RHIC/AP/38

Low Beta Insertions in RHIC – Miscellaneous Issues

S. Ohnuma

University of Houston
Houston, TX 77204-5506

September 21, 1994

Summary

This is an extension of the work previously report, "Localized Control of the Orbit in the RHIC Insertions", AD/RHIC–112, August 1992. The lowest β^* is now 1m at two insertions, 6 o'clock and 8 o'clock, instead of 2m. Although the main conclusions given in the previous report are still valid, the requirement for the transverse alignments of quadrupole triplets at low–beta insertions may not be easy to realize if a truly local control of the closed orbit is required (instead of a global control). Other issues discussed in a qualitative manner are: 1) measurement of β^*, 2) errors in DX and D0 bend angles, 3) vibration of quadrupole triplets, and 4) linear coupling.

1. Introduction

In the report AD/RHIC–112, "Localized Control of the Orbit in the RHIC Insertions", August 1992, it was proosed that correctors be removed from Q1 and a BPM from Q2 in order to ease a certain difficulty in the physical layout of the quadrupole triplet and its neighboring dipole D0. Expected impact of the modification has been discussed briefly in that report but the lowest value of β^* at that time was 2m.

The proposed modification is now implemented in the final design but, at the same time, the lowest β^* is required to be 1m or even less. This change necessitates a review of the previous work in view of very large beta values which will exist in quadrupole triplets at 6 and 8 o'clock. In fact, almost all problems in insertions are dominated by the quadrupole triplets.

In addition to the question of localized control of the orbit within insertions, there are several issues that may require some thoughts before Day–One, and some (but by no means all) of them will be discussed qualitatively in this report.

I am grateful to Steve Tepikian who has been so patient in teaching me the idiosyncrasy of RHIC lattice in general and RHIC insertions in particular. Pat Thompson has kindly provided me with all the data on correction magnets. For understanding the Talman system of correcting the linear coupling, I owe Fulvia Pilat who has acquired some valuable practical experience at CERN. In the course of this work, I have benefited a great deal from two reports:

1. J. Wei, R. Gupta, and S. Peggs, "Magnetic Correction of RHIC Triplets", Particle Accelerator Conference, Washington, D.C., May 17–20, 1993.
2. S. Peggs, "Report on the Interaction Region Working Group", Workshop on Future Hadron Facilities in the US, Bloomington, Indiana, July 6–10, 1994.

2. Localized Control of the Orbit in the Low–Beta Insertions

According to Pat Thompson, the dipole correctors attached to quadrupoles in insertion triplets can deliver 0.285 T–m (integrated bend field) at 50 A. At the maximum design momentum of $(B\rho)$ = 840 T–m, this corresponds to 0.34 mr in kick angle. It is even possible, he says, to think about 75 A corresponding to 0.5 mr.

Since nonlinear effects in quadrupoles and dipoles are not included in estimating kick angles, its value scales linearly with the corresponding orbit change. In real operation, one usually proceeds with a small fraction of the total change required in order to avoid a possible gross error.

Task A. Localized control of (x, x', y, y') at IP.

Reasons for having this control have been given in the previous report and they are still valid. Conclusions in that report are also essentially unchanged even with $\beta^* = 1$m at two IPs.

If four correctors are to be used, the best combination is (Q6,Q2:Q3,Q5) in one direction (horizontal if 8 o'clock) and (Q5,Q3:Q2,Q6) in the other (vertical if 8 o'clock) direction. The avoidance of Q4 is necessitated from a peculiar feature of the insertion optics: when β^* is 1m, beta in the focusing direction at Q4 is smaller than beta in the defocusing direction at the same quadrupole.

$$\beta^* = 1\text{m}, \quad \text{beta} = 29\text{m in the focusing direction,}$$
$$= 46\text{m in the defocusing direction.}$$

Tables 1 and 2 illustrate the required kick angles in four quadrupoles together with the resulting orbit displacements in triplet quadrupoles. To what extent these undesirable displacements affect the dynamic aperture of the ring would ultimately determine the range of control one can have. The capability of correctors does not limit the range (within reason).

