linearly propagated along the lattice, whose linear characteristics are in this formula still considered ideal. Of course, these θ_j need not be the actual lattice errors. They can also be deliberately delivered kicks, which will still produce orbit distortions in an otherwise ideal lattice.

Now consider a non–ideal lattice with many errors which produce orbit distortions R_i, read at n BPM's. To maximize the effectiveness of BPM's we place them beside each quadrupole where the relevant beta function is large. The actual errors will produce effects mainly described by an expression of type (2). Obviously, we do not know the exact nature, position and the magnitude of each error in the actual lattice. However, we do have the readings R_i and we can try to deliberately kick the beam so as to steer it through reflected distortions $-R_i$, in the absence of actual errors. When applied, these kicks will then act toward canceling the effects of actual errors to the leading order.

Now we simply take R_1, R_2, ... R_n, the readings at n BPM's, and demand that the n corresponding correctors deliver such kicks, expressed as angles θ_1, θ_2, ... θ_n, that they generate orbit distortions equal in magnitude but opposite in sign to those being measured, i. e. $Z_i = -R_i$. The expression (2) now yields:

$$\begin{aligned} Z_i = -R_i &= \frac{\sqrt{\beta_i}}{2\sin\pi\nu}\sum_{j=1}^{n}\theta_j\sqrt{\beta_j}\cos\nu\left(\varphi_i-\varphi_j-\pi\right) \\ &= \sum_{j=1}^{n}A_{ij}\theta_j \end{aligned} \tag{3}$$

Since the number of correctors is the same as the number of monitors, the matrix A_{ij} is a square, generally nonsingular matrix which can be inverted. After inverting it, we get the desired kick angles

$$\theta_i = \sum_{j=1}^{n}\left(A^{-1}\right)_{ij}Z_j = \sum_{j=1}^{n}\left(A^{-1}\right)_{ij}\left(-R_j\right) \tag{4}$$

which would steer the beam through the positions $Z_i = -R_i$, $i = 1, 2, \ldots n$, in the absence of errors and will consequently cancel distortions to the leading order in the presence of errors along with nonlinearities. Without nonlinearities the cancellation is complete.

IV. METHODS OF ACHIEVING THE FIRST TURN AROUND

The strategy goes as follows. The beam is injected and its progressing through the lattice is monitored on BPM's. The correctors are turned off, since initially one does not have any information on how to power them. Once the beam is lost by exceeding the available aperture at a certain place in the lattice, one knows the readings on all BPM's preceding the area where the beam is lost. These readings are simply introduced into the expression (4), and the orbit coordinates at the BPM's past the point of loss, where no readings have appeared yet, are simply left to be zero. The expression (4) then predicts fairly accurate values of kick angles for all correctors except for a couple of them around the injection point and where the beam is lost. All the other correctors between the injection point and the point where beam is lost are then energized and the beam is injected again. It then starts with significantly reduced distortions, passes the critical point, and continues along the lattice in the region with the correctors still not energized until it is lost again. The whole procedure of kick angle evaluation is now repeated and the newly found kick strengths are simply added to the previous values. The correctors are then energized again, with more of them being powered at this stage, and the beam is reinjected. This procedure is then continued until the beam makes its first turn around. With RHIC's RMS error levels, under ideal injection conditions assumed so far in the simulations, it usually takes just 2 or 3 injection attempts to make the first turn around.

There is another problem that shows up now. The orbit is established and its distortions are significantly reduced, but it is not completely corrected yet. That means that the injection point does not lie at the current, mostly corrected closed orbit. As a result, betatron oscillations develop the very moment the beam makes the first turn around. To prove that the large readings at the BPM's, which change from turn to turn, are really betatron oscillations, we plotted the readings at a fixed BPM for several dozen turns and observed that they lie on a typical phase space ellipse. At this stage, however, sizable readings, in a 1 - 5 mm range, may still appear at most monitors. But our analysis demonstrates that they are essentially free betatron oscillations which arise because one still does not inject at the actual closed orbit. These betatron oscillations are not desirable and would have to be removed either by an appropriate damping device[4] or by trying to adjust the initial injection conditions to better match the actual closed orbit. For the purpose of simulation, we developed a simple algorithm which on the basis of linear optics properties of the lattice and on the basis of some readings at BPM's evaluates the initial betatron amplitude and phase at the injection point, and then subsequently finds the actual closed orbit at the injection point by subtracting the betatron component out. With this knowledge one can try to adjust the injection initial conditions so that they better match the currently corrected (nonideal) closed orbit. After this readjustment, the betatron motion is significantly reduced, i. e. by one order of magnitude or better.

V. ACTUAL PERFORMANCE OF THE SOFTWARE

We developed a program for carrying out the "first turn around strategy". We installed it in the computer code PATRIS which served as a simulator which replaced a real machine. Special modules were built in PATRIS to simulate the progress of beam going around the lattice, aperture checks and BPM readings. Another module, based on expression (3) was developed to evaluate the kick angles θ_j which were necessary to prevent the beam loss at certain point in the lattice. This module is capable of working on a real machine, once it knows the linear optics properties of the lattice by reading them from an appropriate database, and is completely independent of PATRIS and the ways it simulates closed orbit errors. The only item the module needs is a sequence of BPM readings.

We performed many stringent tests of the software we developed. First of all, we wanted some redundancy so that the software can do more than just a bare minimum, provided there is enough strength available from the correctors to kick the beam properly. We tested this redundancy by shrinking the apertures to just 10% of their nominal values and tried to get the beam around. The software worked fine. Of course, more injection attempts were needed since the beam was lost much more frequently than under the normal operating conditions, but otherwise everything was normal. It is worthwhile to mention that these tests were being performed with the sextupoles at their full strengths and with realistic lattice errors.

Next stage was a large–scale testing. It was done for 10 different Gaussian distributions of random lattice errors, with RMS values given by (1) and with a 2.5 σ cut. The results were overwhelmingly positive. In most cases the code achieved its objective of making the first pass around in just 2 or 3 injection attempts. A little bit more was then needed for fine tuning of several correctors, only around the injection point, and for reduction of the magnitude of betatron motion. All this was done with the sextupoles at their full strengths. The quality of the orbit, established in this way, was excellent and only minute further corrections and adjustments may be needed.

Finally, we tested our software with one or two monitors malfunctioning in which case the corresponding correctors were not energized. The software was capable of establishing the first turn around without any difficulties. Only the quality of the orbit established under these conditions was somewhat degraded, primarily in the immediate vicinity of broken devices.

VI. CONCLUSION

We have developed a linear method of orbit correction which is more general than the simple three–bump method. As a minor drawback, it involves a large 123×123 matrix inversion for each plane, but on the other hand offers a very effective way of both establishing the first turn around and later corrections of the orbit. The quality of the orbit, established at the full sextupole strengths, is excellent - under ideal simulating conditions which include BPM's ideal in both sensitivity and placements, ideally placed and controlled correctors, simulated as thin lenses, ideal sextupoles which are also simulated as thin lenses, and no higher order nonlinearities, but with otherwise quite realistic lattice errors.

VII. REFERENCES

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