Table 1. $\beta^* = 10$m at all IPs.

a) displacement at IPs = 1 mm, angular change = 0

	Q6	Q2	Q3	Q5
kick angle (mr):	-0.016	0.026	0.023	0.011

orbit displ. in triplets (mm): (0.83, 1.30, 1.02; 0.97, 0.73, 0.93)

b) displacement at IPs = 0, angular change = 0.1 mr

	Q6	Q2	Q3	Q5
kick angle (mr):	0.044	0.016	-0.018	0.044

orbit displ. in triplets (mm): (-2.3, -3.6, -2.7; 2.6, 2.4, 3.7)

Table 2. $\beta^* = 1$m at 6 and 8 o'clock 10m elsewhere.

a) displacement at IPs = 1 mm, angular change = 0

	Q6	Q2	Q3	Q5
kick angle (mr):	-0.003	0.030	0.023	0.016

orbit displ. in triplets (mm): (0.26, 0.40, 0.35; 1.58, 1.28, 1.77)

b) displacement at IPs = 0, angular change = 0.1 mr

	Q6	Q2	Q3	Q5
kick angle (mr):	0.023	0.003	-0.009	0.035

orbit displ. in triplets (mm):(-2.41, -3.72, -2.72, 2.64, 2.40, 3.70)

If six correctors, (Q6,Q4,Q2:Q3,Q5,Q7), are used together, the required kick angles are reduced but there is no change in the orbit displacements in triplets. Since the required kick angles are already small even with four correctors, there is no advantage in using six correctors. More important is to find if one can control the orbit at IPs without so much resulting displacements in triplets. It is hoped here that the necessity for changing the beam direction at IPs would not arise in the operation.

Task B. Minimizing the orbit displacements within an insertion.

For $\beta^* = 10$m in all insertions, a global orbit correction with correctors in arcs as well as those in insertions will be the natural choice. The necessity of a strictly local orbit correction within an insertion may arise when β^* is reduced from 10m to 2m at two IPs. This is demonstrated in Figs. 1A and 1B.

In studying the closed orbit distortion, especially when β^* is small, it is important to distinguish two misalignments of quadrupoles in triplets, that is, one common to a triplet (represented by its rms value σ_c), and one within the triplet (represented by its rms value σ_r). Obviously, the effect of the common misalignment is much less than the other because of the partial cancellation within each triplet. In Figs. 1A and 1B the benchmark (relative factor = 1) is the rms closed orbit expected at Q3 (focusing) when β^* is 10m in all six insertions with $\sigma_c = 0$ and $\sigma_r = 10$ mils(=0.254mm). In order to avoid an extensive numerical calculation, it is assumed here that only two pairs of triplets in 6 o'clock insertion and two in 8 o'clock insertion (altogether twelve quadrupoles) contribute to the closed orbit distortion. This is justified since one is primarily interested in the case when β^* is reduced to 2m at these two IPs and twelve quadrupoles with large beta values dominate the contribution.

It is clear from Figs. 1A and 1B that, for σ_r larger than 5 mils or so, the common misalignment is rather unimportant. In the examples given here, 100 random samples have been used for each case and the rms values have been extracted. Roughly 70% of 100 samples will be within the rms values but one can of course be unlucky and may end up beyond the rms values. BPMs and correctors are all at 8 o'clock.

1. $\beta^* = 1$m at 8 o'clock only, 10m at all other IPs.

   $(\sigma_c, \sigma_r) = $ (15 mils, 5 mils)

   (a) horizontal.

   BPMs at (Q8,Q6,Q4,Q3;Q1,Q5,Q7,Q9,Q11)

   correctors at (Q10,Q8,Q6,Q4,Q2;Q3,Q5,Q7,Q9)

   largest kick angle in correctors: 0.23 mr (rms)

   largest residual orbit deviation in triplets: 2.5 mm (rms)

(b) vertical.

BPMs at (Q9,Q7,Q5,Q1;Q3,Q4,Q6,Q8,Q10)

correctors at (Q11,Q9,Q7,Q5,Q3;Q2,Q4,Q6,Q8)

largest kick angle in correctors: 0.24 mr (rms)

largest residual orbit deviation in triplets: 1.8 mm (rms)

2. $\beta^* = 1$m at 6 and 8 o'clock, 10m at all other IPs.

$(\sigma_c, \sigma_r) =$ (10 mils, 2.5 mils)

(a) horizontal.

largest kick angle in correctors: 0.35 mr (rms)

largest residual orbit deviation in triplets: 4.4 mm (rms)

(b) vertical.

largest kick angle in correctors: 0.25 mr (rms)

largest residual orbit deviation in triplets: 4.2 mm (rms)

The combinations (15 mils, 5 mils) and (10 mils, 2.5 mils) are given here with the belief that, in view of the residual orbit distortion in triplets, these are the maximum one can tolerate. If this specification is to tight to be realistic, one is forced to use a global correction when β^* is squeezed to 1m. How much residual orbit distortion in triplets will be allowed for a comfortable dynamic aperture is still an outstanding issue to be resolved.

3. Other Issues Requiring Attention

3.1. Measurement and fine tuning of β^* (and α^*)

The best way to measure beta (and possibly alpha) still seems to be the measurement of the change in tune when a quadrupole strength is varied. It is of course crucial that the effect of linear coupling be reduced as much as possible. Since it is not easy to remove the effect completely, one may have to include an "effective coupling parameter" as an additional unknown quantity in the interpretation of measurement data. One such procedure has been adopted at Fermilab some years ago with a reasonable success. (See, for example, Fermilab EXP–122, July 1985.)

Since it is not easy to introduce a special quadrupole at IP for this purpose, β^* (and α^*) must be deduced from the measurements with each of six quadrupoles in a pair of triplets used one at a time. There will be six nonlinear relations for two unknowns, β^* and α^*, so that a least–square analysis is needed to extract two unknowns. As beta varies rather significant within a quadrupole when β^* is reduced to 1m, it is desirable to use the exact expression for the integral of the quadrupole in each of six relations instead of the usual thin–lens approximation.

The viability of this procedure ("What is the accuracy of β^* from this method?") depends of course on how well one can measure the change in tune with the limited range of variable quadrupole strength. Perhaps more significant question is: once β^* and α^* are known with some accuracy, what are the procedures to adjust them? Although the latest Design Manual (May 1994) touches on this issue, a specific set of procedures are not spelled out. For example, would it be possible to connect trim power supplies and trim quadrupole magnets in such a way that corrections of β^* in two directions become orthogonal?

In addition to β^*, one may want to measure the dispersions X_p and Y_p at IPs as well. With a pair of BPMs in each direction adjacent to IP, it should be easy to find dispersions but their fine tuning is again something one much think about. Finally, it should be noted that the vertical dispersion at IP resulting from rolls in quadrupole triplets is not significant, less than 9mm or so with $\beta^* = 1$m in one insertion with 1 mr roll. Contributions arising from arc quadrupoles are unknown until the achievable roll angle of quadrupole field axes is established.

3.2. Errors in DX and D0 bend angles

The design values for these dipoles are

DX	3.7m long,	bend angle = 19 mrad,
D0	3.6m long,	bend angle = 15 mrad.

From single DX or D0 with 0.1% error, the expected orbit error at IP (with $\beta^* = 1$m) is 0.3mm or 0.2mm. Even with all twelve DXs and twelve D0s combined, the net effect should not exceed 2mm or so. From Tables 1 and 2 in Section 2, one sees that the required kick angles in (Q6,Q2;Q3,Q5) correctors are all very small and the resulting orbit changes in triplets are less than 4mm. Besides, if the bend field errors in DXs and D0s are static or changing but very slowly, position data from the nearby BPMs will be available for a possible feedback.

It should be noted here that if two DXs (or two D0s) in the same insertion have the common bend error, the net effect on the closed orbit at IP should vanish since one is positive and the other is negative in the bend direction.

How accurately one must control the closed orbit at IP must be determined in terms of the expected beam size there. Accepted values seems to be "less than $\sim 0.1\sigma$" where σ is the rms beam size.

protons	$\beta^* = 10$m	$0.1\sigma = (35 \sim 44)\mu$,
	$= 1$m	$= (11 \sim 14)\mu$,
Au	$\beta^* = 10$m	$0.1\sigma = (57 \sim 80)\mu$,
	$= 1$m	$= (18 \sim 25)\mu$.

This also specifies the needed resolution of the BPMs that are located immediately upstream and downstream of IP.

3.3. Vibration of quadrupole triplet

This would be me troublesome than the slow variation in the bend angle of DX and D0 if the frequency is high. Assume that a triplet is vibrating as a whole (all three quadrupoles together) within $\pm 50\mu$. With $\beta^* = 1$m, the resulting vibration of the colliding point will be of the order of 0.1mm, which is much more than 0.1σ. If the mode of vibration happens to be of the unluckiest type, the effect will be three times this value. Nevertheless, the required current in correctors is 1A or so and the feedback should not pose any problem if the vibration frequency is of the order of 10 Hz (corrector inductance 3H, according to Pat Thompson). A detailed study of the mechanical characteristics of triplet assembly is needed for better estimates of the feedback requirement.

3.4. Linear coupling

Two problems associated with linear coupling are recognized as something one simply must take care of. They are: 1) difficulty in diagnostic analysis of data, especially in commissioning, and 2) reduction in the available tune spread when the fractional values of two tunes cannot be close. Beyond this, however, there seems to be no consensus in what types of corrections are essential. For HERA and Tevatron, the control of a single resonance driving term (complex quantity) alone by means of two independent correction parameters is employed while in the SSC Collider design, a more comprehensive correction scheme with many more independent correctors has been proposed. The recent unfortunate event at Fermilab (a rolled quadrupole in the low–beta insertion) further confuses the picture since there is no straightforward explanation connecting the observed poor performance with the linear coupling alone.

In RHIC, there are eight skew correctors (8cm ID) with the maximum integrated gradient of 1.5T each and two correctors (13cm ID) with 1.1T each, in each insertion. The large aperture correctors are attached to Q3; most small aperture correctors are also located within insertions. The measure of effectiveness is $\sqrt{\beta_x \beta_y}$ at each corrector location:

$$\begin{aligned} \sqrt{\beta_x \beta_y} &= 23\text{m} \quad \text{at small–aperture correctors,} \\ &= 100\text{m} \quad \text{at large–aperture correctors when} \beta^* = 10\text{m,} \\ &= 940\text{m} \quad \text{at large–aperture correctors when} \beta^* = 1\text{m,} \end{aligned}$$

Thus four correctors at Q3s in 6 and 8 o'clock dominate the picture when β^* is 1m at these two IPs. Unfortunately, four correctors are almost "parallel" in phase relation so that they cannot provide two independent parameters to minimize the tune separation. (When β^* is 10m at all IPs, it is easy to provide an orthogonal system of corrections.)

Because of the large value of $\sqrt{\beta_x \beta_y}$, triplets in 6 and 8 o'clock should be the major source of linear coupling. With the common roll angle θ in a triplet, the resulting integrated skew gradient is $(200\ \theta)$T. If the three independent rolls add up in a triplet, the worst combination will produce $(700\ \theta)$T. The maximum capability of a corrector attached to Q3 then corresponds to 5.5 mrad (common roll) or to 1.6 mrad (worst combination of three rolls) which seem to be realizable.

Since all four correctors attached to Q3s in 6 and 8 o'clock are "equivalent" in reducing the tune separation when β^* is 1m there, it is not possible to tune them separately. Even with $\beta^* = 10$m, two correctors in 6 o'clock insertion (and two in 8 o'clock insertion) are "equivalent" and cannot be tuned separately if one observed the tune separation alone. It may be possible to tune them independently if the decoupling scheme proposed for the SSC collider (by R. Talman) is used in conjunction with horizontal and vertical BPMs at the same locations. The scheme should be tested with TEAPOT (if it has not already been done) to see if it works for RHIC.

One might consider the following scheme (as it was presented in my talk in August 1994):

> Create a local horizontal closed orbit bump using dipole correctors at (Q4,Q2;Q3,Q5) at 8 o'clock, for example. Observe the change in the vertical closed orbit (subtraction of two closed orbit files) at all vertical BPMs within the bump. Minimize the change by adjusting the skew correctors (upstream and downstream of IP) attached to Q3. The trouble with this scheme is related to unfavorable phase relations between two skew correctors and all BPMs inside the bump. It does not seem possible to have an independent tuning of two skew correctors unless one is willing to adopt the global scheme proposed by Talman.

4. Concluding Remarks

When β^* is reduced to 1m at two IPs, a number of questions still remain unresolved. Since almost all of them are caused by the large beta values created within triplets, they must be clarified before even small values of β^* are considered as the easiest way of increasing the luminosity. The price one must pay could easily wipe out any benefits one hopefully anticipates.